Renewable and Sustainable Energy Reviews 182 (2023) 113343

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Responsive FLEXibility: A smart local energy system

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ARTICLE INFO

Keywords:
Community energy
Decarbonisation
Local energy services
Smart grid
Smart local energy systems
Transactive energy

ABSTRACT

The transition towards a more decarbonised, resilient and distributed energy system requires local initiatives, such as Smart Local Energy Systems (SLES), which lead communities to gain self-sufficiency and become electricity islands. Although many SLES projects have been recently deployed, only a few of them have managed to be successful, mostly due to an initial knowledge gap in the SLES planning and deployment phases. This paper leverages the knowledge from the UK's largest SLES demonstrator in the Orkney Islands, named the Responsive FLEXibility (ReFLEX) project, to propose a framework that will help communities to successfully implement a SLES. First, this paper describes how the multi-services electrical SLES implemented in Orkney reduces the impact of the energy transition on the electrical infrastructure. We identify and discuss the main enablers and barriers to a successful SLES, based on a review of SLES projects in the UK. Second, to help future communities to implement SLES, we extend the Smart Grid Architecture Model (SGAM) into a comprehensive multi-vector Smart Local Energy Architecture Model (SLEAM) that includes all main energy services, namely power, heat and transport. This extended architecture model describes the main components and interaction layers that need to be addressed in a comprehensive SLES. Next, to inform successful deployment of SLES, an extensive list of key performance indicators for SLES is proposed and implemented for the ReFLEX project. Finally, we discuss lessons learnt from the ReFLEX project and we list required future technologies that enable communities, energy policy makers and regulatory bodies to best prepare for the energy transition.

1. Introduction

A radical transformation towards more distributed, resilient, decarbonised and equitable energy systems has started at a global scale. This energy transition originally aimed at addressing the climate crisis, but events such as the COVID-19 pandemic and the recent geopolitical energy crisis, are bringing in new requirements for energy systems, such as national energy autonomy and regulated energy prices. Dealing with the multitude of challenges that come with the energy transition requires cross-cutting initiatives and actions at a national, regional and local level. At a national level, central infrastructures, large energy producers and industrial consumers are encouraged to reduce their environmental impact by investing in large scale novel low-carbon technologies, large offshore and onshore wind and solar, but also industrial demand response. At the regional and local scale, smaller scale solutions are needed to achieve decarbonisation of buildings, transport and energy systems in a cost-effective way. Such solutions include deployment of decentralised energy storage and renewable generation installed in individual buildings and by local communities. Although national scale initiatives are essential to address the multiple challenges our societies are facing, local initiatives are a necessary and complementary approach with shorter time frames that are better suited to meet local requirements and needs.

Among others, local initiatives aim to reduce local consumption, increase collective self-consumption and local resilience [1,2]. Furthermore, smaller scale local projects, such as electricity islands, are suitable to test new solutions before implementing them at a national scale. Electricity islands can be considered as living labs or real-world test beds from which new insights and lessons can be learned about future energy systems. As an example, the Orkney Islands are already dealing with issues related to large penetration and deployment of renewables, which makes them relevant to implement and test innovative solutions that can subsequently be replicated, transferred and adopted at larger scales. The Orkney locality has therefore become an

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https://doi.org/10.1016/j.rser.2023.113343
Received 11 August 2022; Received in revised form 6 April 2023; Accepted 10 April 2023
Available online 30 May 2023

Nomenclature

Abbreviations

AI	Artificial Intelligence
ANM	Active Network Management
API	Application Programming Interface
DERs	Distributed Energy Resources
DLT	Distributed Ledger Technologies
DNO	Distribution Network Operator
DSM	Demand Side Management
DSO	Distribution System Operator
DSR	Demand Side Response
DUoS	Distribution Use of System
EV	Electric Vehicle
GDPR	General Data Protection Regulation
HEMS	Home Energy Management System
HP	Heat Pump
ICT	Information and Communication Technologies
IES	Integrated Energy System
IESC	Integrated Energy System COntroller
IoT	Internet of Things
IT	Information technology
KPI	Key Performance Indicator
LEM	Local Energy Market
LIFO	Last In First Out
LV	Low Voltage
Ofgem	Office of Gas and Electricity Markets
P2P	Peer-to-Peer
PV	Photovoltaics
ReFLEX	Responsive Flexibility
RES	Renewable Energy Sources
SAREF	Smart Applications REFerence
SCADA	Supervisory Control and Data Acquisition
SGAM	Smart Grid Architecture Model
SLEAM	Smart Local Energy Architecture Model
SLES	Smart Local Energy System
TCR	Targeted Charging Review
TNUoS	Transmission Network Use of System
TSO	Transmission System Operator
USEF	Universal Smart Energy Framework
VPP	Virtual Power Plant

early adopter for smart and innovative technologies, such as smart control and optimisation, flexibility provision and digitalisation, including artificial intelligence (AI) and blockchain technologies.

Smart Local Energy Systems (SLES), such as the Orkney paradigm, have established themselves as an essential part of the future energy system and a fundamental supportive approach towards mitigating climate change at a global scale. This is manifested in the numerous deployments of local solutions like SLES and energy communities throughout the world, and increased efforts of policy makers to update regulatory frameworks to enable such solutions [3]. An extensive catalogue for such projects deployed in the European Union can be found in [4] and in [5] for the UK. SLES consist of local energy systems, which typically deal with multiple energy services, commonly electricity, heat and transport, in an integrated way, and that provide value to the local community and economy by provision of fair, reliable and sustainable access to clean energy. Local approaches to energy systems contribute towards several United Nations Sustainability Development Goals (SDGs), more importantly provision of affordable and clean energy and sustainable cities and communities [6]. SLES favour the transition of passive energy consumers towards active prosumers, who participate in a local energy system through the deployment of local energy supply, smart energy demand management and provision of flexibility services to energy systems [7]. One of the greatest strengths of SLES approaches is their capability to achieve local tailored solutions that better reflect local specifications, values and requirements, however this also means that knowledge transferability to other projects or localities is harder to be achieved. As a result, although a large number of SLES initiatives have been launched in recent years [5,8], very few have been successful and many others either failed or had to cease due to a lack of public subsidies [9–11]. One of the prevailing causes for not achieving a successful and sustainable SLES reported in the literature, is the lack of preparation and knowledge about best practices related to the planning and deployment phases of SLES [12].

To bridge this knowledge gap, this paper proposes a framework that assists local communities to successfully deploy SLES. Based on the lessons learned from the Responsive FLEXibility (ReFLEX) project, one of the UK's largest SLES demonstrators, this paper highlights the key enablers and barriers to a successful SLES. Next, building on the learnings from the Smart Grid Architecture Model (SGAM), which focuses on power services, we propose an extended version called Smart Local Energy Architecture Model (SLEAM) that provides a comprehensive view of the main components and interactions that need to be considered when deploying a multi-services power, heat and transport SLES. Finally, we provide an extensive list of SLES metrics and key performance indicators (KPI) that can be used to monitor and assess the success of any local energy system. A practical application of this evaluation method is provided in this work for the ReFLEX project. Note here that while the practical application is specific to the UK case, the lessons learnt and broader analysis is relevant to other places around the globe facing similar challenges to successful deployment of SLES solutions.

The remainder of the paper is structured as follows. Section 2 demonstrates the need for SLES solutions to support the energy transition. Section 3 focuses on the definition of the conceptualisation of SLES and Section 4 presents an overview of the ReFLEX energy system. Sections 5 and 6 describe the enablers and barriers to SLES, respectively. Section 7 provides a comprehensive list of metrics to evaluate SLES. Finally, Section 8 summarises key findings and lessons learnt from the ReFLEX project, while Section 9 provides discussions around innovative solutions for future energy systems and Section 10 summarises the learning from this study. Finally, Section 10 concludes this work. The next section highlights some of the challenges that will be faced by local energy systems.

2. Net zero energy system transition and challenges

In most of developed countries, the power system was conceptualised and designed in the previous century, and adopted a centralised architecture that was well suited to serve a fossil fuel based system. With the proliferation of renewable energy sources (RES), the power system is becoming more decentralised and complex to manage and it is facing new challenges that will further intensify as we transition to a net zero electricity system. Most governments have started programs that aim to achieve net zero carbon emissions economies, such as the Industrial Strategy Challenge Fund from Innovate UK that funded the ReFLEX project. These initiatives require a plethora of actions, such as reducing consumption (e.g. reducing transport and heating demand), shifting some of the remaining usage to electrical technologies (e.g. electric vehicles (EVs) or heat pumps), and producing electricity and gas from low carbon technologies. A short summary of the approaches for the UK economy is listed below [13]:

- *Building sector*: an important plan for building Energy Performance Certificate (EPC) improvement, through the deployment of efficient heat pumps, through end-user behavioural changes and practices, and through the adoption of biogas and clean hydrogen in gas networks.
- *Industry*: efficiency improvement, shift of power conversion technologies towards electrical technologies, deployment of hydrogen based technologies and carbon capture and storage technologies.
- *Transport*: reduction of car usage (approximately 20%) and shift to zero local emissions vehicles such as EVs [14,15], or hydrogen fuel cell based for heavier vehicles. On the aviation side, the expected growth in demand should be limited to only 20% by 2050, whereas planes will be partially powered with sustainable aviation fuel, such as hydrogen.

Regarding the power sector in particular, the UK has set a target to reach net zero emissions by 2035, however it is widely accepted that it needs to go beyond this target towards achieving net-negative carbon electricity to compensate for other economic sectors, such as industry, freight, aviation and agriculture, which are difficult to decarbonise [16]. To make this possible the power sector needs to undergo a deep and radical transformation that entails great volumes of variable renewable generation assets being deployed and large electrification of transport and heat. Sale of petrol and diesel cars will terminate in 2030, these will largely be replaced by EVs, and 600,000 electric heat pumps are to be deployed by 2028. The shift towards electrification is expected to double the electricity generation [13], but also double [17] or treble the electricity demand by 2050 [18]. To cope with such volumes of new generation and demand the system needs to become smart and flexible. Flexibility can be delivered by a combination of supply-side flexibility, energy storage, flexible demand and demand side response, but also hydrogen technology solutions. Key to harnessing the flexibility the system needs is active participation and behavioural change of end users.

The transition to net zero will have a profound effect on electricity systems and will cause several technical challenges that can be broadly classified into two categories, first, violations of safe technical limits caused by increase of demand and second, violations caused by decentralised generation assets.

Electricity consumption will increase at the edge of the network, leading to higher currents in power lines and cables, especially at the distribution grid and low voltage (LV) grid level, where the value of resistance over reactance is significantly higher. This will lead to greater voltage variations that could push the grid to a state out of its operating range. In addition, there is an increasing risk of phase imbalance, which will strengthen the need for use of a neutral cable at the low voltage level.

Adverse effects of new electrical loads at the distribution network can be shown in the simulation analysis performed in this work, which looked at voltage profiles observed at the LV network for different rates of heat pumps and EVs adoption. The distribution grid used for the simulation analysis is the IEEE European low voltage test feeder network [20] shown in Fig. 1, assuming a constant voltage at the distribution feeder bus. Load profiles for heat pumps and EVs were extracted from large scale demonstration projects in the UK, namely the "Renewable Heat Premium Payment Scheme" [21], which monitored 700 heat pumps with a time granularity of 2 min and the "My Electric Avenue" project that monitored 200 EV users over a period of 18 months [22]. Base consumption profiles were extracted from data monitoring realised for the the purpose of the ReFLEX project [23], with a measurement time interval of 1 min. The analysis focused on estimation of the average number of minutes when voltage excursions occur over a period of a day, i.e. when voltage is outside the contractual range (+10%, −6%). Multiple scenarios were generated by random selection and placement of load profiles in the nodes of the network to allow generalisation of results that are independent of the initial load profile allocation. The study was run for varying adoption rates of EVs and heat pumps. Next, power flow analysis was performed using OpenDSS software tool and voltage profiles at each node of the LV network were recorded.

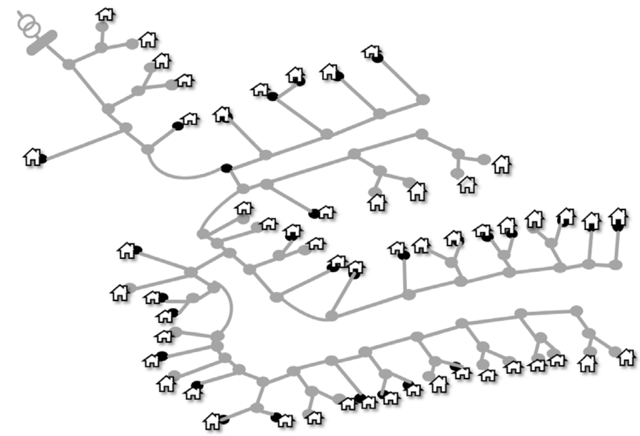

Fig. 1. European LV test feeder grid used to simulate the impact of decarbonisation on low voltage networks [19].

A summary of results for 50 randomly generated communities for each adoption rate scenario is shown in Fig. 2, where the evolution of the daily average number of voltage excursions as a function of the adoption rates of EVs and heat pumps is illustrated. Electrification of heat seems to have little effect on the local grid comparatively to EVs, which seem to have a higher impact. Most important, the result show that it is the combined effect of the electrification of heat and transport that increases considerably the number of voltage excursions in the distribution grid. This is due to user behavioural patterns observed within the demonstrator projects, as charging events and peak heat demand often occur at the same time. Researchers from My Electric Avenue project determined that grid reinforcements required to accommodate EVs will cost around £2.2bn by 2050 [22]. However, this cost might increase significantly if simultaneous deployment of heat pumps is taken into consideration. Finally, Fig. 3 shows that the distribution of load excursions mostly happens in the evening period (see blue curve). Therefore, smart solutions, such as local demand side flexibility with smart charging and smart heating aiming to shift consumption at other times, may enable deferment of grid reinforcement costs. Achieving such cost savings is one of the key objectives of a SLES.

Second, distributed or embedded generation may have similar effects on the electrical grid, including voltage and potentially frequency excursions, especially in areas with high solar PV installation rates [24,25]. Following a similar analysis as above, the orange curve in Fig. 3 shows the daily distribution of voltage excursions due to PV deployment for the LV European test network, which consists mainly of overvoltage effects, as opposed to the EVs and heat pumps analysis, where undervoltages prevailed. Although the daily number of overvoltage occurrences observed is similar to under-voltage occurrences observed in the case of EVs and HPs deployment, these voltage excursions do not occur at the same time and thus, do not cancel each other. A solution would be to reinforce the grid, but the cost estimated for the UK system is at £2.7bn per year [26], whereas Enedis, the French Distribution System Operator (DSO), estimates budgets between 0 and 24k€/MW/year of renewables installed [27]. A different solution is to adopt smart control solutions that extract flexibility from demand and generation assets connected to distribution grids.

In addition to dealing with technical challenges, the electricity sector needs to rethink the economic model practiced, the evolving role of consumers and utilities. Continuous deployment of distributed energy resources (DERs) calls for transformational change in grid regulation

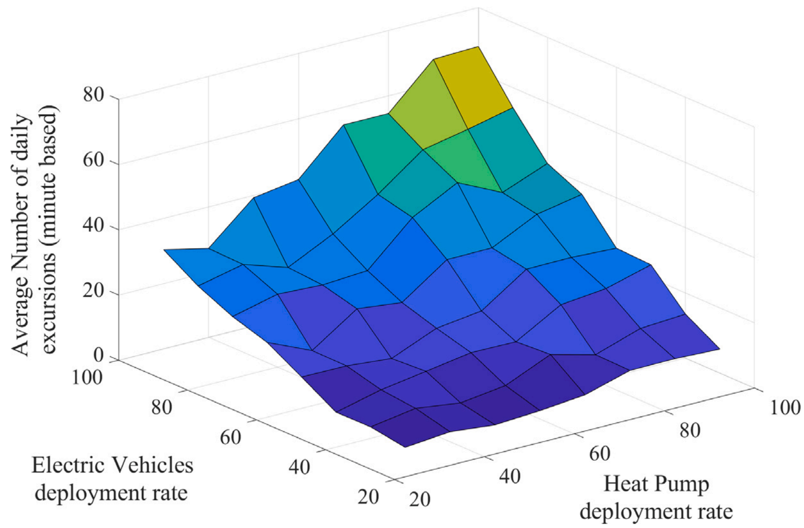

Fig. 2. Number of daily events with local voltage excursions in a typical low voltage network of a neighbourhood as a function of the deployment rates of heat pumps and electric vehicles.

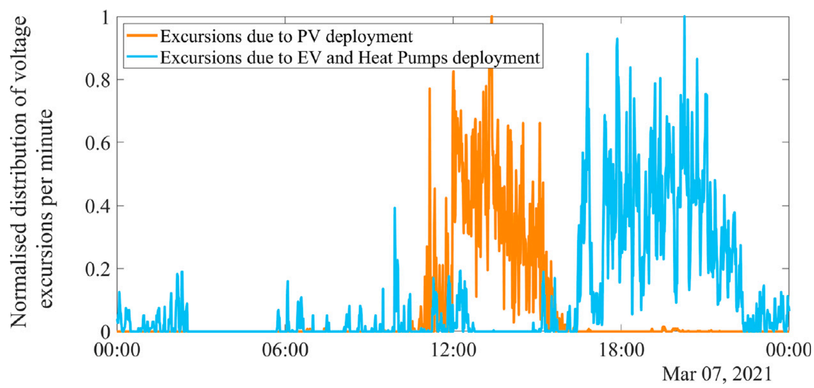

Fig. 3. Daily profile of voltage excursions due to the full adoption of PV (orange) or of heat pumps and electric vehicles (blue).

practices and control: first, given the intermittency of DERs, it will become more challenging to balance supply and demand, as these may vary significantly and may be difficult to forecast. As a consequence, the deployment of non-dispatchable energy sources will increase the need for aggregators and Virtual Power Plants (VPPs), in order to lower the risk of uncertainty when submitting bids to the wholesale energy and ancillary services markets. Second, other market solutions similar to the frequency regulation market may be required. Given the voltage variations expected from the deployment of EVs, HPs and PV, there will be a need for local flexibility services with adapted economic incentives.

