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Perspective

Towards Social Understanding of Energy Storage Systems—A Perspective

Maurizio Sibilla [1,*] and Esra Kurul [2]

[1] Centre for Architecture and Built Environment Research, University of West of England, Bristol BS16 1QY, UK
[2] School of the Built Environment, Oxford Brookes University, Oxford OX3 0BP, UK; ekurul@brookes.ac.uk
* Correspondence: maurizio.sibilla@uwe.ac.uk

Abstract: Renewable, decentralised, and citizen-centred energy paradigms have emerged as feasible and reliable alternatives to the traditional centralised fossil-based infrastructure. In this scenario, energy storage systems (ESSs) are enabling technologies to boost the stability and flexibility of the power grid in the short-to-medium term, allowing local communities to envision energy autonomy in the medium term. Traditionally, ESSs have been installed in individual households for their own benefit. However, new storage paradigms focusing on building clusters and district scale have illustrated the need to revise the role of ESSs and to pay close attention to the social factors, while devising implementation strategies for scaling up these new energy infrastructural models. This study reviews recent research trends (2021–2023), proposing three integrated social pillars for the implementation of ESSs: (i) multi-dimensional geographical and institutional scales of ESSs; (ii) social components of spatial and temporal flexibility of ESSs; and (iii) co-creation approaches to devising ESS implementation strategies. These pillars point out the necessary social factors for the implementation of ESSs at scale, highlighting future research perspectives to operationalise such factors, with a particular focus on the importance of citizens' perception, participation, and collaboration, which are critical for maximising the benefit of sharing and exchanging renewable energy locally. Development of flexible and agile digital platforms that facilitate the co-creation of adaptable socio-technical solutions to adopting ESSs is proposed. The need to tailor these solutions to suit the stakeholders' capabilities is emphasized.

Keywords: energy storage systems; socio-technical systems; social understanding; spatial and temporal flexibility; co-creation

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1. Introduction

1.1. Scenario

The European Union (EU) has climate change targets, such as raising the share of renewable energy in the energy mix by 32% [1]. However, renewable energies (e.g., sun and wind) are intermittent and subject to fluctuations. Energy storage systems (ESSs), which allow the storage and supply of energy on demand and out of sync with production, are seen as enabling technologies to boost the stability and flexibility of the power grid in the short-to-medium term. They also allow local communities to envision energy autonomy in the medium–to-long term.

Traditionally, ESSs have been installed in a property to benefit an individual household. However, emerging paradigms, such as Positive Energy Districts (PEDs) and Positive Energy Blocks (PEBs), have shifted energy issues from individual properties to community scale. PEDs are defined as urban neighbourhoods with a surplus of renewable energy production [2]. PEBs are an aggregation of at least three adjacent buildings with a positive energy balance between them annually [3]. Both these paradigms are based on local aggregation, sharing and exchanging energy, potentially adopting ESSs at scale, allowing the development of new citizen-centred energy systems.

In this scenario, ESSs emerge as an appropriate context for exploring new relationships between technology and society, and accelerating the implementation of new infrastructural models at scale. The issue of ESSs' appropriation and the cooperation of the local communities is indispensable [4], and one of the critical aspects is the citizens' capabilities to create a sense of community ownership and empowerment [5].

This study is a contribution in this direction, with a particular focus on two aspects: the high level of fragmentation, which currently characterises the social components of ESSs, and the factors that can boost the citizens' capabilities to manage the socio-technical integration of ESSs at scale. This study assumes that all social factors should be aligned for the rapid adoption of ESSs, and the social understanding of ESSs is an essential requirement to develop citizens' capabilities to move towards a low-carbon society. Therefore, the key research questions are: What are the necessary social factors for the implementation of ESSs at scale, and what are the future research perspectives to operationalise such factors?

