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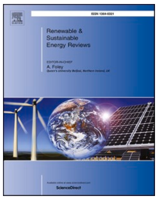

Upscaling smart local energy systems: A review of technical barriers

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ABSTRACT

As the transition towards a more sustainable, distributed energy model has continued to gather pace, the number of Smart Local Energy Systems (SLES) projects has increased. Ranging in age, size, location and complexity, these projects have faced a series of technical, social and economic challenges, with varying degrees of success. This paper presents the results of a systematic, state-of-the-art literature review with the aim of identifying the main technical barriers experienced by SLES in the UK. Originality is provided in the discussion of the key barrier areas identified during the review, which include those posed by multi-vector integration, grid connection, energy storage, smart technology and electric vehicles. The site-specific nature of SLES is identified as limiting the applicability of specific technical barriers, as is the need to view technical barriers within their respective social, economic and regulatory contexts. From the findings emerge three fundamental underlying technical challenges which face all SLES: diversity, uncertainty and integration. The findings also indicate that a more detailed understanding of site and context-specific barriers – and the relationships between them – is required in order to facilitate the mitigation or removal of technical barriers to the upscaling of SLES.

1. Introduction

A growing and increasingly varied number of SLES have been deployed across the UK in recent years. These projects have faced a variety of different technical, social and economic barriers throughout their planning, design, deployment and operation, and have therefore accrued valuable knowledge and experience. This paper aims to capture and synthesise the experiences of existing SLES as reported in both academic and grey literature, via a systematic state-of-the-art literature review. In doing so, this review provides an overview of the key challenges currently faced by SLES projects and the fundamental technical challenges from which they stem. This in turn provides insight into the future direction of research and development within the sector.

Section 2 presents the context of the research, including a preliminary definition of SLES. Section 3 outlines the methodology used in conducting the review. Section 4 examines the definitions of both upscaling and technical barriers as reported in the literature. Section 5 then presents a state-of-the-art review of the relevant literature and the technical barriers to upscaling which are identified therein. A discussion of the novel findings takes place in Section 6, which also includes a summary of the future outlook.

2. Smart local energy systems

The increase in the deployment of local energy systems has been the subject of intensive research and development in recent decades. But as the body of related research has grown, the terms used to describe these systems has also diversified and evolved, as evidenced by the number of distinctive and highly inter-related fields which exist in the literature e.g. microgrids, virtual power plants, community energy, energy hubs, intelligent power systems, decentralised energy systems, energy centres [1,2]. Understanding these terms, and their differences and similarities, is key to ensuring that the present review is appropriately broad in scope and avoids any key omissions.

From a technical standpoint, the key components of any energy system are generation, distribution infrastructure and consumption. The storage of energy and the transfer between vectors are also of particular importance within SLES.

When it comes to conceptualising the terms ‘smart’ and ‘local’, recent research shows that there is currently a lack of consensus among researchers, even those operating within the energy field [3]. This creates ambiguity, and gives rise to a spectrum of definitions which can overlap or contradict one another.

Within the context of SLES research and development, the term

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'smart' has emerged as a commonly used umbrella term. It is typically used to convey the idea of connected and communicative system(s), either signifying greater connectivity between system elements as part of management and operation optimisation/monitoring, or between the system as a whole and its users. Either way, this greater connectivity is characterised by the high availability, accuracy and detail of data, as well as the ability to use it to inform control and optimisation decisions.

Within the wider context of sustainable energy research there is a disproportionately large body of research into small scale, often geographically constrained energy systems embedded within the communities or areas they serve. The factors which contribute towards the prominent role of research in this context include the following:

- In many instances, projects are located in areas which are poorly served by pre-existing centralised energy systems, in terms of quality, security and cost of supply. This creates a stronger motivation for the development of alternatives than is likely to exist in better served areas [4].
- Such projects are suited to small, geographically-defined locations, which tend to be rural or remote, and therefore have significant renewable energy resources (such as wind, hydro or solar) available.
- Projects of this size and scale are well suited to being used as demonstrators.
- Such projects are seen as early adopters of alternative energy models, and can therefore play a significant role in influencing the wider deployment of such models in future.

It is worth noting that much of the research around distributed generation infers that the energy being supplied is generated by low carbon/renewable sources, but this is not inherently true as renewable energy can be – and is – centralised, while local energy systems can include a high penetration of carbon-intensive technology i.e. those which are reliant on fossil fuels, such as diesel generators and conventional technologies such as gas-fired boilers. However, it is acknowledged that SLES are likely to include at least one form of low carbon or renewable generation.

Over the last decade, research focus has begun to shift from electricity systems (often referred to as smart grids) towards multi-vector systems, which also include thermal energy (most commonly district heating) and transport vectors (via electric vehicles, see Section 5.6). The inclusion of multiple vectors within the design and operation of an energy system creates scope for greater operating flexibility as well as greater carbon and cost savings [5,6]. These benefits, and the challenges associated with them, are discussed in more detail in Section 5.4.

More recently, there has been a decrease in the number of community energy projects being developed in the UK [7]. This is linked to the removal of the Feed-in Tariff, and has resulted in a shift in focus towards energy efficiency measures and innovation through the integration of energy storage and integrated transport. This has seen storage and transport gain increased prominence within the most recent SLES projects, as falling capital costs and potential techno-economic benefits become increasingly attractive in a post-subsidy landscape.

For the purposes of this study, the key technical characteristics of SLES are that they:

1. Utilise smart systems/technology.
2. Include at least one on-site source of low carbon energy generation.
3. Serve more than a single building/site, but less than an entire region.
4. Combine both on-site energy generation and demand sources i.e. the aforementioned key energy system components.

3. Methodology

A review of literature has been conducted with the aim of providing a wide and representative view of the key technical barriers relating to the scale-up of SLES.

The first part of the data collection process consisted of keyword searches for academic publications. This was conducted using Google Scholar to maximise the breadth and scope of the publications included in the search. The terms used in the keyword search are shown Table 1 below. Initial searches were conducted using every possible combination, before further searches were conducted using combinations from columns 1) and 2) only, to ensure that gaps in the search coverage were minimised.

This enabled sources of both wide ranging and detailed information to be identified. Initial priority was given to broad-ranging reviews of the subject area, in order to identify key areas of the literature, which could then be subjected to further more detailed analysis. This also ensured that the review was sufficiently broad in scope as to include adjacent fields of research.

This led to a total of 132 documents and reports being reviewed as part of this study. This primarily included academic publications from fields including mechanical engineering, energy policy, renewable energy, computer science, transport, electrical engineering and planning. So-called grey literature i.e. charity/non-profit, industry and government publications were also included. In order to aid in the identification of grey literature sources, generic non-academic search engines were also used (Google, Bing).