To address these challenges, several works and solutions have been proposed by the scientific community that aimed at exploring the potential of local flexibility services, load shifting and demand response in local energy systems, either by improvement of control algorithms or market solutions for local energy systems. These works include smart control solutions for buildings, as proposed in [28–30], but also smart control algorithms for the optimisation of demand side flexibility [31–34]. Researchers have also focused on energy communities, for which they proposed new Peer-to-Peer (P2P) local markets solutions [35–37], but also algorithms to efficiently share energy produced within the community [38–42]. Techno-economic studies have also been proposed for local communities solutions, in order to assess the profitability of Demand Side Management (DSM) [43], to size assets [44,45], or to study the relevance of innovative solutions [46]. Finally, other works also start to investigate acceptability of flexibility by the end-users, as presented in [47], or to integrate comfort as an optimisation objective in the control decision [29]. In summary, most research works have focused either on the technical, financial and social challenges related to successful deployment of SLES, whereas in this study, we focus on a holistic approach across challenges and solutions for planning and operation of SLES based on the practical case study of the ReFLEX project, one of the largest demonstrator projects in the UK. The following section elaborates on the definition and scope of SLES in greater detail.

3. Smart local energy systems: definition and purpose

Smart Local Energy Systems (SLES) consist in energy systems that provide value locally in an intelligent way and consider an integrated approach to energy services, typically consisting electricity, heat and transport. SLES may be connected to the national energy system and aim to deliver clean, fair and reliable energy access to local consumers. These systems adapt to the local context and leverage innovative technologies, such as big data analysis (BDA), machine learning, Internet of Things (IoT) or blockchain technologies that favour the local economy, wellbeing and social development by promoting local initiatives, such as local production, energy management and energy exchanges. The main pillars and main objectives that constitute a SLES are listed below:

Decarbonisation: It is widely accepted that the net zero transition will require global or national solutions typically promoted by central governments, but also local initiatives organised by local authorities and citizen-led groups. Local solutions, such as those listed in Section 2, are becoming more relevant to achieve desired decarbonisation, as carbon footprint reduction increasingly requires local actions, such as end user consumption reduction and development of distributed low carbon technologies at the local level.

Resilience and reliability: With increasing effects of climate change being manifested at extreme weather phenomena and reduction of grid inertia caused by deployment of renewables, the ability of energy systems to avoid outages and restore to normal operating states i.e. reliability and resilience is emerging as a key focus area of SLES. SLES aim to benefit from a connection to the strong high-voltage national network, but at the same time they aim to reduce the risks of consumer power loss, by enabling distributed assets to supply local customers in case of a disconnection with the main grid [48]. This requires SLES to include a diversity of energy production assets and to have the ability to manage these local assets to ensure robust operation in islanded mode. SLES also aim to reduce the community dependency towards imported raw material such as imported fossil fuels and

Fair and accessible energy access: The recent energy price hike brought to the forefront the issue of energy affordability and fuel poverty. SLES seek to provide decarbonised energy at an affordable cost for everyone, especially by lowering the impact of fuel poverty on the most impoverished.

Efficiency: Both energy system decarbonisation and equitable access to affordable energy require the management and reduction of losses. Therefore, SLES aim to improve efficiency across the breadth of the energy system supply chain, including generation, transmission, distribution and final energy demand. Efficiencies can improve by placing generation assets closer to demand resulting in reduction of transmission and distribution losses, but also by taking energy demand reduction measures, such as better building insulation.

Social and local economy support: The empowerment of local communities to actively manage their own energy system is at the heart of SLES, that also seek to develop local employment opportunities, local redistribution of wealth and local energy services in line with social and community values.

Unlike current energy systems that are segregated across different energy vectors/carriers with centralised production and centralised flexibility provided from power plants and large consumers, SLES aim to solve local issues locally, in a cost-effective way. They consider an integrated approach to different energy vectors and services, so that synergies can emerge in the sense that requirements, issues and needs related to one vector can be accommodated by solutions related to a different vector. As an example, smart EV chargers or smart heating systems can help to reduce power generation curtailment caused by excessive deployment of RES by allowing community members to charge their vehicle or preheat their building premises at a lower cost. This differs from current energy system practices that do not provide any incentive or regulatory framework to favour local flexibility against hard local curtailment or centrally provided system flexibility. Furthermore, the current risk increase of load curtailment due to power supply issues as a result of the recent energy crisis is a strong argument in favour of SLES deployment, as SLES would aim to first use local distributed flexibility (batteries or power to gas solutions for the power sector, EVs for transport or smart heating solutions for heat) in order to reduce the demand locally and avoid local load curtailment.

An important actor in SLES are local energy communities, however there is a clear noteworthy distinction between SLES and communities such as those whose purpose relates to self-consumption and for which new frameworks have been established in several countries (see [49] for Spanish and [50] French initiatives for example). A comprehensive list of local energy community projects and policies at the European Union region can be found in [4]. A more detailed analysis focusing on the regulatory framework changes in the EU can be found in [51] and a review on market design options for local energy can be found in [52]. Such local energy communities aim to promote self-consumption at the boundary of the community itself (usually restricted to a geographical area of a few km^2), and are usually mostly focusing on the distribution of local production among community members. Most self-consumption communities are currently considering a single energy vector i.e. power, although gas is is also being considered in energy communities in France, and mostly concern financial aspects of locally produced energy and its distribution. Unlike self-consumption communities, SLES adopt a whole-system approach, considering multi-energy vectors, and integrating financial flows as well as the control of power flow through complex and dedicated information and communication technologies (ICT) and supervisory control and data acquisition (SCADA) infrastructure. When compared to local energy area planning, SLES differ by the fact that apart from planning, they also consider operational decisions. To summarise, SLES may include different local energy community schemes, in addition to considering all energy vectors, while simultaneously considering planning and operational decisions for a local region or community.

The next section describes the relevant case of the ReFLEX project, a SLES implementation in the Orkney Islands that aims to solve local electrical grid constraints by empowering the community.

4. ReFLEX energy system

In a nutshell, the ReFLEX (Responsive Flexibility) Orkney project aims to deploy a SLES, consisting of residential flexible assets and a smart control platform, and whose purpose is to increase local self-consumption, grid services provision and energy market participation. Responsive flexibility can be defined as a change in power consumption or production triggered by an external signal from a remote controller. The main objectives can either be to prevent local renewable energy curtailment, to balance the electrical system or participate in the wider electricity markets through an aggregator, whose aim is to manage its portfolio of assets by changing the shape of energy consumption or production, as dictated by wider markets or system needs. The following sections present the ReFLEX project in greater detail.

4.1. Local context

The Orkney Islands is a 990 km^2 archipelago in the Northern Isles of Scotland characterised by a dynamic agriculture and significant development of Renewable Energy Sources (RES). Orkney is connected to the UK mainland with a 33 kV connection that consists of two submarine cables with an approximate capacity of 20 MVA each, as shown in Fig. 4. This connection allows for Orkney's wind generators to export electricity to the mainland when the production is higher than local electric demand, and to import electricity from the main grid when the production does not match the local demand. Since 2013, the Orkney Islands produce enough annual renewable energy from wind turbines and solar PV to meet their overall annual electricity demand, although production does not match consumption at all times. Around 15% of annual electricity production from local wind turbines is curtailed due to network constraints. Indeed, the installed wind generation capacity reached 44.7 MW in 2019, whereas the local peak demand in winter does not exceed 25 MW. Although the maximum grid capacity was sized to support export of power, one of the subsea cables is disconnected for maintenance purposes, reducing the export capacity to 20 MVA, in which case the local Distribution Network Operator (DNO) curtails part of the wind generation when the net production exceeds the 20 MVA threshold. Furthermore, the distribution grid is also constrained locally i.e. within the orkney islands. Due to capacity limitations in several zones shown in Fig. 4, the DNO often curtails part of the wind generation, depending on the local production and consumption.

Curtailment is not equally distributed between wind generators, it depends on the location of the wind turbines and on the commercial agreement between the wind generators and the DNO. Older generators were installed at a time when the network capacity was adequate, therefore they experience no curtailment, whereas newly installed wind

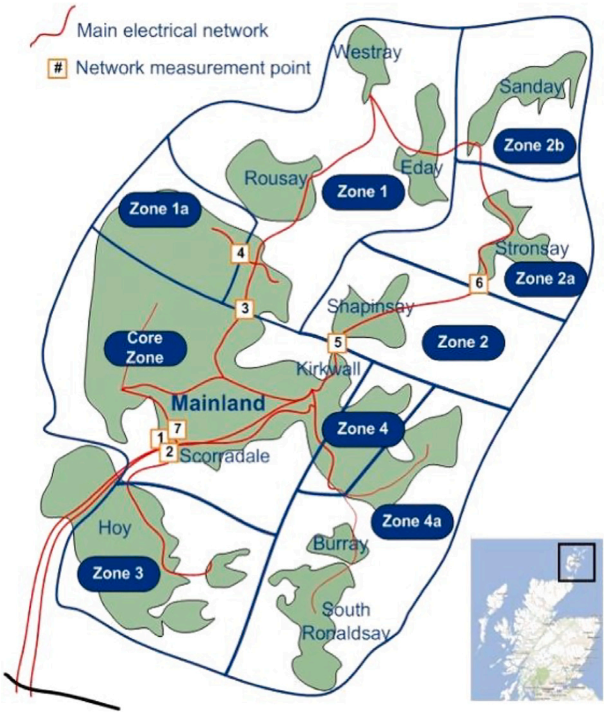

Fig. 4. Orkney's electrical grid representation.

turbines have signed a constrained access agreement that allows the DNO to curtail them in the case of network congestion, following a Last In First Out (LIFO) rule: the last wind turbine installed in a local zone experiencing congestion, is the first to be curtailed. Such curtailment strategies have significant repercussions for the profitability of wind generation projects, many of which are community-owned wind turbines. Hence, the local community is willing to explore SLES solutions, such as the ReFLEX project.

4.2. ReFLEX project

The ReFLEX project started in 2019 and aimed to install battery systems, smart electric heating and smart EV charging technologies to maximise the alignment of local energy demand to the RES production. ReFLEX brings together heat, power and transport services to create an islanded Smart Local Energy System, using a flexible grid system that links renewable generation with consumer demand. The project allows real-time control of local power generation, storage and residential energy demand based on community-led energy initiatives, such as new electricity tariffs schemes and EV smart charging. Its aim is to motivate the community engagement to further decarbonise its energy consumption and increase Orkney's system resilience. This is done through incentives for electrifying transport and heat, but also through the integration of energy storage into the local electric system and through deployment of digital infrastructure that allows real-time coordination and remote control of all flexible assets, including residential battery storage, smart electric vehicle chargers and smart heating systems. Finally, ReFLEX aims to pave the way for other SLES initiatives worldwide. It includes a strong techno-economic approach to highlight the current techno-economic barriers to SLES deployment, and aims to explore business models that allow energy usage decarbonisation at a low cost for the consumers. Indeed, one of the main challenge for a SLES is to ensure the economic viability of the solutions deployed. Storage assets and flexible demand are key to reduce wind curtailment in Orkney, but as shown in [53,54], if batteries are deployed with the sole purpose of local self-consumption, these are currently not financially viable, as they typically provide simple payback periods that exceed ten years for most of commercially available batteries sizes. Instead, storage assets that are integrated and controlled by the ReFLEX control system can be used to participate in wholesale energy markets and therefore increase revenues and ensure economic profitability. Smart chargers, electric storage and heat storage can also be used to provide grid services or to balance an energy supplier's or aggregator's portfolio, as shown in Section 4.2.2. This is possible by integrating a Virtual Power Plant (VPP) service into the ReFLEX control platform, and by selling electric production or consumption in wholesale markets, at the most favourable times. The ReFLEX project focused on three main axes to implement Orkney's SLES. First, the project focused on the technical deployment of a SLES operated locally by an Integrated Energy System Controller. Second, different use cases were proposed to design viable business models for decarbonisation of Orkney's energy consumption. Finally, through a strong community offering, the ReFLEX project aimed to strongly involve the local community to ensure that initiatives will have longevity. The following sections present these directions in greater detail.

4.2.1. Technical deployment of ReFLEX

As a demonstrator project, ReFLEX aims to install assets and operate them in order to provide and demonstrate a pathway towards decarbonisation. In this subsection, we highlight the assets installed within ReFLEX, and then describe the use cases and strategies to control these assets. In terms of assets deployment, the initial aim of the ReFLEX project was to install 500 energy kits in households of the community within three years. These kits included small domestic batteries (with around 10 kWh of capacity), solar PV and heat pumps that would significantly increase the flexibility offered by residential consumers. Regarding transport assets, a rollout of 500 smart EV chargers was initially planned. This would have offered an overall power capacity of 8 MW, for a cumulative investment of £10 millions, with a simple payback period of seven years. Hydrogen assets were also considered, in order to provide decarbonised heat and power through fuel cells. Other pre-existing energy assets were also considered to be included within ReFLEX, such as tidal turbines for electricity production and large scale wind turbines. Finally, solutions such as local heat networks were considered, especially for heat produced from hydrogen combined heat and power assets, but plans were not materialised for financial reasons. Also, although they are not part of ReFLEX assets, the purchase and shared use of electric vehicles was incentivised by the project. The original plan regarding asset roll-out, was amended for several reasons. First, for what concerns hydrogen assets, the strategy was to use electrolysers close to wind turbines with excess power that would be used to produce hydrogen during curtailment events. Hydrogen trailers would bring hydrogen close to consumers of heat. However, the market price of hydrogen did not allow the roll-out at the initial stages of the project and this was postponed for the later stages of the project. The deployment of residential assets, such as residential batteries, faced a strong opposition from the local Distribution Network Operator (DNO), as these assets were thought of as potential producers of energy during curtailment events. As a result, the installation of residential batteries by the ReFLEX consortium was prohibited. This reduced the scope of assets deployment to EV chargers and smart heating solutions, that are leveraged by the integrated energy system controller (IESC) to increase the domestic power load during periods of excess power from wind turbines and curtailment events. The SLES built within ReFLEX is a complex system of both physical hardware (vehicles, production assets, batteries, chargers, etc.) and digital subsystems (control systems, software solutions, numerical models) with an overarching control system referred to as the integrated energy system, called FlexiGrid™. An overview of Orkney's SLES architecture is shown in Fig. 5.

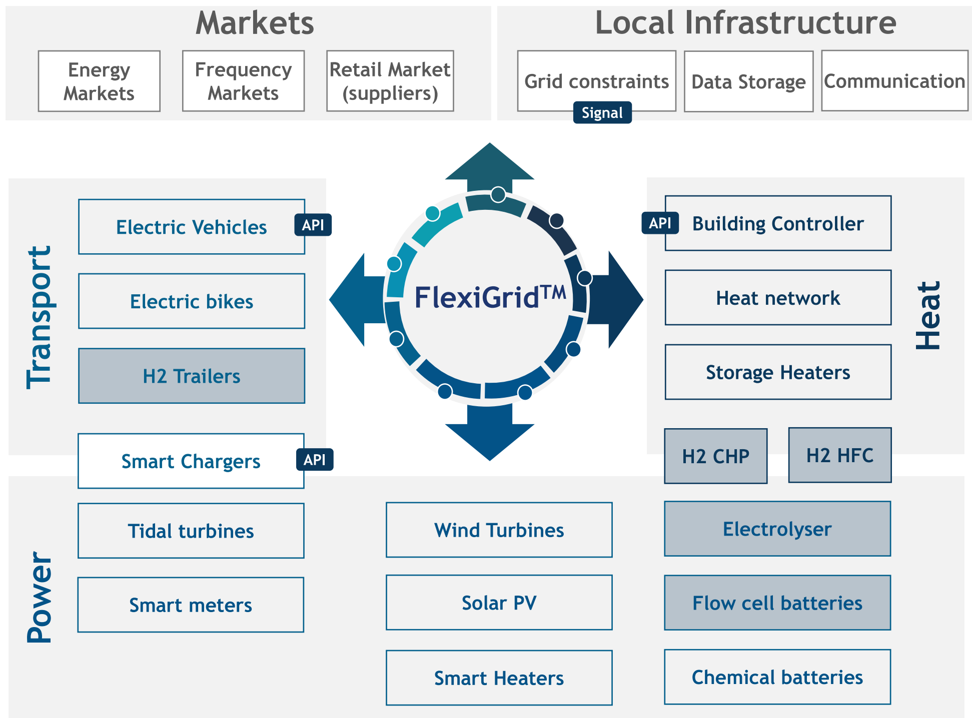

Fig. 5. Architecture of the ReFLEX SLES, where greyed boxes correspond to hydrogen technologies.