Through a critical evaluation of the recent trends in research, and thus, anticipating more detailed studies in this area, the objective is to point out the social pillars concerning the social understanding of ESSs and establish the extent to which such pillars can be integrated to delineate a unitary conceptual framework that is flexible and agile. This study will help drive more social-oriented research concerning energy transition and technological applications, and boost future integration between engineering and social science.

This paper is organised as follows: The following section provides an overview of the state-of-the-art within the debate concerning a socio-technical energy transition. Section 2 focuses on recent research trends in the literature (2021–2023). Section 3 firstly presents the conceptual framework built upon the interpretation of the recent trend, and then discusses its implications. Finally, the conclusion summarises the findings and limitations of this research, and makes proposals for future research.

1.2. EESs: State-of-the-Art

So far, techno-economic studies concerning ESSs have been at the core of the energy transition [6–9]. However, several scholars have recently emphasised that integrating social factors into the implementation equation remains the most significant challenge for scaling such distributed and renewable energy models [10–12].

For example, Nguyen and Batel [13] have argued how a critical social science perspective can help break the "silo thinking" and facilitate a better understanding of the socio-cultural aspects of implementing ESSs. Such a perspective would allow for discussing and including tailor-made strategies in deploying ESSs. In addition, Sovacool [14], argued that these strategies should consider the socio-cultural efforts of the local communities engaged in transforming their energy consumption and production behaviours.

Peñaloza et al. [15] extended Sovacool [14]'s arguments by suggesting a shift from the current focus on explaining and measuring technological acceptance to focus on socio-political and economic aspects to develop alternatives to the current regime. Similarly, Sovacool and Lakshmi Ratan [16] described the acceptance of new approaches in the energy market in terms of an alliance between investors and consumers, while other studies explored the adoption of various ESSs, which involved public and private partnerships [17] and technologies [18].

In summary, social barriers have received limited attention. One of these barriers is the citizens' perception and participation in ESSs implementation. For example, Wüstenhagen et al. [19] described socio-political components of the energy transition, emphasising the policymaking dimension as the most challenging based on local stakeholders' expectations, while Fang et al. [20] stressed how social understanding of ESSs has a strong influence on the level of collaboration among stakeholders, which maximises the benefit of sharing and exchanging renewable energy locally. Krumm et al. [21] noted that omitting the perspectives and capabilities of local stakeholders could compromise the efficacy of policy decisions. Turnheim et al. [22] stressed the need for novel studies to integrate social aspects of the energy transition, which represent real-world advancements, into digital modelling approaches. Finally, Silvast et al. [23] recommended synchronizing social and technological innovation that are currently advancing at two very different paces.

Thus, future ESS implementation practices should operationalise the energy transitions by considering how a local community can effectively engage in niche innovations within incumbent regimes, promoting what Geels called a new socio-technical landscape [24]. ESSs are crucial in promoting sustainable and efficient use of energy resources while also boosting social cohesion and community engagement. However, the state-of-the-art returned a highly fragmented social framework about the social understanding of ESSs, needing more methods and tools to engage diverse stakeholders in implementing ESSs as a socio-technical system.

2. ESSs: Trends in Recent Literature

Social factors of ESSs have been recognised as a fundamental component of fully exploiting ESSs as a disruptive technology to lead the transition towards a low-carbon society [25,26]. The analysis of the literature pointed out several dimensions concerning social issues.

One of the primary social concerns surrounding ESSs is the perception that they are expensive and require significant investment [27]. This perception is not entirely unfounded, as ESSs can be costly to install and maintain. However, it is important to note that the long-term benefits of such systems often outweigh the initial costs. For example, ESSs can help reduce energy bills and provide a more reliable source of power, ultimately leading to cost savings for individuals and businesses [28]. Therefore, distinguishing capital and operational costs associated with ESSs and taking a medium-to-long-term view of the benefits that can be accrued from such cost outlays are in order.