Upon the review of the identified documents, a number of common themes were identified. These are discussed in subsequent sections.

4. Identifying technical barriers to upscaling

The upscaling of SLES can usefully be informed by analysing existing examples and identifying common technical barriers which inhibited their development. Such analysis requires a clear definition of upscaling, and of what constitutes a technical barrier.

4.1. Upscaling

The topic of upscaling is the subject of a wide and varied body of literature. This has led to a similarly broad variety of definitions across a number of fields. A simple definition is provided by Sandick and Oostra, who refer to upscaling as "the process in which broad implementation of an innovation is achieved" [8]. However, more detailed definitions from elsewhere in the literature show that there is variance in how upscaling is defined, and also how it is achieved.

The literature reviewed also suggests that the concept of upscaling, particularly when concerning technology, is commonly conflated with the two specific realms of research which share many of the same characteristics: technology/innovation diffusion [9–12] and strategic niche management [13,14].

Van den Bosch and Rotmans identify two conceptualisations of upscaling [15]. The first of these involves a step-wise development from experimentation through niche development to regime-wide adoption, through the aggregation of knowledge from multiple projects. The second sees upscaling as the embedding of niche methods/practices within the regime or society in which they are applied.

Naber et al. [12] identify four main patterns of upscaling:

Table 1
Keyword search terms.

1) System Qualities	2) System Descriptors	3) Subject matter
Smart	Energy System(s)	Upscaling
Local	Microgrids	Scaling up
Community	Energy Centres	
Decentralised	Power systems	
Distributed		
District		

1. Growing: where an innovation grows in size or activity, with more actors participating.
2. Replication: when a concept is repeated in other locations.
3. Accumulation: when multiple projects are linked to one another, facilitated by intermediaries.
4. Transforming: where projects shape wider institutional change.

There is also an area within energy systems/technology literature which looks specifically at the upscaling of energy systems and technologies. This is seen as being directly relevant to SLES.

In his analysis of the Austrian biomass sector, Seiwald argues that upscaling is an ambiguous term which implies a progression from pilot projects through to industrial scale applications [16]. Instead he maintains that upscaling is achieved over a number of configurations and dominant designs, implemented at a range of scales, often simultaneously. This echoes the four patterns of upscaling identified by Naber et al. (as described above) but implies that the patterns of upscaling can occur simultaneously.

There is a broad consensus in the literature that the development of innovative technologies requires a supportive environment and a shared vision that spans policy, research and industry [2,9,17]. Hargreaves et al. identify the importance of the role played by so-called “intermediary actors” in facilitating scale-up and the replication of SLES [18]. Intermediaries can therefore be regarded as a key stakeholder group when it comes to SLES upscaling. This is reflected in the role played by organisations such as Community Energy Scotland/England in the UK – non-profit organisations who provide support to new community energy projects through the early stages of project planning, development and funding [7].

Chmutina and Goodier argue that innovation, despite having social, financial and governance aspects, is primarily regarded as being technical [19]. As such, innovation risks being perceived as lacking technical maturity and therefore represents a risk to developers and funders.

When it comes to technology, upscaling is a process which sees knowledge and understanding increase through data collection and analysis, the identification of negative and positive aspects of performance and design, and the application of this knowledge in subsequent deployments. It also requires that infrastructure is in place which facilitates this knowledge transfer and analysis, but this can also take time to implement [15].

The highly project-specific nature of SLES makes upscaling (in the context of the definition provided above) inherently challenging, as no single configuration can be widely applied. The barriers faced by SLES differ according to scale, complexity and location. The barriers faced in developing countries are also likely to differ from those experienced in developed ones [20]. Deployment of distributed energy systems, including SLES, can also vary significantly between neighbouring countries [21] thus demonstrating the importance of policy and institutional factors. In addition, planning and social acceptance of distributed energy systems is likely to vary with scale [22]. This shows the extent to which upscaling – and the barriers it faces – can vary with context.

4.2. Separating technical and non-technical barriers

While this paper focuses primarily on the identification of technical barriers to the upscaling of SLES, it is important to acknowledge the extent to which technical factors are interlinked with socio-economic and other non-technical factors. This is a link that is widely acknowledged in the literature [19,23–26]. Indeed, Palm and Thollander go as far as to argue that “differentiating between technical and non-technical barriers is an analytical construct that could lead to important aspects being overlooked or at least oversimplified in analysis.” [24]. This means that few, if any, barriers can be considered to be purely technical i.e. lacking a non-technical component.

However, there are nevertheless a number of significant technical barriers which can impact the rate and scale of the upscaling of SLES. In a report commissioned by Community Energy England and Community Energy Wales [7], barriers to community energy were identified across a range of project types and scales in England, Wales and Northern Ireland. A total of 69 projects were identified which were reported to have stalled or failed during 2018. While the most commonly reported barriers were financial (i.e. the removal of the Feed-in Tariff, lack of an export tariff and access to finance and development funding) the most commonly reported technical barriers attributed to these stalled/failed projects are “Engineering Issues” and “Lack of Expertise”. Though broad, these barriers are highly inter-related and indicate that technical barriers play a significant role in causing community energy projects to falter or fail.

5. Technical barriers

In identifying technical barriers to SLES, it is important to consider the nature and origin of the challenges reported in the literature. These provide a broad indication of the main barrier areas which are most frequently reported.

Technological barriers are those which relate to the design, operation and performance of individual technologies. Often these are subject to extensive research in their respective fields. The more detailed aspects of their research and development are beyond the scope of this study, but certain key trends are referenced in the discussion of the more technologically-focussed areas of this review.

Integration barriers are also particularly relevant in SLES. These barriers stem from the technical characteristics of SLES, which may:

- Consist of multiple forms of generation, including intermittent generation, across multiple vectors;
- Include significant levels of local energy storage;
- Interact with external/adjacent energy infrastructure i.e. national grid;
- Have/require significant levels of user interaction (through Demand Response (DR)).

These factors add significant technical complexity to SLES and require effective integration if a system is to operate in a technically and economically efficiently manner.

The diversity which exists among SLES – in terms of size, technologies used, system configuration, interaction with pre-existing energy systems and more - also adds significant technical complexity by limiting repeatability, and requires the consideration of a variety of both technical and non-technical issues.

The technical barriers identified in the literature reviewed, which are presented in the remainder of this section, stem from these technological and integration challenges. However, rather than categorise technical barriers as being either technological or integration-based, it should instead be acknowledged that technical barriers can have both technological and integration aspects.