FlexiGrid™ coordinates electric transport, heat and power demand to constitute a flexible demand that mostly responds to local production curtailment events to reduce wasting of local renewable energy. Flexible demand is directly controlled by the FlexiGrid™ platform. The controller determines desired power profiles of flexible assets by communicating with APIs provided by the devices' manufacturers (e.g. zappi chargers for EV smart chargers [55]). The load control strategy is adapted and inspired from the algorithm described in [53], where residential flexible loads are used to provide optimal services for end-users (e.g. self-consumption), and respond to the controller's requests in case of local grid congestion events or commitments to wholesale electricity markets. To summarise, the ReFLEX project has set up a remote control platform that aims to send requests to Orkney's flexible loads (batteries, smart chargers, smart heating systems) in order to either reduce the curtailment of local renewable energy production, or participate in wholesale markets (energy or ancillary services) through the integration of ReFLEX' flexible assets into an aggregator's portfolio. Up to date, mostly smart chargers have been installed. They constitute the flexible assets responsive to FlexiGrid™ signals to reduce or prevent curtailment, as they are able to increase their power consumption on request and are able to counterbalance the voltage excursions and thermal limits of network cables described in Section 2.

4.2.2. ReFLEX use cases

This section summarises the different use cases implemented by the ReFLEX project. The *first use case* is utilising the assets deployed within ReFLEX to avoid curtailment of locally produced renewable generation, which can be as high as 15–20% of the energy that could have been produced, leading to a loss of thousands of pounds from the local economy. Within this use case, ReFLEX demonstrates the capability to use its storage assets, EVs but also hydrogen assets (electrolyser and flow cell battery) that could have been used to accept otherwise curtailed electricity which could then have been discharged to the grid when the grid constraints drop. However, this requires contractual and technical agreements with the local wind turbines and real-time information on curtailment events from the grid operator. Although it has not been deployed yet, a local energy market structure has been explored as a research direction in order to determine quantities and prices for energy trading between wind turbines and consumers, as described in Section 4.2.3. *The second use case* proposed by ReFLEX is participation in the grid balancing mechanism. Grid balancing is one of the tools that the electricity system operator (ESO) uses to balance electricity supply and demand close to real time. When the ESO predicts an imbalance between the energy produced and energy consumed at a certain time period, they accept bids or offers from energy assets to either increase or decrease generation (or consumption). This mechanism is used to balance supply and demand within each half hour trading period of in the wholesale electricity market. ReFLEX assets can participate in the balancing mechanism, however participation is currently open to assets with a minimum capacity of 1 MW, hence aggregation of different assets is required for this use case. The *third use case* focuses on the procurement of frequency response services from distributed assets. Frequency response services consist in the commitment of a certain amount of power to change the power production or consumption in real-time depending on the frequency deviation from its nominal value (50 Hz in Europe) to ensure real-time balance between production and demand. When the frequency is below its nominal value, this means that the demand connected to the main grid is greater than production. In this case, assets within ReFLEX can reduce their consumption, and thus help in restoring the frequency back to its nominal value. The required change in power is proportional to the frequency deviation, based on a droop coefficient, and must be provided in real-time. This requires smart control capability deployed at the asset level, rather than through a platform like FlexiGrid™, which could result in communication latencies larger than the required reaction time for participation in frequency control.

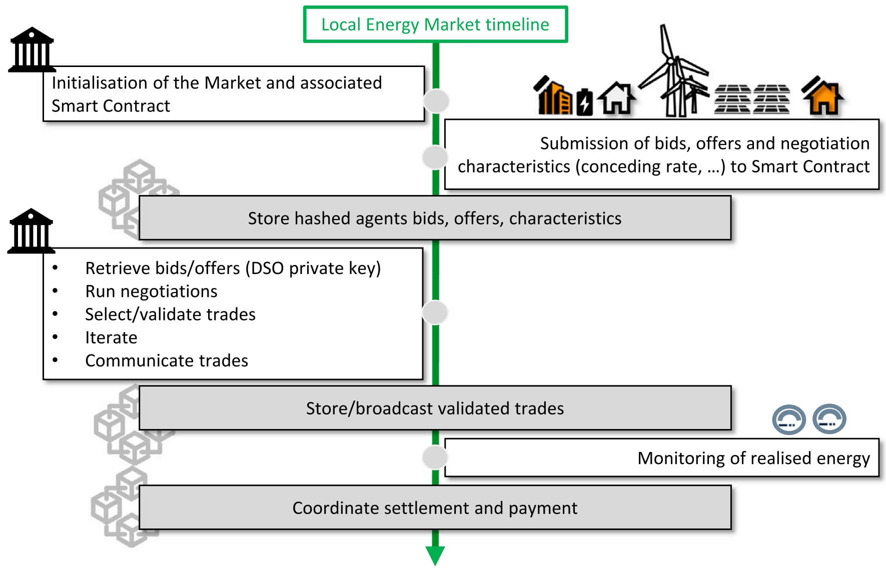

Fig. 6. Process followed by the Automated Negotiation Smart Contract for ReFLEX LEM.

4.2.3. Local energy market

As it was mentioned in the first use case presented in Section 4.2.2, ReFLEX's flexible assets such as residential batteries, smart heating systems or electric vehicles are used to reduce curtailment from wind turbines in the event of high wind. This allows wind turbines owners to increase their profitability whereas consumers could reduce their energy cost if this flexibility was paid for. Although this flexibility service is currently provided for free by consumers during experimental trials, a local energy market (LEM) structure has been explored. This LEM is based on automated negotiations, as presented in [56]. In this LEM set-up, producers (wind turbine owners) are requested to submit their selling prices, conceding rates and energy quantities to sell for all trading time periods considered (slots of 4 h within ReFLEX' setting). The conceding rate represents the speed at which the seller will agree to reduce the price during the negotiations steps. On the other side, consumers are requested as well to provide their energy quantity needs and flexibility, prices and conceding rates for all trading periods. Then, automated negotiations are automatically run at constant time intervals by the trading platform between all consumers and all sellers. Using an iterative process, consumers are first ranked by chronological order of their bid submission. Then, each consumer negotiates with all sellers one after the other and are awarded with trades that suit them the most (in terms of price and preference, as some consumers might prefer to buy energy from their own community wind turbine). Then all the bargains reached between consumers and sellers are validated by the DSO, or optimally reduced in case of grid constraints. These steps are then repeated until no energy remains to be bought, sold, or until no bargain can be reached between Wind turbines owners and consumers.

Furthermore, a smart contract has been developed to allow all these steps to be automatically run in a distributed environment. The whole process is summarised in Fig. 6.

4.2.4. Services to the community

On top of the deployment of assets and control system described in Section 4.2.1, the industrial ReFLEX project proposed several services to the Orkney community to amplify community engagement and ensure the financial viability of the proposed technical solutions. First, ReFLEX set up a community membership programme that gives access to the different services proposed by ReFLEX, but only applies to people who have their primary place of residence in Orkney. This aimed to create a ReFLEX community and promote ReFLEX initiatives. By the end of 2022, the ReFLEX Orkney community counted around 1,000 members, which represents 5% of the total Orkney population. The services proposed to ReFLEX members are as follows: The first service aims to support the decarbonisation of transport through an offer to switch to electric vehicles, which consists in offering members to test an EV, lease a new EV or to buy a second hand EV. Second, ReFLEX members have access to offers for smart charger installation [55] at a lower cost with the added capability of interactive monitoring and remote control thanks to their integration in the FlexiGrid™ platform that allows an increase in charging power in the case of curtailment events. Finally, the latest offering consists in access to the ReFLEX fully electric fleet of pay-as-you go hire electric vehicles with no monthly charge and reduced tariffs. ReFLEX has teamed up with co-wheel [57] to propose this offering, which allows Orkney citizens to hire an EV instead of owning one. By the end of 2022, ReFLEX has allowed an increase of ownership of over 150 EVs, with over 210 residential EV smart charging points, and enrolled over 180 people in the local shared electric car club that offers 5 community electric vehicles.

Power related end-users services mostly aimed to propose ReFLEX members an "Energy as a Service" offer, that allowed them to participate in the flexible integrated energy system, with 100% renewable energy, while reducing their energy consumption bill. This offer proposed a fixed rate tariff by a supplier contracted within ReFLEX. This reduced fixed tariff was designed to include electricity supply from renewable electricity generation, but also to finance the investment in distributed generation and smart consumption assets (solar PV, batteries, smart heating system) that will then be leveraged by the FlexiGrid™ platform to implement the use cases proposed in Section 4.2.2 (local curtailment avoidance, participation in wholesale energy markets and frequency regulation). The tariff corresponds to a "no-upfront cost" model for the deployment of domestic assets such as smart heating systems, PV and batteries for which the investment will be recovered through reduced energy bills over the installations lifetime. However, given the increase in energy prices, the long payback periods (around 15 years for solar PV and batteries) and the obstacles from the DNO to install domestic residential assets, this fixed tariff was proposed for 1 year only without the offering being renewed. Further participation was implemented on a voluntary basis.

Heat services consist in providing support to find appropriate solutions to reduce household heating requirements. In this case, ReFLEX acted as an intermediary organisation that assists its members to identify the right financing or installation solutions.

Finally, a more general service proposed to ReFLEX members is the offer to install monitoring equipment at members' houses in order to identify energy efficiency solutions that could help decarbonising or reducing energy bills. By the end of 2022, the main active power of 115 households with membership were monitored with a time resolution of one minute using hall-effect sensors from Efergy that send data through wifi connection [58]. It is worth noting that during the COVID period, end-users were guided remotely to install these monitoring assets by themselves.

Despite a strong involvement of the Orkney community, the outcomes reached at this intermediary stage of the project do not meet the goals that were set at the beginning of the project. Indeed, although responsive flexibility was planned to be provided by more than 500 residential batteries and 500 smart chargers, several constraints forced the ReFLEX consortium to reduce the targets and only install 150 smart chargers. The rest of this study aims to leverage the current experience on ReFLEX to understand what were the key enablers and obstacles to the deployment the SLES.

4.2.5. Experiments for wind curtailment avoidance

In this section, we present the experiments that were carried out within the first use case that aimed to reduce wind turbines curtailment through the dispatch of flexible assets such as EV chargers. For these experiments, around 40 out of the 150 smart chargers were considered for geographical reasons, as they were physically based in the same geographical area as curtailed wind turbines. During the several trials held within the winter period, around one third of participating end-users actually engaged and provided flexibility to the grid. Building on the connectivity of smart chargers through an Application Programming Interface (API) provided by the chargers manufacturer [55], the ReFLEX' IESC was able to retrieve EV charging power in real-time (with a sampling period of 1 min), and to control this charging power through POST requests sent to the EV chargers manufacturer's API in case of risk of curtailment. Therefore, using wind and curtailment forecasts from [59,60], the IESC automatically anticipates the need for a flexibility event in case of high wind forecast. Using emails and SMS, participating end-users are then contacted to connect their EV to their charger a few hours before the forecasted time of curtailment event. At their connection time, their charging power is then reduced in order to increase their charging time, whereas this power is increased to the maximum (3.7 kW or 7 kW depending on the car's model) at the time of high wind forecast. Fig. 7 highlights the different steps followed by the IESC during curtailment avoidance trials. First, the IESC, represented by the larger box on the right side of Fig. 7 constantly gets the status of all EV chargers (i.e. their charging power and the information about the presence of an EV). In parallel, it sends requests for curtailment probability forecast. In the case of a high curtailment risk, notifications are sent in advance to end-users so they can connect their EV before the time of the curtailment event. Then the IESC remotely changes the charging power in order to avoid the wind turbines curtailment. Finally, a real-time visualisation is provided to the IES management team. The different software components developed within ReFLEX were embedded into a container to ease the deployment, the maintenance and the replication.

In the next section, enablers for successful implementation of SLES are discussed.

5. Enablers for successful smart local energy systems

The design and operation of SLES requires several stages that can be categorised into planning and operational actions. The enablers listed below are learnings gathered during the ReFLEX project and during the review process of other SLES projects from the UK. They have been categorised in drivers for the planning phase of SLES, and drivers for the operational phase of SLES.

5.1. SLES planning

5.1.1. Understanding the local context

The first step towards SLES implementation requires a good understanding and deriving a baseline assessment of the local and national contexts. This incorporates the following categories:

Carbon emissions: carbon emissions of all local sectors should be assessed using carbon calculators officially available. This includes the calculation of $CO2_{eq}$ emissions associated with heating, transport and electricity consumption, but should also include industry, local farming and land use. A geographical assessment is also required to highlight any differences in different geographic areas, so that priority areas can be identified and prioritised. *Local infrastructure and land assessment:* it includes the understanding of the local infrastructure available, such as transport infrastructure (cars, buses, boats, flights, road networks), but also the energy transmission and distribution infrastructure (electricity network, gas network, heat network, hydrogen). This assessment may include evaluation of the reinforcement needs, network constraints and limitations, and operating characteristics (voltage levels, presence of an Active Network Management, etc) in the SLES area. *Local stakeholders mapping and their relationships with national/international institutions:* local stakeholders mapping and involvement approval is key for a successful SLES deployment. Engagement of key stakeholders is then required from the planning stage. Key stakeholders also include local authorities, such as the local council, the distribution network and transport operators, banks or funding bodies. *National scale stakeholders:* As shown in [61], local businesses dedicated to a single SLES are usually not financially sustainable. As a result, SLES planners should map national and regional stakeholders and approach them to leverage their services and expertise to provide local solutions at a lower cost, and for a longer time period. *Local economic and social situation:* the aim of this task is to make an inventory of the local socio-economic situation, in order to identify local strengths and weaknesses, such as what is the level of fuel poverty or the financial capacity to afford EVs in the project locality. Also, this step aims to identify local businesses that could contribute to the SLES directly or indirectly. They could be local manufacturers, energy providers or producers, installers, media, marketing or financing companies, schools and universities. *Geographical and time series specificities:* local assessment of transport, energy consumption and production should be done by considering appropriate temporal and spatial scales. Geographic considerations include characteristics of the local geographical environment, such as mountains, river locations and locations of protected areas. Geographic considerations also provide the distance between different assets or the flow of goods and people required to decrease the carbon footprint of transport. Similarly, temporal characteristics, such as time series considerations, are required to determine the self-production rate. Finally, future geographical and time series characteristics should also be considered, such as what a potential load curve could be after a shift towards electric transportation. It is a necessary analysis to determine the most relevant technical choices to maximise self-production (need for storage assets or load shifting). Within the local context analysis, ReFLEX has highlighted the risk related to the lack of involvement from the local DNO and energy supplier. In the ReFLEX paradigm, lack of early involvement and engagement with the DNO resulted in several types of assets not being deployed. Establishing a strategic partnership with the local DNO is also critical for best informing consumer offerings

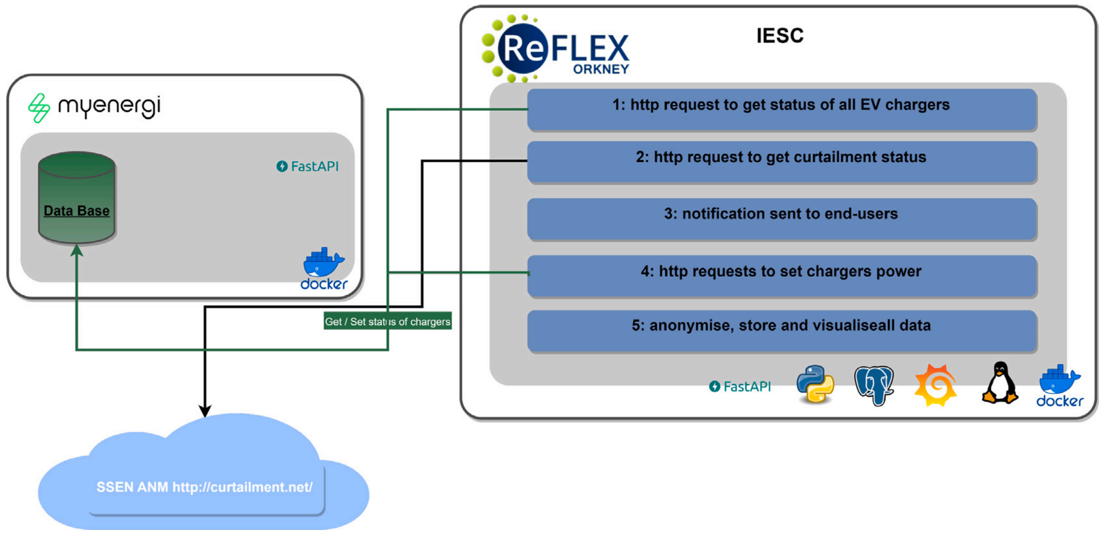

Fig. 7. Architecture of the IESC protocol for EV chargers flexibility for curtailment avoidance.

under different use cases. For example, collaboration with the DNO, enables better understanding of the local Active Network Management (ANM) strategy or algorithm used for wind generation curtailment. The order of resulting curtailment helped targeting those wind generators that would benefit the most from the activation of flexible loads such as smart EV chargers during curtailment events. Furthermore, to better understand the carbon reduction needs, ReFLEX has implemented a carbon calculator [62] for Orkney citizens that helps them to understand what behavioural changes would have the greatest impacts, and at the same time helps the ReFLEX team to propose the right solutions to the corresponding geographic locations.