Another primary social concern is the fear that they may cause environmental harm [29]. While it is true that some types of ESSs can have negative environmental impacts, it is important to note that many different types of storage systems are available [30]. For example, pumped hydro storage systems use water to store energy [31], and compressed air energy storage systems use compressed air [32]. Both systems are environmentally friendly and effective at storing energy.

Such concerns need to be addressed for ESSs to be accepted and understood by the public [33] so that they are widely adopted. This requires the integration of the human dimension [34].

One way to increase social understanding is to educate people on the benefits of such systems and dispel any existing myths or misconceptions [4]. Additionally, it is essential to involve communities in the planning and implementation of energy storage projects so that they feel they have a stake in the process [35]. However, few studies have tackled an inclusive social framework [15] to develop this understanding.

Furthermore, analysing the ESSs in the context of new energy infrastructure (e.g., Positive Energy Districts [2], and Community Energies [36,37]), it emerges that although the number of such new apparatuses is increasing, the integration of ESSs continues to be considered as niches of innovation [38]. ESSs are critical in affirming the new infrastructural paradigms, as they are crucial in ensuring a continuous and reliable energy supply [39,40]. However, little empirical work has examined how EESs might further develop from these niches. One possible solution is to better understand spatial and temporal flexibility in using ESSs.

Spatial flexibility, traditionally, refers to the possibility of locating ESSs in different built environment locations [41,42], allowing the utilisation of excess energy, decarbonising the energy infrastructure [43], and promoting new market mechanisms

[20]. This is crucial because it allows for more efficient energy distribution and use. For example, excess energy generated in one area can be stored in an ESS located in another area that is experiencing a shortage. This helps to balance the energy supply and demand within a district or community, reducing the need for energy imports and exports, and promoting tailored cost allocation mechanisms [44].

Temporal flexibility, on the other hand, usually refers to the ability of ESSs to store energy for use later [45]. This is important because it allows for integrating intermittent renewable energy sources. For instance, solar and wind power depend on weather conditions and may not always produce energy when needed. ESSs can store the excess energy generated during peak production times for use during periods of low production, ensuring a continuous and reliable energy supply, dealing with the challenge of managing renewable energy flows in real-time.

The digitalization processes are progressively resolving this problem through ever more accessible digital models, sensors, and platforms. Digitalisation to manage spatial and temporal energy flexibility in real-time and through ever more user-friendly interfaces is gaining traction. These advances in digitalisation is reflected in recent ESS research which has focused on, for example, developing platform-based approaches adopting computational algorithms and sensing technologies [46,47]. Other studies tested blockchain technologies to promote peer-to-peer (P2P) energy transition amongst prosumers [48]. The primary scope of such platforms is to deliver new services and business models. Their development is fundamental to managing spatial and temporal flexibility during the operational stage of new energy systems. However, the implementation of spatial and temporal flexibility of ESSs may involve social cogitations at the earlier stages of implementing these systems.

In this regard, a new social perspective to the spatial and temporal flexibility of ESSs can promote specific socio-technical solutions for different socio-economic and geographical contexts. This new perspective can significantly impact the economy and society. Considering the high diversity across the EU states, one-size-fits-all perspectives cannot be considered reliable and long-term solutions [49]. Therefore, local guidance for implementing spatial and temporal flexibility of ESSs within local communities is necessary. This guidance is expected to be founded on flexible and agile digital platforms that can be replicated and expanded at the city scale [50].

Such innovative socio-technical solutions derive from new collaborations [51,52] between institutions and local communities to influence ESS integration [53]. However, each actor has a different scope and objective for achieving such integration. For example, local and national governments mainly focus on achieving energy targets promoting incentives and regulations [54]. Local communities and single individuals frequently exchange information on the advantages of undertaking energy retrofit or being involved in renewable energy projects, focusing on financial gains, risk protection, and payback periods [55,56]. In addition, each actor approaches technology integrations and energy services differently [57]. These differences are problematic because the effective implementation and utilization of large-scale renewable energy facilities require the participation of a diverse range of actors, unlike individual forms of ESSs that can be accepted, adopted, and used by individuals (e.g., e-vehicles [58,59]).