5.1. Technological maturity

The technological maturity of the individual technologies that can comprise a SLES vary widely. The maturity of smaller scale low carbon technologies, as well as smart technologies (discussed in Section 5.6) is generally lower than that of more established technologies such as domestic gas-fired boilers or even grid-scale on-shore wind energy.

It is important to acknowledge that technological maturity does not equate to a lack of technical barriers, as novel configurations of established technologies (which are found in many SLES) can create significant technical challenges. For example, despite the relative maturity of district-scale cogeneration technology [27], the integration of heating and power within a coordinated system represents a significant challenge.

There has been a great deal of variety in the pace of development of small-scale distributed energy generation technologies. In each instance, this pace is dictated by a combination of technological readiness levels, market and system needs and economics. As a result, some technologies e.g. photovoltaics, are comparatively mature and well-developed in comparison to more recently commercialised technologies, such as fuel cells.

Lifespan and reliability issues can restrict the growth in acceptance and deployment of a technology [23], even when the technological proof of concept has been long established. Technology Readiness Levels (TRL's) are a widely used scale with which to quantify the stage of development of a new or emerging technology. TRL'S focus on the commercial and technical development of the technology in question from inception, through prototyping to full deployment.

However, when considering the technical maturity of SLES technologies, there is an important distinction to be made between the maturity of individual technologies and the maturity of technologies used in combination within an energy system. For example, while a SLES could consist entirely of individually mature/proven technologies i.e. with high TRL, there may still be considerable uncertainty (and therefore risk) associated with their use in combination and/or at certain scales. This could include issues of interoperability, control and the life expectancy of individual system components under specific patterns of use. Such uncertainty represents a risk not only to system planners, designers and operators, but also to potential funders. This highlights the limits of TRL's in this context and illustrates the potential for real-world use of technology to throw up new and unforeseen barriers, which in turn highlights the importance of demonstrator projects.

Foxon et al. extend their focus beyond early deployment in defining their stages of commercial maturity [10]:

- Basic and applied R&D: includes both university and industry R&D and involves conceptual application of science and engineering research.
- Demonstration: this refers to the period between early prototype development and full-scale installation of a small number of units. This stage is typically funded through R&D grants, and conducted by small spin-out companies or research subsidiaries.
- Pre-commercial: where multiple/larger units of previously demonstrated technologies are deployed for the first time.
- Supported commercial: where a technology is capable of being competitive with generic (non-technology-specific) support. Here, technologies are deployed in larger numbers, by commercially oriented companies.
- Commercial: technologies which can be competitive without support.

This moves beyond the stages of development included within the traditional TRL scale, into the various stages of commercial deployment. This also highlights the importance of policy and regulatory factors by referencing the 'support' that is often required to boost deployment before such technologies can be commercially competitive without it.

Foxon et al. also stress that this should not be viewed as a strictly linear process, as knowledge can flow in both directions. The importance of this flow of knowledge reinforces the view of Hargreaves et al. on the role of intermediaries in the innovation diffusion process (as discussed in Section 4.1).

5.2. Intermittency

The basic underlying technical challenge facing any energy system is the matching of energy supply to energy demand.

This is especially true when the system in question includes a significant proportion of intermittent generation (such as wind or solar) the output of which cannot be scheduled or forecasted with complete accuracy. This can result in temporal and magnitudinal differences between supply and demand. There are two methods of tackling this challenge:

1. Use energy storage to store excess energy when supply exceeds demand (see Section 5.3);
2. Utilise Demand Side Management (DSM) and Demand Response (DR) techniques to adapt patterns of energy demand profiles in order to better suit supply profiles [26,28].

Both methods have significant associated challenges. While energy storage presents a more technological challenge, DSM and DR have a strong behavioural component which is an additional source of uncertainty.

The issue of intermittency can also be addressed at the system design stage, by incorporating operational flexibility in the sizing of dispatchable (i.e. non-intermittent) generators so that sufficient generating capacity is available when intermittent sources are not. Conversely, when output from intermittent sources is greatest, dispatchable or controllable loads can be used to maximise utilisation of intermittent (and often low carbon/renewable) energy [29,30]. Note that more recently, this has included the use of electric vehicles (see Section 5.6).

Similarly, variability in energy demand also represents a technical challenge. However, the source of this variability differs from that of energy generation in that it is primarily behavioural rather than meteorological.

5.3. Energy storage

Energy storage plays a vital role in supporting energy system operation. This is particularly true of SLES, which may have less capacity for generation and demand flexibility/response than larger scale networks. Consequently, energy storage technologies have undergone rapid development in recent years. Effective energy storage can enable increased renewable energy generation, control frequency and voltage fluctuations, maximise the lifespan of electrical transmission infrastructure and improve the quality and reliability of supply [31]. In multi-vector energy systems energy storage has been found to be particularly valuable in terms of operational efficiency [31–33].

There are two primary types of energy storage: electrical and thermal. The following technologies can be used to store electrical energy [31,34]:

- Battery systems (including lead-acid, Na–S, Li-ion and flow batteries)
- Flywheels
- Regenerative fuel cells
- Compressed air storage
- Pumped hydro storage
- Supercapacitors

These technologies vary in their level of maturity, operational life expectancy, operating parameters, maintenance requirements and application. Two of the key characteristics of energy storage technologies – capacity and discharge timescale – are shown below in Fig. 1.

Fig. 1 illustrates the variation in discharge time and capacity range of available energy storage technologies [35]. Considering that cost, lifespan and operating parameters all must also be taken into account, it is clear to see why energy storage can represent a technical challenge to SLES.