5.1.2. Understanding of local and national policies

Solutions such as solar PV, wind turbines, batteries, EV chargers or flexibility mechanisms such as Demand Side Management (DSM) or Peer-to-Peer (P2P) energy trading have to fit in the current regulatory environment. For example, generation assets may not be allowed in certain areas (e.g. solar PV cannot be installed close to historical monuments). Another example relates to the use of private and sensitive data for SLES coordination that needs to comply with national regulations, such as GDPR. These considerations led ReFLEX to set up a Data Working Group to define a process for internal and external organisations to access ReFLEX data. Furthermore, the understanding of national policies was critical for ReFLEX, as it helped defining an economically viable business model to finance the assets deployment, especially at times when regulations change very rapidly [63].

5.1.3. Understanding of existing financing instruments

This stage aims to identify the local, national or international funding instruments that may be utilised to reduce the financial risk for private investors and maximise the value generated by the successful deployment of SLES.

5.1.4. Determination of a viable business model

The success of a SLES is based on the capacity of stakeholders to generate enough revenue to be financially sustainable. Therefore, one of the most important step in the planning phase is the design of a profitable business model for the key stakeholders involved. This requires the identification of the main activities, revenue streams, key partners, customers and cost structure. As discussed in [64], local businesses related to SLES are usually not profitable enough due to high fixed operational costs and small revenues per customer. Therefore, it is necessary that stakeholders contributing to the SLES have access to other sources of revenue [53], or through increasing the number of customers, which can be achieved by being involved in multiple SLES projects. Also, stakeholders can consider either selling products and services or leasing their assets and provide "Energy as a service" models. Within ReFLEX, an "Energy as a Service" offer was proposed to ReFLEX members. This "no-upfront cost model" allowed the deployment of residential PV and batteries owned by ReFLEX, with the investment recovered through reduced energy bills over the installations lifetime. However, the energy crisis and the delay in installation of residential batteries prevented this business model from being quickly profitable.

5.1.5. Understanding of historical SLES projects

Many SLES or equivalent projects have been funded and deployed in the last few years. An overview of most of these projects can be found in [5,12,65,66], where best practices and business models that allowed such SLES to be successful are discussed. Although SLES solutions need to be customised to fit local specificities, lessons learnt from already deployed initiatives can inspire new SLES projects.

5.1.6. Setting up main project objectives and a local governance scheme

Before setting up objectives, the SLES management team should assess the current state of the local energy system, which in turn can be used as a reference or baseline scenario. Informed by previous SLES experiences and by the assessment of the baseline situation, objectives of the SLES can include carbon emissions reduction, fuel poverty reduction, or local resilience improvement. Section 7 provides a comprehensive list of KPIs for SLES. In parallel, the involvement of the local community is key to achieve SLES objectives. To initiate citizens engagement, a common approach is to invite citizens to contribute to key decisions by forming a local governance system that is responsible to validate main strategic actions, including specific objectives and goals, data protection strategy, funding validation, etc. This is why these two preliminary tasks should be considered in parallel. Due to regulatory changes and obstacles, some objectives within ReFLEX had to be changed several times during the project lifetime. This is why a local governance team was set up in order to make objectives evolve depending on regulations and local specifications.

5.1.7. Whole energy system modelling

After the initial local assessment and determination of the SLES objectives, the SLES planning phase requires the utilisation of different modelling tools that are able to determine the type, number of assets and infrastructure required. These models should enable a multi-services and multi-vector approach with particular focus on:

Electricity: Models that allow time series simulations for end user production, consumption and grid modelling infrastructure can identify the need for specific local generation system, storage assets, demand side management, or grid reinforcement [38]. Assessment of associated costs may lead to compromises between the SLES objectives and available budget.

Heating: Models should aim to identify the heat reduction potential through insulation and energy efficiency measures considering different building archetypes [67,68]. Next, optimisation simulations can lead to the identification of specific smart heating system for the community, either through larger scale heat pumps, district heating, individual heat pumps or green gas networks. Models should identify suitable system sizing and associated costs required, and finally should identify any compromises between the objectives and investment requirements.

Transport: Starting from the initial assessment of flows of goods and people, several software simulation tools such as in [69–72] can optimise the mix of EVs, hydrogen vehicles, public transportation and infrastructure investments required to achieve SLES goals.

Economic modelling: A SLES need to be economically viable. Therefore, it is necessary to assess potential business models using historic market prices and to assess potential costs and benefits over the following years, using time series data. Economic studies should also identify needs of local skills, employment and education programs. Multi-agent modelling is a relevant framework to study economic behaviour of energy stakeholders, producers and consumers, that can be used to design new business models or market mechanisms for future energy systems [38,73].

Social models: The energy transition will undoubtedly require significant end-user behavioural changes, therefore it is necessary to study the responsiveness of citizens to flexibility requirements and their acceptance towards technological solutions such as smart EV charging or remote load control. Social science research should inform studies about user acceptability and results should then be integrated in multi-agent models that aim to determine optimal smart energy management solutions [74].

Finally, whole system models that include different energy vectors and services can be very useful in the planning phase of SLES so that optimal energy system designs are identified for a specific community. Note here that such models can be complex and may require cross-simulations between different software packages. In relation to energy models, European Telecommunications Standards Institut (ETSI) has proposed a smart grid architecture model (SGAM) framework to guide engineers and researchers through the different levels of interactions that should be considered in the design of a smart grid project. Inspired by SGAM, we propose a broader Smart Local Energy Architecture Model (SLEAM) that focuses on SLES providing multiple energy services across all energy vectors, as shown in Fig. 8. The aim of such an architecture is to highlight all the building blocks that constitute a SLES project and their interactions. Similarly to SGAM, ReFLEX reused the concept of zones and domains, with a layered architecture. Domains at the bottom left represent the different geographical scales of SLES subsystems, starting from the *customer premises* at the bottom right of the domains axis in Fig. 8, and ending at the connection point with the national energy system at the far left (*National scale generation & transmission*), that corresponds for example to the transmission system for the electricity vector or the highways for the transport vector. Other geographic scales considered in the SLEAM are the *distribution* networks for electricity, heat and transport (roads), and then the *distributed energy sources*, such as wind and solar PV farms, heat, fuel or gas stations. Zones at the right side of Fig. 8 represent different levels of data or information management. *Assets and power conversion* level is the starting zone followed by the *end users actions*, the *monitoring and control* chain i.e. sensors, concentrators and servers that take operational decisions, *stakeholders*, such as installation and manufacturing companies, and *local energy markets*. The zones connect then at the far right with the *national scale information link*, that includes external stakeholders or national scale regulators and markets. Finally, vertical layers of the SLEAM consist of the *component layer* containing all physical assets, including power conversion, monitoring, and data processing assets. The *ICT layer* that corresponds to the protocols and data models, the *function & services layer*, that contains all actual functions (such as technical control, optimisation, or financial transactions) and the services created by or provided to the SLES (forecasting, market clearing, fault detection, etc), a *behavioural layer* that allows the SLEAM to take into account the interactions between the SLES, the community and end users. Finally, as for the SGAM architecture, the *business layer* and the *regulation layer* provide the dependencies to local businesses and regulations requirements. As the SLEAM covers all three main energy services, such as power (in blue in Fig. 8), heat or gas (green) and transport (yellow), it allows direct links between each of these vectors, as it is shown by the lines at the "Assets and Power conversion" zone. Indeed, electrical distribution can supply electric cars used for transport. Although the integration of a multi-service approach is the main difference with the original SGAM, other differences have been added. First, SGAM's business layer was split in two, in order to have a specific layer for regulation. Furthermore, SLEAM introduces a behavioural layer, which is important to consider in a flexible system where the energy system requires end-users to provide flexibility services. Then, because SLEAM only focuses on local systems, it connects to larger scales systems, such as the transmission grid domain for the electrical grid. Also, domains include DERs at two locations: at customer premises first, but also at higher voltage levels (but still connected to the distribution infrastructure). Finally, in terms of zones, SLEAM differentiates from SGAM in the fact that all stakeholders are now integrated into the local energy system (including social services), and markets are now split into local energy markets, and upstream markets such as the wholesale or balancing markets, in order to be more comprehensive and to provide more flexibility in the design of a local smart grid.

SLEAM provides SLES planners with an overview of the system needs, and ensures that all layers, zones and domains are considered by SLES stakeholders. The links with the national scale level are multi-fold. First, SLES can provide or receive power, gas or transportation flows (i.e. train or cars). Then, SLES can also participate in national wholesale markets to provide either grid services (e.g. frequency regulation), or to sell energy to energy suppliers or to balance responsible parties. In this case, SLES can work as an aggregator that can commit with better reliability to energy quantities on the wholesale markets. In the case of ReFLEX, FlexiGrid™ is a platform that acts at the *Function and Services Layer*. It interacts with the Business layer by submitting bids on the wholesale energy or frequency markets, or by providing local energy services to the SLES. Among these services, the ReFLEX project aimed at creating a local energy market in which prosumers were able to sell electricity surpluses to their neighbours with a reduced network and supply cost. FlexiGrid™ also enables local grid services in which consumers were able to increase their consumption, especially through smart chargers and smart heating system in order to self-consume local wind production, and reduce curtailment of the wind turbines due to grid constraints. Hence, Flexigrid™ uses the flexibility from three energy vectors, such as chemical batteries for the power vector, smart chargers for the transport vector, and storage heaters for the heat vector, to provide energy services. Looking at the SLEAM, Flexigrid™ leverages assets at the *customer premises* domain level to provide services (*Function & Services Layer*) or revenues (*Business Layer*) at the *distribution* and *distributed Energy Sources* levels. Within ReFLEX, several models were designed to help in the planning and

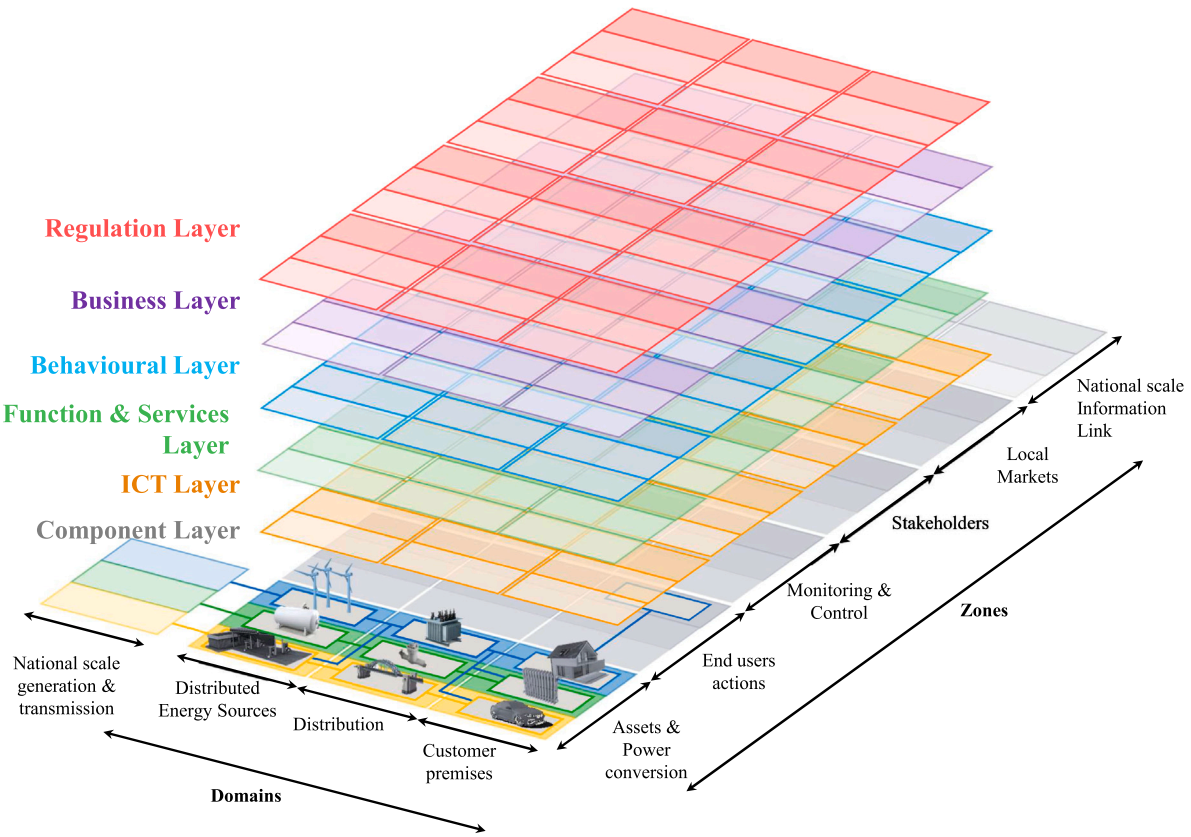

Fig. 8. Smart Local Energy Architecture Model (SLEAM) overview.

operational phases. Planning models first, in order to assess what were the possible evolutions for the whole energy system (district heating, electric car conversion, ...) [75], and what changes could have the greatest impacts on decarbonisation, especially for buildings consumption [76]. Then, operational models, especially for renewable generation forecasting, but also for distributed assets control [53], or for local energy communities coordination [38]. Although the SLEAM model is more comprehensive and adapted to multi-services SLES, it cannot be considered as a recipe for SLES deployment in countries in the world. Indeed, this SLEAM was based on the learnings from European projects including ReFLEX, and might not be well-suited for other countries implementations. Indeed, layers, domains and zones work as placeholders to ensure that all required categories have been considered in the design and operations of SLES, but SLEAM does not describe explicitly the details of each category (layer, domain, zone). Another limitation of SLEAM, as for SGAM, is the fact that there is only one cell per entity. This can make it difficult to represent SLES that focus on energy communities, as there is only one cell for customer premises, which makes it difficult to display interactions between different members of the same community.

This concludes all steps required to be considered during the planning phase of SLES. In the next section, we summarise the steps undertaken at the operation stage level.

5.2. SLES operations

Actual deployment and operation of SLES require undertaking several specific tasks that are analysed in this section.

5.2.1. Project management

Once the planning phase has been completed and objectives well defined, a project management team bringing together main stakeholders and project leaders is required. A steering committee including community members, local authorities and funding bodies is also recommended to regularly assess the progress and main project decisions. The project management team should also determine the main key performance indicators (KPIs) corresponding to the objectives of the SLES, as discussed in Section 7. It is also recommended to set up working groups that will address the diversity of the tasks. Working groups can include a steering group, constituted by main stakeholders, customer management group, data management, assets management group, safety group, business and policies working group and an Integrated Energy System (IES) group, that will aim to determine the decision strategies to be adopted when controlling flexible assets, but will also analyse progress and obstacles for energy services. Within ReFLEX, several working groups were set up by the steering committee in order to solve specific tasks. Among others, this helped designing a procedure to access data and the design of the SLEAM architecture.

5.2.2. Community involvement

To facilitate community involvement and participation, SLES should incentivise the community to actively engage in their energy system decision-making. This includes physical workshops that enable cross-community discussion and communication of possible ways to participate in the SLES, such as participation through demand side management, insulation, smart charging or renewable energy production. This requires an awareness campaign and positive communication to explain the benefits and potential constraints of SLES actions. For instance, it is important to raise awareness of the benefits and the modes of operation of demand response to favour a strong adoption within the community. Additional services to DSM could also be added within Home Energy Management Systems (HEMS), such as smart home automation actions, in order to increase the acceptability of end-users. Then, gamification towards a low carbon community can also be a source of motivation at the beginning of a project, whereas local, national and international events around SLES can promote the community at a national and international scale. This might require setting up in-home user interfaces so end-users can visualise their energy consumption patterns and the benefits obtained from participation in the SLES. Learning from the ReFLEX project, it is necessary to support community members during the deployment phase, and to provide clarity on the responsibilities of the different SLES parties (stakeholders, producers and end-users). What SLES has to offer, should constantly evolve and adjust to end-user feedback. Regulator audits are strongly recommended, either through public surveys or using in-home displays. SLES stakeholders should constantly ensure that they can meet different end-user objectives, such as financial, environmental or social objectives. Regular evaluation of benefits for end-user participation in SLES should be set up and communicated at appropriate time intervals. Finally, to increase the community involvement, SLES can also leverage the emergence of innovative local services solutions, such as adopting community currencies, smart last mile delivery, autonomous shuttles, etc. For all the services proposed within the SLES (Time of Use flexibility, special tariffs for smart charging, etc), it is a good practice to propose trials in the first months or years of implementation, with the possibility to switch back to their original offer without incurring an additional cost. This will allow SLES stakeholders to adapt their offers depending on the percentage of end-users reverting to their original offer. The community involvement was one of the greatest achievements within the ReFLEX project, as around 5% of the population agreed to become a ReFLEX member. This was made possible by a complete involvement of all the partners through the participation to many local and national events, but as well as by regular communication in local communication channels, by the dedication of a community manager, and by the deployment of a ReFLEX center in the main city centre, so citizens can physically reach out to ReFLEX organisers and get the opportunity to ask questions.

5.2.3. Data management

SLES should aim to collate relevant data to help achieving their objectives, such as end user consumption profiles, heating needs, distributed generation, weather data, grid operation information (networks topology, congestion, voltage excursions), transport requirements with associated schedules, pricing history, etc. A data management strategy is necessary to deal with the large amount of data and requests that will come with the deployment of SLES. In certain areas, such in Europe for example, it is mandatory to comply with regulations, such as GDPR, therefore data management processes should be set up from the beginning of the SLES deployment. Furthermore, as found in [26], customers that trust their supplier's strategy for data privacy, were more likely to accept DSM schemes, which are one of the main control strategies deployed within SLES. This demonstrates the importance of privacy consideration and communication with customers involved in order to ensure their understanding and obtain their consent. Data should be stored locally in stakeholder-owned servers or distributed ledgers, or remotely through cloud services, and requires encryption, adapted logging to keep track of every connection, and should meet relevant consumer rights (user consent, privacy policy, accessibility, such as the right to access or erase data, transparency about third-party data sharing, notification of users in case of a data breach, etc.). Within ReFLEX, a data exchange framework was set up by the data working group, that defined eight social, ethical, technical and legal elements: (i) every collected data requires a data owner or controller, mentioned in the metadata information, (ii) a data sharing agreement must be defined (iii) and signed, (iv) data sets must be curated, (v) a valuable analysis or algorithm should be defined and highlighted, (vi) data users should be identified, (vii) the purpose of data should be shared by the data governance team, and finally (viii) a secured data exchange software platform should be set up.

5.2.4. Stakeholders engagement

The deployment of SLES involves the contribution of many different stakeholders. A key stakeholder for example, is the Distribution Network Operator (DNO), who authorises the installation of electrical assets and provides local network data information. Other stakeholders are assets manufacturers and local installers, who may require training and made mindful of the whole SLES project. Finally, local authorities and community associations are crucial for the success of SLES projects, as they have best knowledge on the community needs and expectations. Then, as described in [64], the complexity and competition of energy and flexibility services markets may require partnering with other communities or third party service providers, such as aggregators or suppliers, to ensure an economically sustainable SLES solution. Coordination of flexible assets such as residential batteries, heating systems, EV chargers and to some extent large RES, can be integrated within a SLES control solution, called Integrated Energy System Controller (IESC), a controller embedded within the IES. The aim of an IESC is to determine and send optimal recommendations, requests, price signals and set points to flexible production and demand assets based on external signals, such as market requests, grid operator requests, energy prices or environmental impact. The IESC real time control strategy for local flexibility should be carefully determined from the SLES governance objectives. Indeed, such decision engine can accommodate several objectives, such as it can reduce power outage, provide low cost energy, minimise greenhouse gases emissions, or it can implement a multi-objective approach. One of the challenges of the IESC is therefore to arbitrate between potentially opposing recommendations that address different objectives, such as increasing local self-consumption, participating in energy markets or providing grid services at the same time. Achieving these multiple objectives may require a compromise between these objectives. For example, local grid constraint issues might dictate a reduction of local consumption, whereas participation in the wholesale or ancillary services markets might dictate an increase at the aggregator's portfolio's consumption, at the same time. In addition, multiple objectives may refer to delivering services at different timescales, meaning that the IESC system needs to be capable to realise actions with different time horizons, ranging from months for energy markets bidding, to minutely or second timescales for control decisions. Similarly, diversity of asset types may constitute a technical constraint, as the IESC needs to be able to communicate with multiple protocols and equipment of different type of manufacturers. The same applies to the interfaces of services, third party providers and business platforms (e.g. interfaces with the Transmission System Operator (TSO), Distribution Network Operator (DNO), suppliers, Balance Responsible Party, etc.) for which web services must be designed and run continuously to enable connection with the relevant APIs (Application Programming Interface). A solution for recording monitoring and data streams, requests and connections is required for issue detection. This should be considered from the system design stage. Furthermore, the IESC must include a real-time dashboard to visualise potential faults, and must implement real-time fault detection. Other challenges include the requirement to integrate end-users preferences in control algorithms but also to allow end-users to overrule control commands that cannot be satisfied, such as a flexibility activation requests at times not suitable to the end-user. The IESC should be capable of learning from end-user overwriting frequency, to better tailor customer recommendations and to increase the acceptability of users. Finally, it is important to ensure transparency on the way the IESC is operated, and especially ensure that all stakeholders' objectives have been considered during the design phase. As an example, financial gain objectives might not be adequate to incentivise end-user participation and engagement in some communities, and this should be considered from the design phase.

5.2.5. ICT infrastructure

SLES deployment requires a strong ICT infrastructure to monitor and control the energy system in real time, to store and analyse data, or to interact with other stakeholders such as wholesale markets participants. A good practice is to ensure digitalisation of main assets (for control or monitoring) at an early stage of SLES deployment. A unique ICT architecture that would fit all SLES is not possible, however, Fig. 9 summarises commonly used existing architectures. As DNOs evolve towards becoming Distribution System Operators (DSOs), they develop their own ICT infrastructure to operate their assets such as tap changers, D-STATCOM through RTUs (Remote Terminal Unit) or to gather data from distributed devices, such as smart meters. These bi-directional data flows can rely on Radio Frequency (RF) based protocols over the air such as Lora or GSM to send data to/from the DSO servers, or can be based on Power Line Communication protocols, such as G3-PLC for data flows between distributed assets and a concentrator located at a higher level in the architecture [77]. Other SLES stakeholders such as Virtual Power Plant operators, suppliers or Demand Response aggregators usually interact with distributed assets through an internet connection between their servers and distributed assets (Home Energy Management System, electric heaters, boilers, solar panels, batteries, etc.). It can either be a direct connection between the assets and the aggregators (as shown in blue in Fig. 9), or through an API (Application Programming Interface) provided by the asset manufacturer (depicted in orange in Fig. 9), that provides, for example, a list of HTTP REST (Representational state transfer) requests that the aggregator can send to the manufacturer or service provider to interact with assets. APIs can similarly be used between DSOs and SLES aggregators to retrieve smart meter data, or send specific requests to activate flexibility. Finally, the SLES ICT infrastructures also include ICT solutions for the interaction between SLES stakeholders and wholesale or local markets to generate revenues, as depicted in the upper right corner of Fig. 9. Again, this link is usually provided through an API made accessible by the market operator. Although current ICT architectures mostly rely on central servers, distributed technologies such as blockchain technologies are paving the way towards a more decentralised and democratised access to data, reducing single point of failure and distributing the ownership of data to the community members [7]. As an example, smart contracts, which consist in automated programs running on a virtual environment constituted by the nodes operating a blockchain for example, can efficiently be used to automate financial transactions between the SLES community members or to automate control of distributed assets [78]. Along with this schematic architecture, ICT infrastructures for SLES require a strong cyber security approach [79]. Indeed, the diversity and large number of stakeholders and assets manufacturers in a SLES constitute a high risk of cyber attack, as each stakeholder could be the source of an attack on all other SLES members. First, each stakeholder should ensure that all devices or assets are well protected by a standardised authentication and secure connection process (e.g. using TLS (Transport Layer Security), but also by ensuring that manufacturers' default passwords or keys are changed for each device when applicable). Secure connection should be achieved by use of symmetric or asymmetric encryption for communication between devices, while digital certificates may be good solutions to authenticate SLES stakeholders and devices [80]. This requires each stakeholder to define a security keys strategy and security certificates governance. Security audits should be provisioned within the budget to ensure secure operation and storage of data. Finally, a cybersecurity by design approach for SLES should include relevant training of the main stakeholders, a risk assessment by external third parties, and digital and physical access control to stakeholders working spaces. Within ReFLEX, Flexigrid ™ platform was deployed on Amazon cloud services and connected to different API based services to retrieve real time data, and take real time decisions. Therefore, all flexible and monitoring assets were bought or upgraded with an internet connection capability through WiFi or 4G connectivity.

5.2.6. Asset management

SLES require the installation or renovation of multiple assets. This requires a dedicated team to address different challenges, such as obtaining approval from the grid operator to install and control flexible assets, approval from suppliers to adapt customers subscriptions, but also to manage the installation process, in order to ensure that every asset can be integrated into the IESC. Local installers should be trained to safely install different technologies, and remote assistance should be made available by phone or the Internet to guide installers or end-users in the installation and asset management.

5.2.7. Policy management

Regulations and policies around SLES and flexibility are still in their infancy, hence they may evolve at a fast pace. Regulatory changes may significantly impact the viability of SLES projects. As an example, the proposition from Ofgem the UK energy system regulator for the Targeted Charging Review (TCR) in 2020 brought significant stress on some VPP and flexibility provider business models [63] as the TCR stated that sites with electricity storage were liable by default for the residual charge of the transmission and distribution charges (TNUoS and DNUoS respectively). As a consequence, SLES stakeholders should survey any regulatory changes and seek to inform new regulation and policies.

5.2.8. Customer relationship management

SLES aim to actively integrate end-users in the energy system, by facilitating adoption of low carbon technologies, or by allowing them to access local renewable energy or to provide flexibility to the local or national grid. End-users will in turn obtain access to new services and new revenues. It is therefore necessary to implement a customer relationship management solution to address the diversity and potentially large number of customers, by proposing them appropriate services, adopt the right communication channels for each customer, etc.

5.2.9. Training and education

With the deployment of assets within the community, local stakeholders will need to acquire installation skills for each type of assets (insulation, batteries, solar PV, smart chargers, heating systems). These particular tasks will be performed by local engineering teams, which will require specific skills. Local academic institutions could benefit from SLES related activities to propose new educational programs, so that required skills are developed locally. This point was highlighted early by ReFLEX consortium who worked with the University of Heriot Watt to set up graduate programs taught in Stromness in Orkney, and dedicated to the topic of Smart Local Energy Systems, including offshore and onshore power production modules (including wind energy, tidal) located in Orkney.

5.2.10. Financing

Procurement of assets, monitoring and control solutions and the financing of SLES related jobs require continuous funding. Funding can come from SLES customers enrolment, but also from internal and external investors. Therefore, a specific activity of SLES stakeholders is usually dedicated to the search of funding sources. As presented in [64], one way to maintain financial sustainability for SLES activities is to capitalise on the newly acquired knowledge to develop remunerative activities consisting in helping other communities to deploy their own SLES.

This section presented the main enablers for successful deployment of SLES, as experienced in the ReFLEX project and other UK based projects. The next section presents the barriers experienced by the ReFLEX consortium, that could inform actions undertaken by other organisations that seek to deploy SLES.

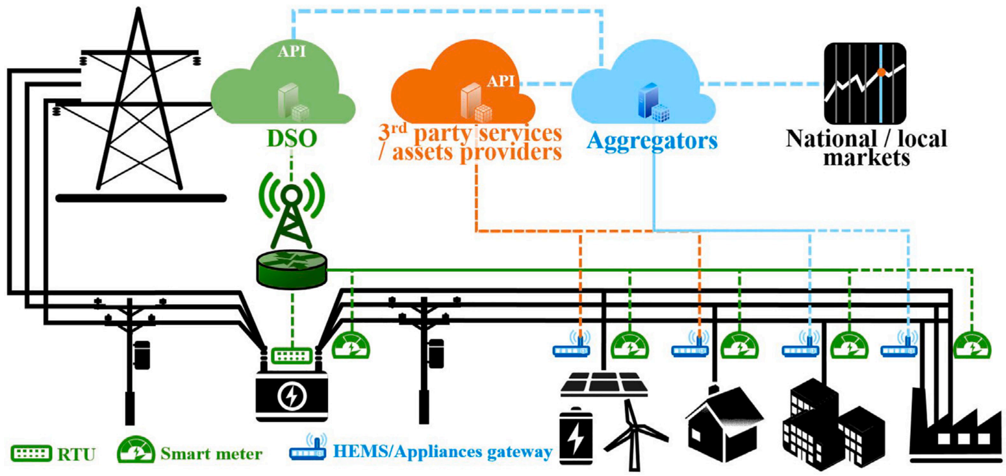

Fig. 9. Schematic of ICT infrastructure for electricity vector in SLES.

6. Barriers to SLES

Although SLES are a necessary step to achieve the energy transition at a lower cost, they face significant barriers This section describes the main obstacles identified during the planning and operating phases of SLES projects such as ReFLEX. These barriers can be categorised into five categories, infrastructure related barriers, social barriers, environmental barriers, economic and legal barriers.

6.1. Infrastructure

The first barrier to SLES is related to infrastructure, including the infrastructures of the power system, transport, heating and ICT. Existing infrastructure or lack of infrastructure might have a detrimental effect on the successful deployment of SLES, as discussed in greater detail below.

6.1.1. Electricity

Low robustness of the local and national electrical grids can either be a catalyst for SLES or an obstacle to the deployment of flexible electric assets. Indeed, a grid with frequent voltage excursions or cable overload could strongly benefit from flexibility schemes such as the ones proposed within SLES. However, DNOs might be reluctant to let other partners operate assets that could exacerbate voltage excursions if not operated correctly. This can lead DNOs constraining the installation of SLES assets [81,82]. In addition, *grid management* strategy followed by the DNO could be a barrier to SLES if both control schemes are not synchronised. This is the main reason why SLES governance should include the DNO. Finally, the *low number of assets* already deployed could be an obstacle to the deployment of SLES. Indeed, a community without any distributed energy resources or flexible assets would need to commit a larger investment to deploy such assets before forming a SLES.

6.1.2. Transport

Similar to the power infrastructure, transport infrastructure can constitute a barrier to the deployment of SLES. *Bad quality of roads* might lead the community to support the renovation of its road network instead of supporting the deployment of SLES transport solutions, such as cycle lines, car-sharing enabler solutions, public transportation or electrification of transport. Also, a limited number of *already deployed low carbon transport solutions* such as EV or public transportation might affect the deployment of SLES as they will require more investment and time to motivate the community acceptance. Finally, the *lack of maturity* of innovative technologies should be carefully considered. For example, hydrogen based vehicles are currently not cost-effective, leading to a reduced interest from SLES stakeholders to invest in such technologies, which might hinder decarbonisation of transport.

6.1.3. Heating and gas networks

A lack of *existing infrastructure* such as the lack of a gas network, hydrogen network or district heating will be a strong barrier to the deployment of such solutions as it will increase the SLES deployment cost considerably. These solutions might not be financially viable if relevant infrastructure is not already inplace. Similarly, the *type of buildings* in the community can prevent the reduction of energy consumption in the SLES. Although insulation is one of the main step towards decarbonisation of heat, it is not always possible depending on the type of buildings (historic buildings). Finally, a low *density of buildings* will increase the need and cost of insulation and smart heating solutions.

6.1.4. Information and communication technologies

Delay in the deployment of smart meters might require to first invest in such devices that would increase the visibility of the state of the grid, end-users consumption and voltage. These data are usually necessary to train forecasting algorithms and ensure an optimal operation of decision engines. Also a weak *communication coverage* such as low Internet access rate, or a low 4G/5G/LoRa coverage in the community will affect the deployment of smart flexible assets as all these equipments will require a connection to a cloud or local server. Assets and ICT solutions' lack of *interoperability* is also an important obstacle in SLES deployment as they require to develop middleware solutions for each communication technologies. Furthermore, the absence of APIs (application programming interface) to interact with different manufacturer products is usually a reason to disregard particular assets. Finally, the lack of *local ICT* solutions such as storage will require new investments to either deploy a dedicated community based server, with a specific operation and maintenance team, or deploy IT solutions on the cloud, with substantial costs.

6.2. Technical barriers

Technical barriers correspond to engineering systems or services characteristics that are required for successful SLES, but that have been highlighted as difficult to achieve. Technical barriers have been classified into different categories as shown below.

6.2.1. Low accuracy of artificial intelligence models

Artificial Intelligence (AI) tools, such as forecasting or clustering, are required to plan for next day operation, to bid on a market or to target specific needs [83] in the use cases implemented. However, successful deployment of AI tools requires specialised skills and technical knowledge that is not widespread yet. To mitigate this barrier, interoperable and open AI services could be proposed in a Software as a Service (SaaS) solution.

6.2.2. Low assets deployment

SLES propose innovative energy services that build on top of other mature technologies deployment, such as distributed energy production or smart appliances. Therefore, a low deployment rate of mature assets could hinder the deployment of SLES in specific areas. As an example, the low deployment rate of smart meters in a community would stop the implementation of energy services such as Peer-to-Peer energy trading. Similarly, a low deployment rate of monitoring on the electrical grid could reduce the interest of the DNOs for local flexibility and would not allow them to identify the key locations where to implement and incentivise flexibility.

6.2.3. Low diversity within communities

The economic success of SLES requires an increase of local self-consumption and provision of flexibility services to external stakeholders. However, these requirements can only be met if there are diverse energy patterns within the community. As an example, if all members of an energy community have similar-shaped electric load profiles and use constraints, it will be more difficult to provide flexibility services and to decrease the energy imports from the main grid.

6.2.4. Assets technology readiness

As mentioned previously for transport, a *low maturity and accessibility of technology* can be an important obstacle to the deployment of SLES in general. For example, the current maturity and cost of hydrogen based solutions, such as hydrogen based co-generation, or novel energy storage solutions hinders adoption from local communities.

6.2.5. Data and security

Implementations of SLES require solutions that need to monitor, collect, store and analyse data. Data may often be privacy sensitive. This is considered as a barrier to the deployment of SLES in the sense that it requires a large range of skills and services, ranging from IoT to cyber-security, including data storage and servers maintenance. The associated costs to these solutions and expert recruitment must be accounted for in the SLES budget, and may reduce the profitability of the energy system. As explained in Section 5.2.3, two options usually exist for data storage. Either SLES stakeholders store and maintain data access in their own servers, or they subcontract the storage to third party companies with associated long term costs and dependency.