While all of the above have solutions and circumstances to which they are well suited, there is a widely acknowledged lack of technically and economically effective electrical storage methods [36]. More recently, the cost of battery storage has begun to fall as increasing demand has given rise to economies of scale and improved manufacturing techniques. As such, energy storage continues to be a key area of SLES development. However, the current regulatory and policy environment surrounding electrical energy storage is highly complex, acting as a

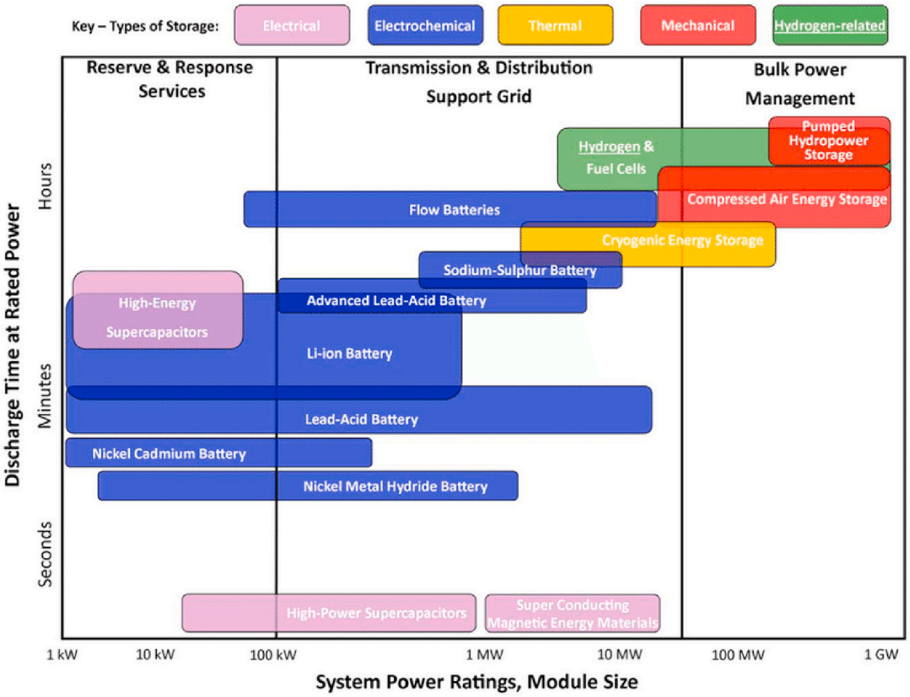

Fig. 1. - Comparison of power rating and discharge timescale of electrical storage systems [35]. Reprinted with permission from Elsevier.

further barrier to more widespread deployment [37]. The continued development of the various storage technologies, along with experience gained through their deployment with SLES, should improve understanding of their suitability. This is particularly true at larger scales, where upscaling (in terms of installed capacity) may result in different technologies being deemed optimal.

The storage of heat is also of importance in SLES, particularly when it comes to combined heat and power (CHP) as system operation may be governed by electrical demand, meaning that thermal generation may not coincide with demand, resulting in greater storage requirements – both in terms of capacity and duration.

Traditionally, thermal energy has been stored in the form of sensible heat, using water as a medium. Recent decades have also seen the development of latent thermal storage technologies such as Phase Change Materials (PCM) which utilise latent heat capacity [38,39]. While this technology is still immature in comparison to water storage, it has been shown to be well suited to operation within specific temperature ranges [38].

Another of the main technical challenges facing energy storage – both electrical and thermal – is the increased demand for long-term energy storage which can occur in SLES. While the wider electricity grid itself can be thought of as providing long-term electrical storage (for grid-connected systems) the impact of energy losses over such timescales can have a limiting effect on the effectiveness of seasonal storage for locally deployed technologies.

Storage also presents an opportunity for cross-vector integration i.e. using heat to produce electricity and vice-versa, or using electric vehicles as a form of energy storage. This is one of the primary benefits of multi-vector integration, particularly within SLES, which lack the ability to absorb fluctuations in demand and supply which larger systems have.

5.4. Grid connection

Depending on variety of engineering, social and geographic factors, SLES can be designed to operate on a stand-alone basis or to be connected to existing energy transmission and distribution infrastructure, commonly referred to as 'the grid'. Connection to (and ongoing interaction with) grid infrastructure represents a key barrier area for SLES. This is reflected by the findings of Soshinskaya et al., who identify the following four categories of technical barriers in their review of barriers and success factors experienced in microgrid projects [23]:

1. Technological issues
2. Dual-mode operation i.e. grid interface
3. Power and frequency control
4. Protection and safety.

While their review relates primarily to electrical systems, this categorisation highlights the importance of grid connection, with three of the four barrier categories relating to grid connection and interaction, either directly or indirectly.

5.4.1. Grid connected systems

Grid connected SLES operation requires the successful integration of new generation and/or storage equipment within existing grid infrastructure. This can bring a range of technical benefits, such as:

- Providing a back-up or supplementary source of supply, which can reduce the need for additional on-site generation capacity and can guarantee security of supply
- The ability to use the grid as an energy store for surplus generation (to offset consumption during periods of supply deficit). This can allow on-site generation to operate at higher plant load factors, which improves the economic viability of the SLES [40].

However, there are significant barriers and challenges associated with grid connection which have been found to delay or even prohibit distributed generation projects.

In their wide-ranging review of grid interconnection barriers and their impacts on distributed generation projects, Alderfer, Eldridge and Starrs state that such barriers are largely associated with "engineering compatibility of interconnected generators with the grid and its operation" [41]. This is often referred to as 'interoperability', particularly when discussing electrical equipment such as inverters [42,43].

The connection of distributed generation poses a number of risks to existing networks, including the risk of losses, voltage and frequency control, power quality and system protection [44]. As such, network operators are risk-averse when dealing with new connections, and have rigorous and highly standardised requirements when considering new connection applications, such as the need for protection studies, protective equipment and adherence to safety standards also represent technical barriers [41]. These can pose significant technical and financial issues to SLES, particularly if there is a lack of familiarity with project characteristics or scale. The relative cost of adhering to these requirements is greatest at smaller scales. In this regard, upscaling in terms of SLES project size may reduce the relative financial impact of these requirements.

Suggested measures to reduce these barriers include the adoption of uniform technical standards and equipment testing and certification procedures [41].

New connections to grid infrastructure are typically made at the nearest possible point of connection. In more urban locations, this is not likely to represent a significant challenge, but in more remote, rural areas this could require significant expansion. At the extremities of the existing infrastructure, the supply and export capacity may also be insufficient to accommodate new connections and the energy exports they will produce. This therefore requires that the existing infrastructure be expanded or upgraded. The cost of doing so can be prohibitive to SLES, and can result in the decision being made to operate on a stand-alone basis (discussed below).

5.4.2. *Stand-alone systems*

In some instances SLES are intended to be operated on a purely stand-alone basis i.e. with no connection to grid infrastructure. This is most common in remote or island systems, which lie at or beyond the extent of existing infrastructure. The reasons for stand-alone operation in these cases stem from the lack of viable alternatives, as the cost of extending or upgrading existing grid infrastructure can be prohibitive. Low quality and security of supply from existing networks can also serve as a driver for SLES development in these instances, as can high energy costs.

While stand-alone operation avoids many of the challenges associated with grid connection discussed above, it brings with it its own technical challenges. Many of the principal challenges stem from the need of stand-alone SLES to match energy supply to energy demand in order to guarantee provision and reduce wasted or inefficient production. Matching energy supply and demand is a complex, dynamic challenge that includes significant socio-economic aspects as well as technical aspects [26]. The principal technical challenges, such as intermittency and the need for energy storage have already been discussed above.