6.3. Social barriers

SLES are usually specific to a given community, and require a strong involvement of the community members. Success of SLES relies on active participation and acceptance of technological solutions from local community members, often combined with community ownership. Adoption of solutions deployed may encounter opposition due to a lack of awareness and understanding of the benefits that SLES or low carbon technologies deployed within SLES can offer. Community members may be driven by different individual values leading to a lack of cohesion in common values across the larger community, which in turn hinders participative decision-making. The demographics constitution of the local community may play a role in the adoption of SLES. Scepticism around renewable technologies and negative perceptions around technology solutions such as automation and AI may also affect adoption of SLES.

6.3.1. Education and media

The education level of a community can either be a driver or an obstacle to SLES deployment. *Low Education* and lack of technical skills in a community could prevent the success of SLES, as mentioned in several research articles [84–87]. For example, SLES deployment requires local engineers and commercial agents. A low unemployment rate in the community can correspond to a lack of dynamism that will slow the SLES progress. The *absence of local media* is also seen as a barrier. Indeed, weak local media coverage may hinder SLES adoption due to a lack of a suitable channel to communicate with community members that in turn may not stimulate collective motivation. Lack of expertise in *social science* could also prevent the SLES governance team to ensure that the project is in line with the community expectation.

6.3.2. Behavioural

Finally, some behavioural aspects of the community could be barriers to SLES deployment. *Incompatibility between proposed incentives* and local specifications reduces end user acceptance of and participation in demand response and flexibility schemes [88]. *Reluctance to change* would prevent citizens from understanding the value of SLES, and thus would strongly affect their involvement, especially their acceptance for new technologies that would enable energy consumption flexibility, such as energy storage or demand response. Absence of *local initiatives* is a barrier to SLES. SLES success is highly dependent on the dynamism of communities, as it was seen in the ReFLEX Orkney community. The best practice would be to assess beforehand if a community has the willingness, dynamism and ability to launch new activities, or to address an issue as a community. *Environmental consciousness* is also a strong enabler for SLES. Therefore, communities that are not convinced by the need to act quickly to address climate change will most likely constitute a barrier to SLES. Finally, the *lack of SLES related services* that SLES could leverage can be a barrier to the deployment of SLES in a community, as it will not demonstrate the full potential and added value of SLES. As an example, the absence of services such as EV charging roaming service (consisting in the fact that EVs can be charged at any location seamlessly) are a real barrier to the electrification of transport.

6.4. Environment

Local environmental features and characteristics may be an obstacle to SLES: *Geographical constraints*, such as topology obstacles (mountains, sea), or the presence of protected areas for biodiversity or sea routes can negatively impact SLES as they might affect the deployment of assets. *Lack of primary energy resources* such as solar, wind, biomass or rivers could also strengthen the dependency of the community to the national energy production system, and limit the opportunity to create a local energy system, especially in urban areas.

6.5. Economic barriers

The uncertainty of future financial incentives and future prices for energy services discourages many investors and companies to finance SLES initiatives [89]. As a result, the majority of current SLES projects rely on public funding schemes, which are likely to be substantially reduced or removed in the middle term [5]. Public authorities should therefore work on the reduction of economic uncertainty around future energy services in order to allow the private sector to invest with greater confidence. Also, current market practices, such as wholesale energy markets, are inherited from the centralised electricity system, and have not yet evolved to include new technologies and constraints. As an example, the minimum capacity requirement of 1 MW for participation in wholesale energy markets acts as a barrier on the participation of communities in wholesale energy markets, and therefore prevents them from increasing their source of revenues. The economic situation of the community should be strong enough before starting to plan a SLES. Economic barriers include a low GDP, a low private investment capacity or an absence of public funding schemes. Other factors include the level of household debt or level of fuel poverty, which will affect the ability of community members to invest in low carbon technologies and SLES. The absence of entrepreneurship in a community could negatively affect SLES deployment, as SLES require specific local activities, such as local engineering, maintenance, relationships with other regional and national businesses. In general, lack of culture of local entrepreneurship might reduce the pace of emergence of new business models around SLES activities (batteries operation, EV leasing, etc) and thus slow down the search for funding.

6.6. Regulations and standards

Finally, the last and perhaps most important aspect of SLES barriers is related to the existing regulatory framework and policy initiatives. The main barrier related to regulation corresponds to uncertainty around current and future regulation. This prevents SLES stakeholders from building robust business models and investment strategies, which are vital for SLES economic viability. Current regulations and practices inhibit SLES implementation. For example, the current long processes required to change one's energy supplier or inability to subscribe simultaneously to more than one energy supplier hinders the implementation of local Peer-to-Peer energy trading. In addition, many standards related to SLES, e.g. standards on demand and production flexibility or low carbon technologies adoption are still under development. As a result, although it is seen as key for most of SLES stakeholders, the absence of well accepted standards for some technologies or use cases is a barrier to the deployment of assets, whose integration depends on interoperability. Regulation around data is also important, as meeting GDPR requirements can be a considerable task to be addressed. SLES often leverage local flexibility and most frequently residential flexibility, therefore it is necessary to take into account GDPR requirements in the data management process. Other regulations applicable to SLES are regulation around the installation of distributed generation assets (size limit, specific hardware certification, etc), regulation around the participation in markets (critical size, licensing, etc), regulation around cost, as shown in [90], but also technical regulations that concern the integration of assets in distribution networks (e.g. the maximum percentage of hydrogen to be added into the gas network, Active Network Management constraints for local electricity networks, etc). Regulations should constantly be monitored by SLES stakeholders as they may change in fast pace.

7. SLES evaluation metrics

In this section, we propose an extensive list of evaluation metrics for SLES, based on the experience built on the ReFLEX project. These KPIs are important for governments and funding bodies, as a way to assess the progress of SLES implementations, but also for SLES stakeholders to inform and guide them in the deployment of SLES. The main list of KPIs, their detailed description and computation methodology are described below and in Appendix A.

As shown in Table 1, SLES metrics have been classified into nine categories listed below: (i) the *energy* category corresponds to the assessment of all activities related to energy consumption and production, such as energy imports reduction, increase of local flexibility, the number of local energy resources installed, etc. (ii) The evaluation of the impacts on the *environment* contains the direct and indirect $CO2_{eq}$ emissions reduction, but also considers other types of pollution or impacts on the environment. (iii) *Social* aspects are also considered and include all social factors that make any local initiative successful, such as the rate of involvement of members of the community, the impact on education or services provided by the SLES ecosystem to the community members. (iv) Next, the impacts of SLES on the local *economic* situation are assessed through estimation of the financial cost of the SLES, the bill reduction for community members, the number of job opportunities from the SLES deployment and the payback period. (v) The *resilience* of the proposed SLES is also an important category that analyses the increase in local supply, the reduction of the annual downtime or system outages and the redundancy of activities, such as the redundancy of renewable energy sources. (vi) The *assets & infrastructure* category studies the condition of the available infrastructure, and evaluates the deployment rate of communication technologies across all networks. (vii) *Data management* is also assessed because it is important for communities to set up a local data governance body to determine the modalities of data sharing. These aspects are evaluated by the data management category, along with the storage characteristics. (viii) *Regulation & policies* are also considered, especially the assessment of the involvement and participation of the SLES in the development of regulation. (ix) Finally, *replication* is also assessed as SLES should aim to be fully documented to enable replication and pave the way for future SLES implementations and inform successful strategies. A comprehensive list of Key Performance Indicators (KPIs), including their description and how to compute them is shown in Table 1 in Appendix.

This list of detailed KPIs has been used to inform the evaluation of the progress and outcomes of the ReFLEX project. Table 2 in Appendix B shows the result of this assessment for the ReFLEX project. As the ReFLEX project is still in the deployment phase, these KPIs are not representative of the final contributions of the project. Moreover, issues related to the roll-out of hydrogen solutions and inability to install batteries at residential households, due to concerns raised by the DNO, prevents the project to achieve the originally planned and forecasted KPIs.

8. Lessons learnt

An important aspect of SLES deployment is the replication and knowledge transfer on future SLES projects, which might face similar challenges, as the ones identified during the execution of the ReFLEX project. This section discusses lessons learnt, which are classified in different categories.

8.1. Planning

The ReFLEX project highlighted the importance of techno-economic modelling to determine optimal sizing and locations of energy assets, but also to determine relevant use cases and business models. ReFLEX showed that hydrogen solutions were at the time of consideration economically infeasible, in the context of the Orkney islands. For example, the fuel cell system installation initially proposed to produce heat and power for a specific neighbourhood was not executed as its nominal power exceeded the required power demand. When fuel cells are partly loaded, especially at low loads, their efficiency drops considerably, as heat production is significantly reduced. An alternative proposed, was to use a hydrogen engine, but the cost of hydrogen was deemed prohibitively high to allow installation. Although ambition and vision are very important for driving the success of SLES deployment, the planning stage resulted in a rethink of several parts of the project, so that new scenarios could be explored. As a result, heating services that would be provided by hydrogen, were replaced with electric heat pumps. Similarly, it is important to understand the community budget distribution over different energy services (power, heat and transport), in order to prioritise a service. Within ReFLEX, a typical rural area located in the north of Scotland, the cost for heat and transport are prevailing, hence most of the efforts focused on proposing offerings for these services. Finally, it is important to be aware that access to energy data and permit approval for installation of assets takes time, hence such activities should be preferably be planned at the early stages of the project. and Similarly, key stakeholders, such as the local DNO, should agree on the location where assets should be placed. This was the greatest obstacle encountered within ReFLEX, as the DNO did not allow installation of energy producing assets at end-user premises. Such as restriction, shifted significantly the strategy of the project as other sources of flexibility had to be investigated to avoid curtailment.

8.2. Operations

In the operational phase, it is important to set up a strong link with customers, as their participation is critical for the provision of flexibility services, as are local installation experts. Within ReFLEX, strong links were established with the local community as 5% of the population became members of the ReFLEX initiative. This is mostly achieved because customer engagement was done in parallel with larger community engagement. Community engagement was secured through participation in numerous events with local, national and international outreach, by developing a strong presence on local communication channels, but also by the installation of a local point of contact (local shop), which accelerated understanding of the project objectives and needs. Furthermore, a strong corporate identity and style guide helped the citizens to better identify with the ReFLEX initiative and think positively of it.

Regarding end-users and their interaction with devices installed at their premises, it was observed that they often omit reading the general description of assets before use (EV, batteries) and often lack understanding of the assets' basic working principle and best practices, resulting in issues in the functionality of assets, which required additional work related to debugging of assets, which had not been anticipated in the original planning. This issue was most prominent during the COVID-19 lockdown as end-users had to install assets themselves. A similar approach of self-installation could be adopted in future SLES projects, as significant financial gains can be obtained by reduction of installation costs, however extensive debugging time needs also to be considered. Additional services could also be added into the SLES offering in order to increase the positive impact and acceptance of the SLES. These services could include data services (visualisation of energy consumption data), building services and welfare services. For example in ReFLEX, the integration of customers into a flexibility scheme, first focused on friendly members (members of the ReFLEX consortium organisations), and next on customers that could reap significant benefits from the energy flexibility achieved.

8.3. Technical solutions

Selection of particular technological solutions should consider factors, such as the compatibility with final end-user usage and interoprability with the current infrastructure. For example, when considering implementation of EV charging infrastructure in ReFLEX, a local survey showed that customers charge mostly at home. This meant that original plans for installation of public 3-phase 22 kW EV chargers had to altered to 7 kW EV home chargers at end-user premises. Another finding was that most flexible or control devices should be remotely accessible through APIs, this ensures interoperability. Finally, a testing phase for software and physical assets, including compatibility testing, should be considered before the SLES deployment phase. The compatibility between control signals and asset protocols should be carefully tested. As an example, several residential batteries were tested within ReFLEX before choosing the right technology that would provide the necessary data and would fulfil the remote control capabilities.

8.4. Data management

Although data can sometimes be accessible through external operators portals,the ReFLEX project showed that having a dedicated energy monitoring solution to measure demand and local production is more likely to be accurate and avoid potentially unnecessary actions. Furthermore, it is good practice to determine the requirements in terms of data collection frequency, storage size and infrastructure. For example, regarding smart EV charging, collecting data every minute for the 150 registered smart chargers was determined to be the best compromise between latency and accuracy.

8.5. Management and stakeholders

As mentioned in Section 5, early engagement with the main local stakeholders was critical for the smooth development of the project. To achieve this, drawing a map of the key stakeholders for each energy service was found to be a useful first step. Mapping showed that engagement with the DNO or local energy suppliers is critical for the success of a SLES project. According to the ReFLEX experience, it was found that partnering with an energy supplier could add significant value to the project, as it would enhance the support provided to customers. Finally, supply chain delays should be anticipated, and project management should include these delays at the project planning. Risk mitigation should also plan as best possible for unforeseen circumstances, as for example the COVID-19 pandemic had an important impact on the delivery of the ReFLEX solutions.

8.6. Legal challenges

A lesson learnt from ReFLEX is that issues, such as monopolisation of customers (the fact that only one energy provider is allowed for each customer and that Orkney has a main historical energy provider), data management and licensing needed to operate proprietary systems are at least as important as technical challenges. Furthermore, regulation changes pose a significant threat to every SLES project, as they could change the whole business model as it was explained in Section 5.2.7. Similarly, complexities around GDPR and personal data require careful consideration. Regarding concerns about legal requirements applied to technical systems, it is important to understand the difference between individuals installing their own assets, and an entity installing assets for individuals. The installation process and requirements are different and the entity must comply with them. Similarly, when the SLES lease assets, stakeholders should ensure to build warrant agreements.

8.7. Financial

The SLES budget should include licensing costs for installation of new assets, which can affect the profitability of the project. Furthermore, SLES assets finance plan should be checked carefully to avoid any issues. For example upfront financing of storage assets, such as batteries, is not permitted under the Financial Conduct Authority regulations, as discovered by the ReFLEX project team.

9. Discussion

The current energy crisis highlights the fact that societies should aim to reduce their dependency on external fossil fuels while limiting the cost of energy for the end-users. SLES are seen as an enabler of the required energy transitions, but it does not go without obstacles. This section summarises the potential opportunities and limitations of SLES.

9.1. Potential opportunities for SLES

SLES allow communities to seize their own energy consumption and production characteristics, while generating local economic activities. They hold the promises for an increase in local renewable generation, and for a reduction of energy consumption bill and environmental impact. With the recent evolution of legislation worldwide, it is most likely that several energy communities will emerge in the near future, providing a novel way to increase the share of renewables in the local energy mix and contribute towards delivering the sustainability agenda and United Nations sustainable development goals [6]. SLES should then focus on the integration of flexibility capacity to maximise self-consumption of renewable energy. As for the ReFLEX project, flexibility can be added through controllable loads such as EVs, smart heating systems, or storage facilities, that are currently ready to be remotely controlled for SLES purposes such as renewable energy curtailment avoidance.

Although the road towards fully functional SLES in most communities is still very long, current legal frameworks are evolving to allow multi-vector energy communities, whereas current technologies are getting more and more inter-operable, which makes it possible to quickly use them in any Integrated Energy System. Therefore, the current landscape seems to be ready to favour the deployment of SLES in many communities. However, it now requires a better communication to communities, through the sharing of practical guidelines to quickly help communities getting started with their own integrated energy system. It also requires technical and legal knowledge to design and operate SLES. Although the authors and members of the ReFLEX project have the feeling that most of the barriers to SLES will soon be lifted, there are still some challenges to overcome.

9.2. Challenges of SLES

First, the experience of the ReFLEX project showed that even to provide support to the local grid, the installation of residential batteries by a company at end-users premises was forbidden as there is currently no framework to ensure that these assets will only provide the required service. Indeed, current frameworks do not provide the tools that would ensure that flexible assets such as EV smart chargers or batteries will not make the grid situation worse. Therefore, although regulations are evolving in the right direction, there are still some needs for improvements to foster the emergence of initiatives willing to provide services in favour of the energy transition. The second challenge of SLES is the motivation of communities. Setting up an energy community and then a SLES with adoption from all or most of the community members requires a lot of effort and dedication from the community management team. Indeed, it requires an acceptation and involvement from the majority of the community members to achieve sensible results. In the case of the ReFLEX project in Orkney, known for a strong community involvement, the ReFLEX community consists in 900 voluntary members, among which 140 members accepted to participate in trials around flexible EV charging to avoid local curtailment. However, depending on the time of flexibility trials (morning, afternoon or evening), only one third of these active members were usually able to effectively participate in flexibility events. Although these numbers can seem low, they are a good reference on what to expect in the first phases of SLES deployment without strong economic incentives. Therefore, several mechanisms to incentivise community members should be considered, from the empowerment of the community to financial incentives, and preference should be given to technologies that do not require actions from end-users, while not hindering the customers habits, such as smart heating solutions. The third challenge corresponds to the financial burden of investments. Although the current energy prices are increasing considerably, it is still difficult to find liquidity to invest in renewable generation or in flexible assets mostly because they have a return on investment greater than 10 years. This big challenge is usually mitigated through subsidies until technologies or new markets become mature and reduce costs. However, subsidies for DER have been decreased in most countries. Therefore, it becomes urgent to find financial solutions that make investment in low carbon cost technologies more profitable than investment in fossil fuel based technologies (through carbon taxes or other triggers), in order to incentivise either private bodies investments or community investments. Finally, the last challenge highlighted in this study is related to the technical solutions. Indeed, most SLES projects require the installation of assets for energy production, assets for flexibility procurement (storage, heating, EVs) or for optimal control (EMS). Although most of assets are usually inter-operable (through REST APIs), it requires a lots of effort to effectively achieve communication between all assets. The challenge is that the choice for assets is usually different from one SLES implementation to another, resulting in the need to restart from scratch all the integration work everytime a new SLES is implemented. This challenge could be solved by having all-inclusive solution providers that bring to SLES fully functional solutions already including generation, consumption, flexibility and control solutions embedding communication between each other. This would relieve SLES deployment team from the burden to design all the middlewares that allow each component of an IES to be connected with the others. Similar to most of SLES implementation, ReFLEX had a dedicated team of engineers from diverse backgrounds to achieve all the required tasks to set up a SLES trial, including mechanical, electrical, chemical, software and system tasks.