It should also be noted that variation between stand-alone and grid connected operation is possible. This presents both technical and regulatory challenges, and while solutions to these issues do exist, they tend to be highly project specific in nature [23].

5.4.3. *Non-electrical connectivity*

When considering the connectivity and interaction of SLES with existing infrastructure, it is also prudent to acknowledge the possibility that they may be required to connect and interact with non-electrical infrastructure i.e. heating and cooling networks. While the likelihood of SLES co-locating with existing thermal networks is much lower than with electrical ones, there are nevertheless challenges associated with connectivity.

Here, the principal requirements of interoperability, safety and security of supply remain largely the same as for electrical grid connectivity. However, the challenges faced are often more project and technology-specific in comparison to the larger scale and heavily standardised electricity network. For example, the technical challenges reported in the literature include the need to consider the impact of new connections on distribution temperatures and carrier fluid speed imbalances [45]. Dealing with smaller scale, less regulated and potentially co-located network operators is likely to require less time and expense than electricity network operator negotiations.

The challenges faced are therefore primarily engineering ones rather than regulatory ones, though the current lack of regulation and standardisation in heating and cooling networks [46] could also be seen as worsening rather than removing technical challenges.

5.5. *Multi-vector systems*

Within the context of SLES, multi-vector systems can be defined as those which incorporate one or more vectors i.e. heating, cooling, electricity and transport. The successful integration of multiple vectors requires careful consideration and a detailed understanding of how the system is likely to operate under an expected range of conditions.

The most common multi-vector combination reported in the reviewed literature is electricity and heat. This has been driven by the increase in the use of CHP systems, often deployed as part of district heating schemes. Fig. 2, below, shows the growth in the number of CHP installations in the UK from 2008 to 2017.

Fig. 2 shows the recent growth in CHP deployment, and in particular the increase in the number of smaller scale deployments, i.e. less than 1 MW (MW) of electrical capacity, though it should be noted that not all of these will have been deployed as part of a SLES. This can be attributed to an increase in the availability, efficiency and cost-effectiveness of small scale CHP units, with the financial viability being boosted by incentives such as the Renewable Heat Incentive, launched in November 2011 (for non-domestic buildings). In their review of distributed multi-generation, Chicco and Mancarella also cite the emergence of trigeneration (combined cooling, heating and power) technology as evidence of technical development shifting towards multi-vector systems [1].

The increasing focus placed on local heat networks is also exemplified within industry by the release of the Heat Networks Code of Practice by the Chartered Institute of Building Services Engineers (CIBSE) and the Association for Decentralised Energy (ADE) in the UK in 2015 [47]. Intended to ensure that heat networks are designed to best practice and to act as a minimum standard that can be specified in the tendering/contracting process, the release of this document illustrates the extent of the anticipated role that heat networks will play in the future. Upscaling in the coming years will focus on both expanding existing systems and establishing new ones [48].

Within heat network design there is an ongoing shift away from gas-fired cogeneration and traditionally high flow/return temperatures towards heat pump-based, low temperature networks [27]. This poses a slightly different integration challenge, as future heat networks may need to accommodate multiple heat sources, including from renewable sources. While heat network research and design is relatively well established, there is currently a lack of research into the role of district cooling at the local level [49]. This can largely be attributed to the lack of demand for cooling in comparison to heating (at least in the UK and

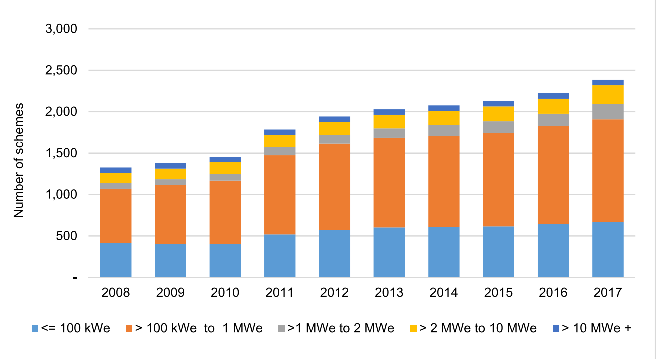

Fig. 2. Number of CHP schemes in the UK. Source: Graph created from DUKES statistics (2018).

most of Europe), but may become more prescient as building design continues to focus on increasing air-tightness and the reduction of heat-losses [50].

Multi-vector integration also poses a significant system scheduling and control challenge, due to the need to reconcile different energy demands e.g. if electrical appliance load coincides with instantaneous hot water demand, or electric vehicle charging requests. This requires a detailed understanding of demand patterns, some form of vector load prioritisation and the ability to predict and plan for such events in advance, all of which have a strong technical component. This is referred to 'system optimisation' or more broadly as 'energy management' [51, 52].

The use of modelling and analysis tools – a key aspect in the integration of multi-vectors systems – is discussed in Section 5.7.

5.6. *Smart technology*

In their framework for understanding and conceptualising smart local energy systems Ford et al. [3] identify four aspects of "smartness", which arose from a review of literature and a series of expert interviews:

1. The integration of information and communication technologies
2. Automation and self-regulation
3. Ability to learn user preferences
4. Smarter engagement with people

For the purposes of this study, 'smart technology' is defined as that which facilitates the integration of energy system components, consumers and operators. This intentionally broad and technically focused definition has been selected so as not to neglect any element of smart technology which may potentially help to remove or reduce barriers to SLES upscaling.

Smart technology is regarded as having a key role in the operation of SLES, thanks to its ability to facilitate the integration of multiple consumers, plant items and energy vectors. It is feasible that the role of smart technology within SLES will span all elements of system operation, from plant operation and scheduling, system monitoring, demand aggregation and metering, domestic and commercial appliances, load shifting/scheduling, billing and energy market operation etc. It is therefore regarded as a key technical component of SLES design, particularly in the future as technological capability and reliability increases, and costs decrease.

Such is the breadth of potential scope and applications, as shown in the list above, smart technology has been the subject of a rapidly growing body of research in recent years [53]. In the context of energy, 'smart grids' have provided an umbrella term for intelligent, distributed and highly connected energy systems [54]. Until recently, this has applied almost exclusively to electricity networks, but this has changed as research interests have expanded to include multiple energy vectors. However, as the term 'smart' has been applied to a range of contexts in recent years (thanks in part to its wide ranging potential) it therefore lacks a common broad definition.

The broad and poorly defined nature of the term 'smart' [3] is mirrored in the development of smart technology, with Gungor et al. identifying a lack of uniform accepted standards in smart grid systems as being a key challenge and arguing that this limits interoperability and prevents integration [55].

Research into smart energy systems and technology has largely been focussed on demonstrating and analysing its various potential applications, and the debate over how best – and to what extent – smart technology should be applied.

As with all technological innovation, acceptance from users, consumers and prosumers has a crucial role in determining the success of smart technology. While a higher degree of autonomy could be met with resistance by consumers, it is likely to provide greater and more consistent/predictable control. The challenge for researchers, planners and designers alike is to establish levels of autonomy which are both acceptable to consumers, whilst also providing sufficient system benefit. However, as with many aspects of SLES development, solutions are likely to be highly project specific. The social implications surrounding residential DR are summarised by Darby and McKenna [56].

The widespread deployment of smart technology can also prove to be a significant challenge in itself, as illustrated by the delays to the ongoing rollout of smart meters in the UK. Kim and Shcherbakova identify the slow penetration of DR technology and uncertainty regarding costs as some of the main barriers to the spread of DR [57].

5.6.1. *Areas of relevance for SLES*

Specifically, the potential benefits of effective smart technology in the field of SLES include, but are not limited to, the following:

- Increased data availability
- Accurate energy metering and billing
- Consumer signalling for the purposes of demand side management and response
- Automated demand response, including load shifting and curtailment
- Enabling communication between distributed generators/stores, for the purposes of performance monitoring, optimisation and control
- Automated and optimised system control and operation signalling

These factors are all relevant to the scale-up of SLES, both in terms of the size and number of SLES projects.

The ability of smart technology to facilitate DR has been the subject of considerable research interest is the role of smart technology in facilitating DR [57–61]. The conventional method of implementing DR is through price-based incentives, but while this may still be the case in smart technology-equipped SLES, it is likely that more dynamic, reactive pricing strategies will enable finer levels of control [62]. The extent to which smart technology is used to automate consumer response (i.e. to pricing signals) is a key area of debate [53] with the emergence of smart technology leading to a rapid expansion in the potential scope of DR [62].

The ability of smart technology to facilitate flexibility services is also of particular relevance to SLES. This sees owners of distributed generation assets provide grid balancing/support services in response to signals from network operators. Such services are an emerging and potentially lucrative sector in the field of distributed generation, but have to date been limited to larger grid-connected assets. The potential for SLES is twofold. Firstly, should the current technological and regulatory constraints be removed, SLES assets could provide grid balancing/flexibility services, thereby providing additional revenue generating potential. Bloomberg identified the need for new sources of flexibility (in the near term) as being a key facilitator of increased renewable penetration [63]. Secondly, grid balancing and flexibility services could be applied on an internal basis i.e. within SLES themselves. This would require smart metering and real-time network management [64] but could provide significant operational benefits.

The use of smart technology is also a key requirement of the widespread integration of electric vehicles (EVs) into SLES. This is discussed in more detail in Section 5.6, below.

5.7. *Transport*

Transport is a relatively recent addition to local energy systems research, and has been accelerated by the emergence of EVs and the consideration of their impact on energy demand and energy system operation.

The shift away from conventional fossil-fuelled, internal combustion driven transport towards more sustainable alternatives has seen a number of technologies emerge. Those which show the most potential to play dominant roles in the future transport market, as identified by

Dominković et al., are biofuels, hydrogen, synthetic fuels and EVs [65]. From this shortlist, the authors identify EVs as having the greatest potential benefits. This is reflected in recent market development and the relative technological maturity of EV's and plug-in hybrid electric vehicles (PHEV's). This is also reflected in the large and increasing body of research surrounding EVs, and their integration with electricity networks, both at a local and national scale.

Despite the fact that EV's currently have a market share of less than 1% [37], it is estimated that the cost of EVs will reach cost parity with internal-combustion driven vehicles by 2022 [66]. While concerns remain about the deployment of the charging infrastructure required to support it, this is likely to cause an increase in already rising sales. Bloomberg estimates that by 2040 EVs will account for 35% of all new vehicle sales [66]. Currently, policy is focussed on supporting this uptake, by reducing the financial cost of EV's and increasing access to charging infrastructure [37].

For the purposes of this study, emphasis is placed on the challenges posed by the integration of EVs within SLES, rather than on the more technological challenges associated with electric vehicle development in general.

5.7.1. *Electric vehicle integration*

The integration of electricity and transport systems can increase system stress, and represents both a significant risk and a multi-faceted opportunity for SLES [67].

The benefits of EV integration are not limited to technical aspects of SLES performance however. Touted benefits also include improved energy security, reduced emissions and increased renewable energy penetration [68]. Of particular relevance to SLES is the potential to alleviate network stress. This can be achieved using smart technology, infrastructure investment, vehicle-to-grid (V2G) technology and consumer incentives [5,69,70].

Of these benefits, the most significant are arguably enabled through V2G interaction and smart charging, as this creates the opportunity to optimise charging patterns to match the generation profiles of the SLES technologies [71]. Lauinger, Vuille and Kuhn identify the main technical challenges surrounding V2G are battery degradation, smart charging/discharging, and reliable aggregation of EV's offering grid services [72]. While the context of SLES may address the latter of these issues at least partially, these still represent significant technical barriers. Useful reviews of EV-smart grid interaction are provided by Mwasilu et al. [73] and Sovacool and Hirsh [74].

The realisation of the potential benefits of EV integration requires their successful integration within the monitoring and control of SLES. Failure to do so effectively could create additional difficulties by exacerbating mismatches between energy demand and supply, causing system stress/capacity shortages and interruptions to both transport and energy services for consumers. The aforementioned efforts to increase access to charging infrastructure is already causing interoperability challenges, which stem from the lack of widely adopted standards for charging technology [75].

There are other potential negative impacts to consider. If included within a SLES, EV's have the potential to add significantly to energy demand, particularly if the aforementioned estimates regarding sales and market penetration are accurate. The impact of this is demonstrated by Fernandez et al., who show that investment costs and energy losses can both increase dramatically depending on charging strategies [69]. However, simulation tools have also been used to demonstrate that operating costs can be minimised if optimal dispatching is used to shift and shave loads [76]. This reinforces the need to adequately control the interaction between EVs and SLES.

In terms of upscaling, the inclusion of transport as an energy system vector effectively widens the breadth of scope of SLES, but given its recent emergence the focus of upscaling may lie in achieving repeatability, and transferring the knowledge and understanding that results from EV-only schemes, which are themselves currently undergoing a growth phase.