9.3. Future research opportunities

In order to address the many challenges mentioned in Section 9.2, different research directions are of interest for the scientific community. First, it was discussed in [74] that current researches building models on energy systems with economic agents (households, aggregators, investors, operators,...) could focus on a better integration of behavioural factors. Therefore, there is a need for current energy researchers to team up with social scientists in order to better understand how end-users behaviours can be integrated in energy models. Then, with the development of energy communities comes the need to find equitable ways to distribute renewable energy and the financial benefits from the community [91]. This area of research can have quick applications as many communities are already setting up, looking for best ways to make their investment profitable to everyone. Third, a field of research that has still not been fully investigated due to the complexity of gathering relevant data, corresponds to the behaviour and incentives for end-users to participate in demand side response (DSR) programs. Although solutions already exist for frequency response even at the residential level, the subject becomes more complex when addressing voltage issues or energy markets commitments. Therefore, DSR for smaller assets but larger number of end-users is still an active field of research, that aims to find ways to incentivise usage flexibility without impacting end-users comfort.

Fourth, a still active field of research corresponds to the arbitrage between different revenue sources, such as wholesale energy or ancillary services markets, and local energy or flexibility markets. Although industrial frameworks already exist, such as USEF that was created in 2016 [92], the lack of maturity of local energy or flexibility markets makes it difficult to foresee the potential use of flexibility at different levels of the network. Fifth, planning and operational models for multi-vector energy systems is still a field of active research to reduce the simple payback period of assets installation [74]. It requires comprehensive planning models, that include the modelling of the different vectors' network, but also operational models based on multi-vector and multi-objectives optimisations. This includes all the different works that relate to technologies optimisation, which aim to increase the whole energy system efficiency. Sixth, according to [93], the manufacturing and material extraction for low carbon technologies usually has a considerable impact on bio-diversity, local people's life, and material availability. As a result, there is an active field of research to design alternative technologies that will no longer depend on materials with low availability on earth. Finally, digitalisation of energy introduced a new set of research trends in energy, that are related to data privacy and to security aspects for energy applications. Indeed, smart meters hold very sensitive information from every households, and should then be strongly secured by design. This requires new ways of designing products, but also of designing communication protocols. Similarly, DSR from end-users brings up a strong challenge of connectivity at the end-users premises. This requires a robust, self-healing and AI-assisted network.

9.4. Future of smart local energy systems

Based on the research opportunities mentioned in the previous subsection, this subsection presents innovative solutions that will most likely be relevant in future deployment of SLES. Note that the level of maturity may differ across the initiatives discussed below. Nevertheless, these are promising in the context of SLES.

9.4.1. Local energy communities

As energy prices are increasing [94], end users have started forming local energy communities that aim to produce and consume their own electricity. This allows communities to invest in their own energy assets, to become actors of their own energy consumption and production, and to reduce the price of electricity by reducing taxes, energy production and network costs. Local energy communities are expected to provide a new source of revenues for DER owners that could support the deployment of distributed renewable energy sources, as direct financial incentives are reduced or removed. From the grid management perspective, local energy communities form a strong incentive to increase local self-consumption, which can reduce the technical impacts of low carbon technologies on the grid, such as voltage violations. As a result, local energy communities appear like a technical, social and economical solution to the energy transition providing both incentives to the deployment of low carbon technologies. This has led regulatory bodies to implement frameworks that incentivise the deployment of such local energy communities. As an example in France, citizens living in an area determined by a radius of approximately 2 km can form a local energy community for with a maximum capacity of 3 MW [50,95]. The actual definition of energy communities differs in every country and there is no formal definition widely accepted. In the case, of the ReFLEX community participants are connected with each other through the public distribution grid, as opposed to other communities hat use privately owned infrastructure such as private wiring. The ReFLEX project supported studies on energy communities in order to better understand the benefits and drawbacks from individual and community-owned generation assets.

9.4.2. Local energy markets

Local energy markets (LEM) allow prosumers to sell excess electricity to other members of the community, through a specific market mechanism [96]. Market mechanisms can implement a full P2P market or bilateral trading, where a community member “*A*” sells electricity to another community member “*B*”. Promising solutions in this case can be automated negotiations schemes, as shown in [56]. Other mechanisms can implement a peer to community scheme, in which case electricity from a specific community member is sold to the community, without knowing exactly who will benefit from this electricity. In this case, such schemes can be implemented through double auction market clearing mechanisms [97]. In both cases, multi-agent systems modelling can be an enabler that can model community members in a more realistic way and that can determine algorithms that satisfy community objectives. Practical applications of such schemes are still in their infancy in large-scale, however, diverse implementations have been proposed in proof of concept or pilot projects [7,98]. Large scale implementation of these novel solutions faces several challenges. First, in most countries energy consumers are not allowed to have more than one electricity supplier, as it would be the case in P2P energy trading. Second, technical challenges include the implementation of a fair clearing market mechanism, but also a reliable ICT solution. Furthermore, such schemes often require optimisation techniques and direct load control, which may not be accepted by consumers. In fact, the main challenge is the social acceptance of such schemes. Economic incentives might not be substantial enough to overcome the potential inconvenience from load shifting related to P2P schemes, even if they are designed in a transparent way. Within ReFLEX, virtual P2P energy exchanges were implemented between community members through the fixed ReFLEX tariff. In addition, the ReFLEX research team has proposed innovative frameworks for P2P energy trading based on automated negotiations [56], that allow consumers and producers’ HEMS to bargain between each other to find a compromise on energy quantities and prices for each time period in the local market.

9.4.3. Flexible communities

To increase profitability of assets, a common practice is to diversify the source of revenues by allowing assets to participate in different markets [53]. Wholesale energy markets are currently not accessible to small assets with a capacity lower than 1 MW [99]. For this reason, residential assets need to be aggregated within an aggregator’s portfolio, before further trading. Local energy communities can be considered as a first level of aggregation that can participate to wholesale energy markets, potentially via an aggregator. Also, future SLES will take part in markets at different levels, such as local flexibility markets that provide regulation services to the DNO, or wholesale energy or ancillary services markets at a national level. A significant challenge emerging then will be to coordinate LEM commitments at different levels. In ReFLEX, flexibility is provided by domestic smart chargers and smart heaters that help the community to decrease CO_2 emissions. However, in ReFLEX we identified a few challenges related to the robustness of residential flexibility. For example, residential flexibility requires accurate operation of the remote controller even when no information on domestic assets is available. Moreover, a significant amount of data needs to be managed in addition to increasing robustness to uncertainties. Flexibility requirements must be anticipated and quantified, which are areas of current active research.

9.4.4. Artificial intelligence solutions

Flexibility from end-users and distributed control can be enabled by artificial intelligence (AI) based solutions, that are generally defined as smart software and hardware solutions that have knowledge of their environment and take actions that maximise their chance of successfully achieving their goals. AI solutions can be classified into three main categories of functions, which are regressions, mostly used for forecasting, classification, used to identify hazardous situations or to classify patterns, and optimisation solutions, used for example to control appliances. To achieve these three main functions, different techniques exist, such as Artificial Neural Networks (ANN), deep neural networks, support vector machines, k-means algorithms, etc. These techniques are usually classified by types (machine learning, deep learning, bio-inspired algorithms, etc), as shown in Fig. 10, inspired by [100].

The main applications for artificial intelligence solutions in the energy field consist in smart monitoring analysis, smart planning and optimisation, control and scheduling [101]. In ReFLEX, AI solutions were used to forecast energy demand and wind turbines production. It was shown that accuracy can be maintained even with a few weeks of data for training, instead of several years. Also, preference was given to technologies with a low computing cost. Therefore, for a similar level of accuracy, k-Nearest Neighbours algorithms were preferred over artificial neural networks. The rest of this subsection lists areas in which AI solutions are relevant for SLES.

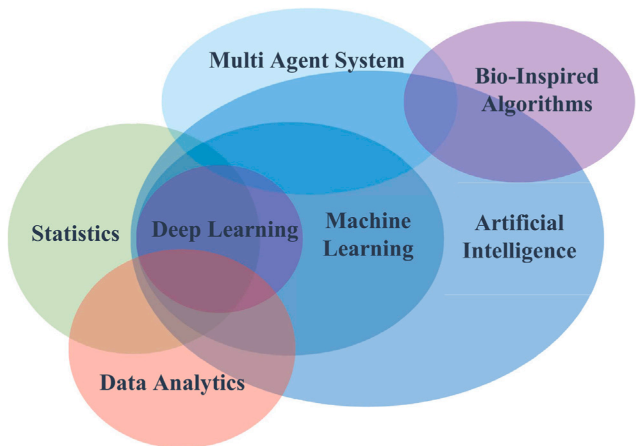

Fig. 10. Overview of the AI ecosystem covering different types of AI techniques.

First, in smart monitoring and analysis, AI solutions can be used for forecasting, e.g. forecasting of energy consumption or production [102–104], but also to achieve fault detection or fault prediction. Forecasting allows SLES operators to anticipate the needs at the local level (e.g. consumption needs), and to prepare for the best control operation. Similarly, fault detection and prediction allow a better control of energy networks, by identifying when assets are not behaving as they should and by identifying the nature and location of the fault [105,106].

Then, AI solutions can be used to optimise the control of assets. This is the case for several Home Energy Management Systems that schedule appliances based on the requested comfort by the user and energy prices. For example, smart control solutions can leverage nature inspired algorithms (Particle Swarm Optimisations or evolutionary algorithms) to optimise complex scheduling problems in HEMS, or it can be based on reinforcement learning techniques [107–109], such as Q-learning, to make the control evolve autonomously and to align with end-user expectations [83]. As an industrial project, ReFLEX control implementation mostly used well-known technologies and did not investigate innovative algorithms.

Finally, AI solutions are also an important tool to classify behaviours, which can then be used to assess the relevance of different solutions during the planning of SLES operations. For example, classification and clustering algorithms, such as decision trees, k-nearest neighbours and k-means, have been used to cluster end-users, in order to identify which customers would be most inclined to provide electric flexibility to an aggregator [83]. Such classification solutions are of great importance to enable residential flexibility, and will be the focus of the next phases of ReFLEX.

9.4.5. Distributed ledger technologies and smart contracts

With the development of local initiatives such as LEM, there is a need for local solutions that enable secure data sharing, secure financial transactions or distributed assets control. Distributed ledger technologies (DLT) are seen as a reliable solution to store local data in local blockchains, or to automate payment and control through smart contracts running on a local blockchain constituted by computing resources of an energy community. Several works in the literature have focused on the identification of suitable DLT and blockchain technologies applications for the energy sector including their relevance for local energy solutions [7,110,111]. In addition, numerous projects, commercial initiatives and start-ups have used blockchain solutions for local energy trading between peers in communities, most notably the well known case of the Brooklyn Microgrid project [112] and the notable initiatives from PowerLedger that span in over 12 countries [113]. Although there are still challenges to be solved such as the design of efficient consensus mechanisms and efficient storage solutions. Blockchain technologies also bring many benefits: redundancy in storage increases reliability, whereas end-to-end encryption improves security and privacy. Finally, DLT also increase transparency and traceability by allowing blockchain users to track the origin and characteristics of the energy they are buying [7]. Similarly, smart contracts are software codes that run on the virtual machine constituted by the blockchain nodes, and can be automatically triggered by any given condition [78]. Therefore, they are suitable for automatic payment, especially in LEM applications or can be utilised for decentralised control [53].

9.4.6. User-centric approaches

The net zero transition needs to follow a bottom-up and user-centric approach that starts with each individual consumer's needs, then with the local community needs and finally satisfies operational and system needs. Relevant approaches related to end users are presented in this section. SLES operations require User-centric control solutions at different aggregation levels. The first one is the SLES level, which should coordinate the operations of assets and stakeholders within the SLES. In the ReFLEX project this was implemented by the IESC mentioned in Section 4.2. Next, control operations aim to maximise benefits for and at each stakeholder's level. Finally, at the end-user or asset level, smart control strategies aim to optimise the use of assets so that requirements from higher levels are met, while at the same time constraints from the local environment (e.g. user preferences, irradiation, external temperature, etc) are within the operating range. Several works have discussed such approaches, as in [114–120]. Control solutions for future deployment of SLES will not have a successful outcome if users are not placed at the centre of the system, while considering social, economical and physical constraints, within a multi-vector and multi-objective (environmental, financial and comfort goals) optimisation environment.

Then, active participation of end-users in the energy system requires the implementation of user-centric smart HEMS that will optimise the control at end-user premises, considering requirements from the other energy stakeholders, but also preferences of end users. HEMS in future SLES will have to interact with end-users in order to include smart appliances schedule constraints, to extract comfort requirements or preferences over the consumption of energy (e.g. green energy, local energy, etc.) and to better assess the flexibility potential of each user. Optimisation algorithms will enable HEMS to determine optimal schedules for flexibility assets in order to minimise their environmental impact, minimise energy bills without affecting negatively the comfort of end-users.

Acceptance of flexibility requirements and behavioural change will be one of the greatest challenges of the energy transition. Therefore, the design of HEMS should integrate end-users feedback and software installed in HEMS will have to include the ability to learn from the end-user behaviour in a non-intrusive way. For example, if users are overwriting or not responding to flexibility requests, this can be perceived as indirect feedback, which can in turn be taken into account both in the optimisation algorithm of HEMS and in the design of future flexibility propositions and offerings to consumers. The ReFLEX demonstration project did not integrate HEMS at end-user premises, however, this possibility was investigated thoroughly by researchers of the ReFLEX team, who proposed HEMS algorithms that allow maximisation of self-consumption and participation in wholesale markets [53]. In future work, this will be extended with the integration of end-users preferences, comfort and implicit and explicit feedback from end users.

9.4.7. Digitalisation and interoperability

Digitalisation consists in the transformation of the energy sector by using digital technologies, that aim to create or convert information into a digital format interpretable by machines. Digitalisation should lead to a greater access to data for industrials, public organisations or individuals, and is based on a strong and shared IT infrastructure, on standardised and interoperable communication protocols and data formats, and on secure by design solutions for communication. Digitalisation also requires appropriate regulation and governance to ensure preservation of rights for all citizens. Finally, digitalisation along with Big Data analysis will bring additional value to all energy stakeholders and end-users by enabling the creation of additional energy related services [121,122].

The main recommendations towards digitalisation provided by Ofgem, the Office of Gas and Electricity Markets in the UK, include the need to have exploitable data, through the adoption of standard data models, or through the addition of relevant metadata. Ofgem also highlighted the need to make data discoverable, to maintain data access and quality, to ensure interoperability through standard communication protocols [123,124] and through well-adopted ontologies (SAREF, SAREF4ENER) or smart data models (Fiware in Europe), but also to protect assets and data through cybersecurity, privacy and resilience actions, and to find appropriate storage solutions to enable data access to relevant stakeholders while favouring open access to data and scripts [125]. For what concerns ReFLEX, which is an industrial project with high TRL (Technology readiness level) expectations, the project did not use any innovative communication standard, and relied on APIs to remotely control flexible assets and share real time data.

Digitalisation allows a continuous monitoring of the state of the SLES, and enables a remote control of assets for an efficient and coordinated operation [126–129]. This requires however that most assets and devices are accessible remotely through gateways and implement standard protocols, such as the Internet Protocol. A local governance should also ensure ethical considerations in the data collection, storage and use, as well as transparency and visibility on the data usage by third parties. Following recent regulations on data privacy, digitalisation should ensure that end-users are given real control over their data through customer data management platforms [130–133].

10. Conclusion

Smart local energy systems consist in a mix of solutions that aim to support the deployment of low carbon technologies, while reducing their negative impacts and increasing their economic, social and technical viability. Based on the experience of the ReFLEX project, a SLES implementation in the Orkney islands, this paper proposed to describe how SLES can be successful in the current context. It was shown that due to restrictive regulations, the ReFLEX project encountered significant obstacles to install domestic flexible assets at large scale, such as residential batteries. Adapting to these restrictions, it then demonstrated the reduction of local renewable generation curtailment through the use of EV smart chargers' and smart heating systems' flexibility. As a result, we introduced an extension of the smart grid architecture model to include the multi-services approach proposed by SLES, and especially the ReFLEX project. This Smart Local Energy Architecture Model (SLEAM) constitutes a road map to follow in the SLES planning and deployment phases, and mostly differentiates from the well-known SGAM as it adopts a multi-services approach, and includes end-users behaviours and local markets considerations. This framework helps SLES stakeholders to understand the layered structure of SLES, from the physical components to the social, economic and regulation framework. SLES stakeholders should also consider several important steps, such as the set up of multi-services models for techno-economic planning purposes, or the involvement of the community and main stakeholders into the project, but also the implementation of a data management strategy. As a result, we proposed a comprehensive list of SLES key performance indicators that will guide SLES stakeholders through the different themes to consider when designing a SLES. It was emphasised that SLES projects are multi-disciplinary initiatives that must consider social, technical and economical barriers in both the planning and operational phase. Although the case study analysed in this paper is more relevant to the UK context, the lessons learnt from the ReFLEX project and review analysis in this work, are relevant to various stakeholders, local authorities, energy system operators, industry, policy makers and citizens, who aim to deploy local solutions to other parts of the globe, as part of their sustainability agenda.