5.8. *Modelling and analysis*

The use of computer modelling, simulation and analysis tools is increasingly essential in the planning, design and operation of energy systems. As such, these tools have undergone rapid development and have achieved high levels of effectiveness and sophistication in recent years, as evidenced in the review conducted by Connolly et al. [77].

The modelling of SLES is carried out at varying levels of detail and resolution [78] using a wide variety of tools. As the sophistication and capability of these tools has increased, so has their range of potential applications. Such is the extent and significance of their role in SLES planning, design and evaluation, it is prudent to consider not only the benefits that can come from their effective use, but also the associated challenges and limitations.

Given their complexity, SLES are well suited to the use of such tools in a variety of applications, including:

- Energy demand profiling
- Energy supply scheduling (for dispatchable generation) and forecasting (for non-dispatchable generation)
- System performance optimisation
- Multi-vector integration
- Modelling/predicting user consumption behaviour

Tools can be split into two main categories – those which relate to the prediction of energy demand and supply, and those which relate to the integration and optimisation of energy system operation.

5.8.1. *Energy demand and supply*

Given its strong behavioural component, the prediction of energy demand is the subject of vast research interest.

Demand profiling is typically conducted using either physics-based or statistical models. Physics based models involve dynamic building simulation tools which are primarily developed for the purposes of building design e.g. building services and building physics, and are sufficiently detailed as to serve well as demand profiling tools. However, the recent emergence of the so-called 'performance gap' highlights the importance of using such tools appropriately, and the mismatches between design and performance that can otherwise result [79].

Statistical demand profiling tools can be based on census and survey data, as well as data gathered in dedicated studies. Such models can be used to predict building occupancy and therefore consumption behaviour, and can be used to characterise certain consumers types/groups. The resulting demand profiles can range from low resolution predictions of annual consumption to more detailed models. One such tool is the CREST Demand Model, developed by Loughborough University. This tool creates disaggregated (i.e. appliance level) demand profiles at minutely resolution, based on predicted building occupancy levels [80]. This rivals the detail typically provided by physics-based models.

The link between energy demand patterns and system operation is arguably stronger and more direct in SLES than at larger scales. This makes the prediction of demand a highly important aspect of SLES modelling and analysis. However, at this scale the aggregation effects which are visible across much larger consumer groups (and help to 'smooth' demand profiles, reducing the scope for unexpected peaks or troughs) are less pronounced, which adds to the challenge of accurately predicting demand [81].

The modelling and prediction of consumer behaviour is also an area of significant interest when it comes to energy market analysis [82]. This can inform design decisions by helping to reduce the uncertainty associated with consumer behaviour. The modelling of behaviour typically requires a more descriptive, bottom-up approach [83] with results indicating what is likely to happen rather than indicating an optimal course of action. As such, differing modelling techniques are used.

On the supply side, key challenges stem from the difficulties in predicting output from intermittent sources of generation. This includes solar, hydro and wind, which is a particular challenge given the highly stochastic nature of the resource [84]. This can now be done to a reasonable degree of accuracy, particularly at medium to long term timescales. In some instances however, particularly where generation outputs are being aggregated across multiple technologies, component models have been found to be overly simplified and therefore not representative of real-world operation [85]. While a certain level of abstraction may be prudent where multiple sources are combined within a complex energy model, this can limit the accuracy of the model results.

5.8.2. Multi-vector integration and optimisation

The complexity of modelling and optimising multi-vector systems represents a significant technical challenge. While the modelling of individual vector systems such as heat or electricity networks is well established, there is a need for modelling solutions which fully integrate multiple vectors i.e. heating, power and transport [86]. This is particularly relevant to upscaling, as it can provide SLES planners, designers and operators with the ability to model increasingly complex systems.

Historically, multi-vector analysis has largely been limited to larger scales e.g. national scale evaluation of the relationship between the gas and electricity networks [84]. However, some smaller scale examples exist which highlight the complexity of multi-vector system optimisation whilst also demonstrating the level of detail that is required to do so [6,87–89].

Multi-vector modelling has been shown to help identify constraints and opportunities [90]. Potential synergies have been shown to enable higher penetration and utilisation of renewable energy, whilst also providing cost and efficiency savings [91]. The holistic modelling of multi-vector systems can also be used to assess the robustness and flexibility of design options under stress [88]. As identified by Allegrini et al., the development of a holistic SLES model can require a number of individual tools to be combined within a single environment [92].

In their review of modelling and optimisation techniques, Reynolds, Ahmad and Rezgui call for a more holistic approach in response to the growing demand for multi-vector systems [85]. Their review identifies the following key areas as requiring research focus for the holistic optimisation of multi-vector systems:

- Data logging (from existing buildings and systems)
- Improvement in the modelling/prediction of energy supply and demand
- Optimisation
- Communication
- Interoperability/integration of distinct models.

Of particular relevance to SLES, and especially when considering integration barriers, is the optimisation of system components and the way in which consumers interact with the system. Optimisation models are prescriptive, in that they can illustrate how best to act in a given situation, given a predefined objective or goal [93]. Commonly used optimisation techniques are reviewed by Allegrini et al. and Hiremath, Shikha and Ravindranath [92,93]. Of the various techniques used, Mixed Integer Linear Programming (MILP) is reported to be the most common [85]. This approach can also be used to assess system flexibility under stress [88].

Other notable approaches include the use of multi-objective optimisation, which allows for a combination of technical and non-technical aspects to be factored into the optimisation process [94–96]. This can include technological efficiency, renewable energy utilisation, energy cost, capital expenditure, operating costs, consumer disruption, environmental impact and others. Multi agent systems theory has also been used to explore the consumption behaviour of consumers within SLES [97,98]. Whilst this is primarily focussed on modelling consumer behaviour, the results can provide insight into energy demand levels which in turn informs system design and optimisation.

Perhaps the most interesting recent development has seen the emergence of embedded or artificial intelligence (AI) being used to help optimise the sizing [99] and operation [100] of SLES. Reynolds, Ahmad and Rezgui identify the broad suitability of AI techniques for use in system modelling, including in real-time [85] or in instances where input data is incomplete [101]. This represents a shift away from the prescriptive methods described above, towards a more intelligent and agile approach to optimising SLES operation. Given its apparent potential to address technical complexity and its scalability, this area is expected to be increasingly prominent in the coming years.

6. Discussion and conclusions

This paper has presented the findings of systematic state-of-the-art literature review conducted to identify the technical barriers to the scale-up of SLES. This involved the review of 132 documents and reports, consisting primarily of academic publications, but also including grey literature.

The emphasis of this paper is placed on the identification of technical barriers to SLES upscaling. However, the extent to which technical and non-technical factors are interlinked means that consideration of purely technical challenges risks neglecting important socio-economic factors. Despite this, a number of key technical barriers were identified (see Table 2).

These include challenges which are both emerging and longstanding, and provide an indication of likely research and development focus in the near future.

It should also be stressed that the nature of these barriers can change over time, as technology continues to adapt and improve. This change can best be observed in the more longstanding barrier areas such as

Table 2
Summary of identified technical barriers.

TECHNICAL BARRIER	BARRIER DESCRIPTION
Technological Maturity	Uncertainty surrounding the performance, longevity and reliability of emerging technologies, and of established technologies used in novel combinations/configurations.
Intermittency of Renewable Energy Supply	Stochastic, non-dispatchable nature of renewable generation, resulting in the need for either the integration of dispatchable (often non-renewable) generation, energy storage or the use of demand side management and response.
Energy Storage	Various available forms at varying stages of maturity and cost-effectiveness. Differing operational characteristics also present further specification/design challenges. Also requires integration with generation, demand and wider infrastructure interaction.
Grid Connection	Technical, operational and regulatory requirements associated with connection to (and interaction with) existing 'grid' infrastructure.
Multi-vector System Integration	Introduces design and operational complexity, with greater need for intelligent control. Efficient operation requires interoperability and interaction with any wider infrastructure/systems.
Smart Technology	A broad term which currently lacks definition. Can potentially impact all areas of system operation, and is therefore a highly complex aspect of system design and operation.
Transport	Introduces the concept of mobile supply/demand/storage and requires integration with user lifestyle/behaviour. Relative technological immaturity (and rate of development) also creates uncertainty regarding future energy demands.
Modelling and Analysis	Particularly important given the complexity of multi-vector systems. Integration of vectors represents a significant technical challenge and requires consideration of socio-economic and other non-technical factors.

modelling and analysis, where capability has progressed from primitive, steady-state calculations to dynamic and holistic system models. The identified barriers are seen as stemming from three fundamental challenges of SLES design and operation, which represent the origin of the majority of the technical barriers identified in the review:

1. The diversity of SLES characteristics i.e. their highly project-specific nature
2. The uncertainty associated with the complexity of SLES design and operation
3. The need for integration, both between SLES system components and between SLES and any interconnected networks or systems.

Fig. 3 shows the extent to which each of the technical barriers identified in the literature falls within each of these fundamental challenge areas.

While this review has presented common themes from the literature, it should be stressed that the specific barriers encountered by individual SLES projects are likely to vary significantly with scope, location, scale, available resources, policy environment etc. This makes drawing extensive and detailed conclusions as to the specific nature of technical barriers difficult. As such, the barriers identified are necessarily broad in scope. In order to provide more meaningful and specific insight into the technical barriers faced by SLES projects, a more detailed understanding of the context-specific barriers – and the relationship/interactions between them – is required.

While every effort has been made to provide a wide and representative view of the key issues, it should be noted that the resulting findings are limited by the breadth and detail of the literature review.

6.1. Outlook

The broad barrier areas identified in this review reflect issues present in the literature, and as such should be seen as an indication of recent research focus. However, they also provide some indication of worthwhile areas of future focus for research and development as well as policy and regulatory support. In particular, emergent themes such as multi-vector system integration (including the integration of sustainable transport into SLES) have been the subject of rapid recent development and are likely to play a prominent role in SLES-related research in the near future.

Among the key challenges which are evident in the literature is the extent to which the technical barriers faced by SLES are context-specific. It is therefore suggested that further research is conducted into identifying the contributing factors that give rise to technical barriers to SLES upscaling in specific contexts. It is envisaged that this will usefully inform the discussion regarding how to mitigate or remove such barriers in future and may enable more tailored support to be offered to prospective SLES in future.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

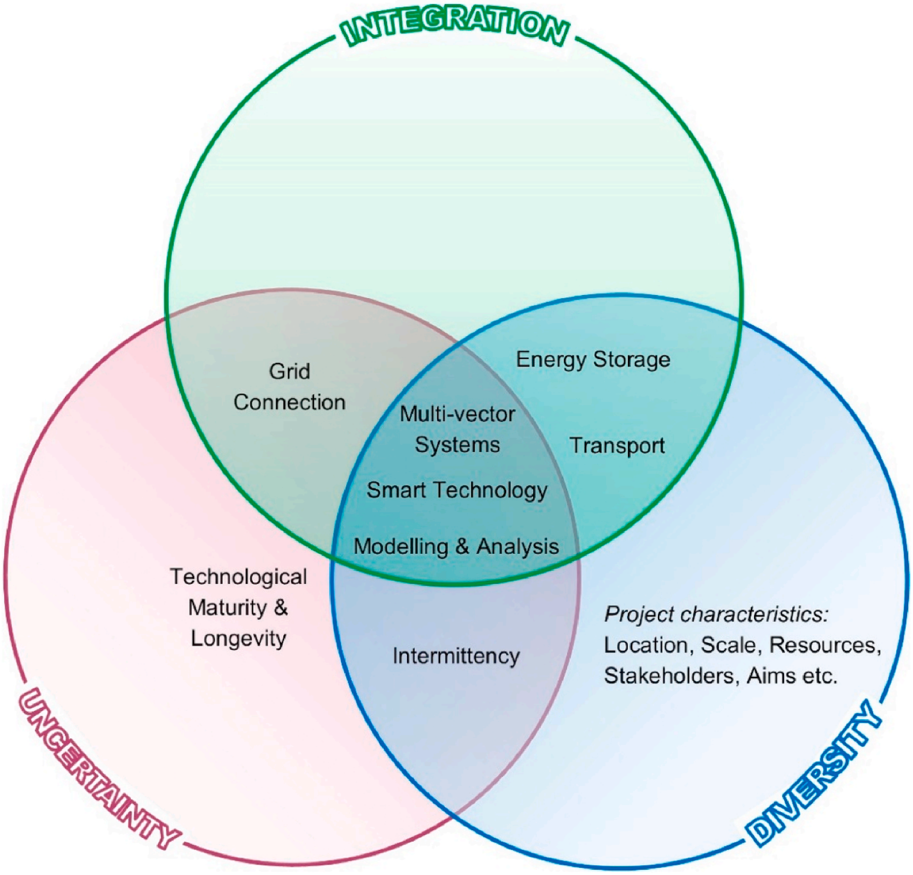

Fig. 3. Allocation of identified technical barriers to the three fundamental challenge areas.

the work reported in this paper.

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