Although SLES success can be quantitatively assessed through the proposed KPIs, the implementation of an evaluation framework to the ReFLEX project showed that it is yet too soon to see sensible positive impacts of the measures implemented by SLES, especially when using it at an intermediary state of a project. Indeed, most of SLES projects mostly consist in setting up flexibility tools that will allow a better management of assets when and if they are deployed. Nevertheless, current regulations or economic constraints often prevent projects to deploy a large quantity of production or consumption assets, as it was the case for ReFLEX. Therefore, effects of these SLES implementations will become more tangible in the long term after a larger integration of low carbon technologies. However, a stronger deployment of low carbon technologies such as EV, HP, solar PV, hydro or wind turbines will require new economic incentives provided by new regulations or local market mechanisms that will aim to motivate end-users, communities and other economic agents to massively invest in energy assets. Based on these learnings from the ReFLEX project, this work proposes a summary of most of enablers and obstacles to the implementation of SLES, which will help in the replication of such novel flexible, decarbonised, and user-centric energy systems

Finally, although SLES innovative technologies such as AI based smart control or flexible assets aim to seamlessly solve technical challenges arisen from the deployment of low carbon technologies, they will not avoid to resort to sensible changes in end-users behaviours. This requires researchers, social bodies, and companies to actively integrate the end-users in their models, and to identify what levers can be used to incentivise citizens to act in favour of the energy transition without too much changes in their daily habits.

CRediT authorship contribution statement

Benoit Couraud: Conceptualization, Methodology, Software, Data curation, Writing. **Merlinda Andoni:** Validation, Writing. **Valentin Robu:** Conceptualization, Project administration, Funding acquisition. **Sonam Norbu:** Validation, Resources. **Si Chen:** Validation, Writing. **David Flynn:** Conceptualization, Methodology, Supervision, Validation, Project administration, Funding acquisition.

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

Households consumption data come from ReFLEX project, which is confidential and not publicly available. Other data used for the paper is publicly available data, that is referenced in the paper

Acknowledgements

This work was supported by the following UK Research and Innovation (UKRI) projects: Innovate UK Knowledge Transfer Partnerships (KTP) Project based at The Crichton Trust, Dumfries in partnership with the University of Glasgow [KTP-13052], the InnovateUK Responsive Flexibility (ReFLEX) [GrantNo:10478], Decarbonisation Pathways for Cooling and Heating (DISPATCH) [EP/V042955/1]. Valentin Robu was supported by the project "TESTBED2: Testing and Evaluating Sophisticated information and communication Technologies for enaBling scalablE smart griD Deployment", funded by the European Union Horizon2020 Marie Skłodowska-Curie Actions (MSCA) [GrantNo:872172].

Table 1
Key performance indicators for SLES.

Category	Index	Description	Type/unit
Energy	Energy imports	Quantifies the annual energy imports from geographical locations out of the SLES zone	MWh/year
	Energy exports	Quantifies the annual energy exports out of the SLES zone	MWh/year
	Improvements in energy independence	Improvement in energy self-sufficiency compared to a base year of reference	%
	Reduction of energy requirement (electricity/heat/transport)	Measures the reduction in demand for energy (electricity/ heat/ transport) of the SLES compared to an initial energy requirement (base year of reference)	%
	Reduction of curtailment	Percentage of energy curtailment avoided thanks to SLES actions	%
	Flexibility potential	Maximum hourly energy flexibility potential for electricity and gas. Includes battery storage, thermal storage, EVs flexibility, including V1G and V2G. Expressed as percentage of the SLES peak hourly energy consumption, and the duration this flexibility quantity can be activated	%, hour
	Annual flexibility activated	Annual energy used within the SLES for flexibility purposes	MWh
	Local storage capacity	Installed storage capacity and power, including electrochemical batteries, thermal storage, V2G assets reduced by the time percentage where EVs are not connected to the grid	MWh, MW
	New low carbon energy sources installed	Power of renewable energy installed in the SLES	kW
	New low carbon technologies installed	Number of potentially low carbon technologies installed (production, consumption, such as EV, heat pumps, etc)	$\mathbb{N}$
	New Energy related services	Number of energy services provided by SLES to the stakeholders and end-users (market related, remote monitoring, etc)	$\mathbb{N}$
Environment	Community $CO2_{eq}$ emissions	Operational $CO2_{eq}$ emissions per capita	$tCO2_{eq}$/capita
	Energy vectors emissions factors	$CO2_{eq}$ emission factors per energy vector	gCO_2/kWh
	% of operational $CO2_{eq}$ reduction	Percentage of annual $CO2_{eq}$ emissions reduction per year and per vector compared to a baseline reference	%
	Indirect $CO2_{eq}$ reduction	Percentage reduction in annual indirect $CO2_{eq}$ reduction	%
	Noise pollution reduction	For noisy locations, assesses the percentage reduction of dB due to SLES actions, such as removal of a gas turbine	%
	Biodiversity impact	Gathers information regarding possible disruption to biodiversity of local species as well as danger to certain animals and plants. Assessed by the number of animal species threatened by SLES actions	$\mathbb{N}$
	Hot air/water use reduction	Assess the reduction of steam and heat production from energy production compared to a baseline reference	%
	Assets life cycle emissions	Assess the life cycle equivalent carbon emissions due to installed assets within the SLES	$kgCO_{2_{eq}}$
	Use of land	Surface of area no more available for agriculture of biodiversity because of SLES actions	m^2
	Rare earth element consumption	Assess the resource consumption for the deployment of SLES, including rare earth material	kg/type
	Supporting mitigation	Assess the impact of actions such as primary forest development used to reduce $CO2_{eq}$ emissions.	$kgCO2_{eq}$ avoided per year
Society	Households involvement	Assess the percentage of households involved in active power management, or contributing to demand response events	%
	Organisations involvement	Assess the percentage of business and organisations involved in active power management, or contributing to demand response events	%
	Rural involvement	Quantification of rural population involved SLES	%
	Urban involvement	Quantification of urban population involved in SLES	%
	Citizens consultation	Percentage of the population responding to surveys, co-design workshops, and polls	%
	Local governance	Assess the representativeness of the people constituting the local governance team	%
	Local representation	Percentage of stakeholders who are living in the local geographical area	%

(*continued on next page*)

Table 1 (*continued*).

Category	Index	Description	Type/unit
	Social energy empowerment	Percentage of the population feeling responsible for their own energy consumption	%
	Social business development	Number of social businesses including consideration for energy and fuel poverty	ℕ
	Citizens satisfaction	Through surveys, this KPI indicates the degree of satisfaction of the population due to SLES measures. Assessed in percentage of the population surveyed that is satisfied	%
	Local employment	Number of newly created job by SLES stakeholders, that are local	ℕ
	Inclusiveness	Percentage of population types surveyed or included during the SLES design and deployment	%
	Elderly support	Percentage of elderly population personally interviewed and considered in the SLES deployment	%
	Consumer financial benefits	Percentage of SLES members with a reduction in cost per kWh	%
	Stakeholders diversity	Diversity of types of stakeholders involved in SLES (large private companies, SMES, public organisations, etc)	ℕ
	Diversity of SLES offering	Diversity of sectors addressed by SLES (residential, industries, commercials, etc)	ℕ
	Services diversity	Number of new non-energy services provided or supported by SLES	ℕ
	Local Innovations	Number of innovations (product, services, etc) from local community and stakeholders	ℕ
	Intellectual Property	Number of patents registered by the community	ℕ
	Education programs development	Number of new energy related local educational programs created within the SLES deployment project	ℕ
	Event dynamism	Number of project forums, workshops, seminars and total number of participants	ℕ, ℕ
	Social media	Number of followers of SLES actions on social media	ℕ
	Internet visibility	Number of visitors on SLES websites and average engagement time	ℕ, min
Economic	Energy bills reduction	Percentage of reduction in energy bills in the community	%
	Energy unit price	Price of one unit of energy for each of the different energy vectors (electricity, heat, gas, transport)	£per kWh
	Fuel poverty reduction	Percentage of population originally in fuel poverty situation that is not in fuel poverty any more	%
	Investments	Quantifies the private and public investment	ℕ, ℕ
	Infrastructure investment	Budget allocated to local investment in infrastructure (roads, EV chargers, telecommunication, etc)	£
	Reduction of infrastructure investments needs	Quantifies the reduction (in percentage) of the planned investment in infrastructures	%
	Economic incentives	Yearly number of economic tools such as green or white certificates to decarbonise energy	ℕ
	SLES cost	Investment cost to deploy SLES solutions	£
	Payback period	Estimated payback period based on the current year's revenues	years
	Business creation	Number of new businesses created within the SLES design and deployment	ℕ
	Businesses diversity	Number of businesses types involved in the SLES	ℕ
Resilience	Annual downtime	Annual downtime experienced by the local community	hours
	Energy independence (per vector)	Measures the percentage of annual energy consumption produced from local energy resources	%
	Diversity of Energy Consumption technologies	Quantifies the mix of technologies per energy vector. Assessed by the variance of a distribution consisting in the annual energy consumption per technology (in kWh) where each technology is separated by one unit	σ ($\mathbb{R}$)
	Diversity of Energy Production mix	Quantifies the mix of energy resources in the energy production mix. Assessed by the variance of a distribution consisting in the annual energy production per energy source (in kWh) where each energy source is separated by one unit	σ ($\mathbb{R}$)

(*continued on next page*)

Table 1 (*continued*).

Category	Index	Description	Type/unit
	Diversity of local Energy Production mix	Quantifies the mix of energy resources within the community. Assessed by the variance of a distribution consisting in the installed production power (in kW) where each energy source is separated by one unit	σ ($\mathbb{R}$)
	Local supply chain	Percentage of products or services supplied from national businesses or institutions	%
	Black start	Assesses the capability of the SLES to restart supplying customers in case of outage of the whole national infrastructure	boolean
	Distributed data storage	Percentage of SLES data that is stored using redundant storage facilities with different locations, including distributed ledger technologies	%
Assets & Infrastructure	Geographic coverage	For heat, electricity, gas and transport, it assesses the percentage of the population that is not connected to a distribution network/road/gas or heat network	%
	Networks capacity usage	In average over the whole networks, the spare capacity from each vector's infrastructure based on maximum demand over a year	%
	Reduction in system's power losses	Measures the reduction of systems losses (technical and non technical, for all vectors). Percentage of the annual reduction	%
	Connectivity	Measures the proportion of SLES assets that are connected to a cloud service	%
	Communication networks coverage	Percentage of the SLES areas with assets or consumers that have access to communication channels (LTE, cable internet, optical fibre, LoRa, etc)	%
	Asset monitoring	Assesses the capability of the SLES to provide real time assets monitoring. Corresponds to the percentage of local equipment that are monitored in real time	%
	End-users automation	Percentage of SLES loads (including residential) remotely controllable through an API	%
	Assets automation	Percentage of local infrastructure assets remotely controllable (secondary substation, tap changers, valves, etc)	%
	Low carbon individual vehicles deployment rate	Assessment of the deployment rate of low carbon technologies for individual transport	%
	Low carbon public transportation vehicles deployment rate	Assessment of the deployment rate of low carbon technologies for public transport	%
	Cybersecurity	This index should be considered as a whole category, and corresponds to the number of risks that have been controlled by all stakeholders among OWASP top 10 cybersecurity risks (access control, cryptographic storage, injection, etc)	$\mathbb{N} \leq 10$
Data management	Open Data Access	Percentage of anonymised or aggregated monitored data accessible to the public through an API	%
	Local Data governance	Indicates if a committee of citizens and stakeholders (industrial, academics, social scientists, etc) has been established to work on different aspects of local data (sharing agreement, monitoring agreement, GDPR support, transparency, etc)	boolean
	GDPR compliance	Percentage of stakeholders following GDPR regulation	%
	Local storage	Percentage of datasets stored locally	%
	Standard data models	Percentage of data that is using standard linked data models such as Fiware, SAREF, etc	%
	Awareness of data transparency	Number of events to raise awareness of data transparency, how to retrieve personal data, etc	$\mathbb{N}$
Regulations and Policies	Involvement	Assess the active participation in the design of new policies. Measures the number of working group for regulation and policies that SLES members are involved in.	$\mathbb{N}$
	Experimentation	Measures the number of new regulation or policies that are experimented in the SLES	$\mathbb{N}$
Extension and replication	Communication	Number of reports, tutorials, publication for replication of the SLES developed	$\mathbb{N}$

(*continued on next page*)

Table 1 (*continued*).

Category	Index	Description	Type/unit
	Open access of solutions	Percentage of the proposed solution that is available in open source for replication	%
	Replication sites identification	Number of sites (in same country or internationally) that could replicate the SLES solution	$\mathbb{N}$
	Worldwide events	Number of events in which the proposed SLES was presented	$\mathbb{N}$

Table 2
Key performance indicators for ReFLEX project.

Category	Index	Value	Comment
Energy	Energy imports	502 GWh/year	
	Energy exports	60 GWh/year	Not including oil transfer
	Improvements in energy independence	2%	Mostly due to transportation shift toward EV
	Reduction of energy requirement (electricity/ heat/ transport)	5.15%	For buildings (electricity and heat)
	Reduction of curtailment	2.6%	
	Flexibility potential	0.6%, 24/7	Currently mostly smart heater and Smart Chargers (700kW) out of which only 100 kW are considered flexible all the time
	Annual flexibility activated	0 kWh	Not fully implemented yet
	Local storage capacity	740 kWh	V1G EV not considered, includes smart heating
	New low carbon energy sources installed	3 MW	Considering storage assets and hydrogen programme
	New low carbon technologies installed	210	
	New Energy related services	3	Flexibility and self-consumption, local P2P
Environment	Community $CO2_{eq}$ emissions	8.7	in 2019
	Energy vectors emissions factors	0.09, 0.35, 0.25 $kgCO2_{eq}/kWh$	Electricity, heat, transport
	% of operational $CO2_{eq}$ reduction	0.1%	
	Indirect $CO2_{eq}$ reduction		
	Noise pollution reduction		
	Biodiversity impact		
	Hot air/water use reduction	0%	
	Assets life cycle emissions		
	Use of land	100 m^2	
	Supporting mitigation	0 $kgCO2_{eq}$ avoided per year	
Society	Households involvement	1.6%	
	Organisations involvement	0.66%	
	Rural involvement		
	Urban involvement		
	Citizens consultation	4.9%	
	Local governance	95%	
	Local representation	80%	
	Social energy empowerment		
	Social business development		
	Citizens satisfaction	66%	
	Local employment	28	
	Inclusiveness	20%	
	Elderly support	35%	
	Consumer financial benefits	0%	
	Stakeholders diversity	4	public, industrials, consulting, academics, SME and large enterprise

(*continued on next page*)

Appendix A. Key performance indicators for SLES

See Table 1

Appendix B. Key performance indicators for reflex project

See Table 2

Table 2 (*continued*).

Category	Index	Value	Comment
	Diversity of SLES offering	2	residential and commercials
	Services diversity	3	Self-consumption, energy market participation, Peer-to-peer trading
	Local Innovations	1	P2P under grid constraints
	Intellectual Property		
	Education programs development	2	Stromness Campus
	Event dynamism	137	
	Social media	1,659	
	Internet visibility	4900, 3:30 min	
Economic	Energy bills reduction		
	Energy unit price		
	Fuel poverty reduction		
	Investments	£3.1M, £5.6M	private, public
	Infrastructure investment		
	Reduction of infrastructure investments needs	0.2%	Effect of flexibility on peak power admissible
	Economic incentives		
	SLES cost	£8,753,323	
	Payback period		
	Business creation	0	
	Businesses diversity	5	public, industrials, consulting, academics, SME, large enterprises
Resilience	Annual downtime	NA	
	Energy independence (per vector)	56%, 20%, 0.1%	Electricity, Heat, Transport
	Diversity of Energy Consumption technologies	162.3	
	Diversity of Energy Production mix		
	Diversity of local Energy Production mix	162.1	
	Local supply chain		
	Black start	yes	
	Distributed data storage	100%	
Assets & Infrastructure	Geographic coverage	86%	
	Networks capacity usage	0%	
	Reduction in system's power losses	4.75%	
	Connectivity	100%	
	Communication networks coverage	65%	https://www.nperf.com/en/map/GB/-/322.Three/signal/?ll=58.92449914384962&lg=-3.13934326171875
	Asset monitoring	45%	
	End-users automation	90%	
	Assets automation		
	Low carbon individual vehicles deployment rate	3.8%	
	Low carbon public transportation vehicles deployment rate	2.1%	
	Cybersecurity		
Data management	Open Data Access	0%	
	Local Data governance	yes	
	GDPR compliance	yes	
	Local storage	66.66%	EV data stored on proprietary clouds
	Standard data models		
	Awareness of data transparency	2	
Regulations and Policies	Involvement	2	OFGEM events
	Experimentation	1	P2P energy trading

(*continued on next page*)

Table 2 (*continued*).

Category	Index	Value	Comment
	Communication		
Extension and replication	Open access of solutions	40%	Storage control algorithm
	Replication sites identification	115	
	Worldwide events	106	

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