Therefore, ESS implementation should start by considering community values, priorities, and concerns instead of what is techno-economically admissible within the current legislative framework [60].

In this regard, co-creation practices may be a solution to achieve a consensus on distributed and renewable energy infrastructure. Such a consensus must be sustained by the whole community, which will act as a low-carbon society. Co-creation and co-design approaches have become increasingly popular in implementing social acceptance of public–private-people partnership business models [61,62] and exploring the consumer-citizen attitudes to business models for decentralized energy storage [63].

The extensive dissemination of user-friendly digital platforms is one of the reasons for the increasing popularity of participatory approaches. Digitalization has the potential to enable different groups of actors to utilize their capabilities to synchronise their actions to achieve a shared objective in terms of spatial and/or temporal flexibility of ESSs. However, while the literature is rich in studies focused on digital platforms for peer-to-peer energy trading systems [64–66], digital tools to support the early-stage social organisation of emerging energy paradigms integrating ESSs are rare and not sufficiently explored.

3. ESSs: Social Pillars

3.1. Towards a Unitary Framework

The recent literature highlighted many social topics concerning ESS (e.g., environmental, financial, and legislative issues, among others). All these issues may be considered fundamental components for a socially oriented implementation of ESSs. However, the review of the current trends in the literature confirmed that the fragmentation of the social aspects in ESSs continues to be an unresolved issue. No studies dealt with the whole geographical complexity of a territory, which is fundamental to implement a citizen-centred renewable energy system.

As a possible resolution to such fragmentation, Table 1 shows our categorisation of the research trends, pointing out key concepts that underpin our unitary framework. The table reports the authors' comments and perspectives on implementing ESSs at scale. The former focuses on what the social implementation of ESSs at scale demands, while the latter suggests future trends.

Table 1. Factors required for the socio-technical implementation of ESSs at scale, and future research perspectives.

Sources (2021–2023)	**Social Implementation of ESSs at Scale**		
	Key Social Component	**Authors' Comment on the Necessary Factors**	**Authors' Perspective of Future Research**
[27,28]	Financial mechanisms	(multi-level) institutional capabilities to support innovative social initiatives	To deal with the multi-dimensional aspects that characterise the geography of a territory rather than to focus on single or limited social components
[29–32]	Environmental awareness		
[4,15,33–35]	Social understanding		
[2,20,36–44]	Spatial organisation (Energy Cluster/Districts)	the re-definition of spatial organization of renewable-energy based settlements integrating ESSs inside and outside buildings	To explore the role of stakeholder groups in the spatial and temporal flexibility organisation of the citizen-centred energy system
[45–50]	Temporal flexibility (Renewable sources)	a focus on the temporal flexibility of ESSs in relation to the community needs	
[51–60]	Stakeholders' groups (Social norms and capital)	the development of energy transition routes designed by and for the different types of actors	
[64–66]	Digital platforms (Energy services)	digital platforms to deliver a new set of energy services to manage the spatial and temporal flexibility of the renewable and decentralised systems controlled by different actors	To develop digital platforms to facilitate the collaboration among stakeholder groups in the early stage of citizen-centred system organisation
[62,63]	Co-creation/ acceptance (Collaborative platforms)	co-creation approaches as opportunities to promote awareness and new forms of collaboration	

Based on the trends presented in Table 1, we elaborated a unitary framework to illustrate relevant overlaps between the key social components. Figure 1 shows our conceptual framework organised around three social pillars concerning the ESSs' implementation, which synthesise research perspectives. These three pillars are: multi-dimensional geographical and institutional scales of ESSs, social components of spatial and temporal ESSs flexibility, and a co-creation approach in ESS implementation strategies. It also stresses the connections across such pillars, with a particular focus on the role of stakeholders.

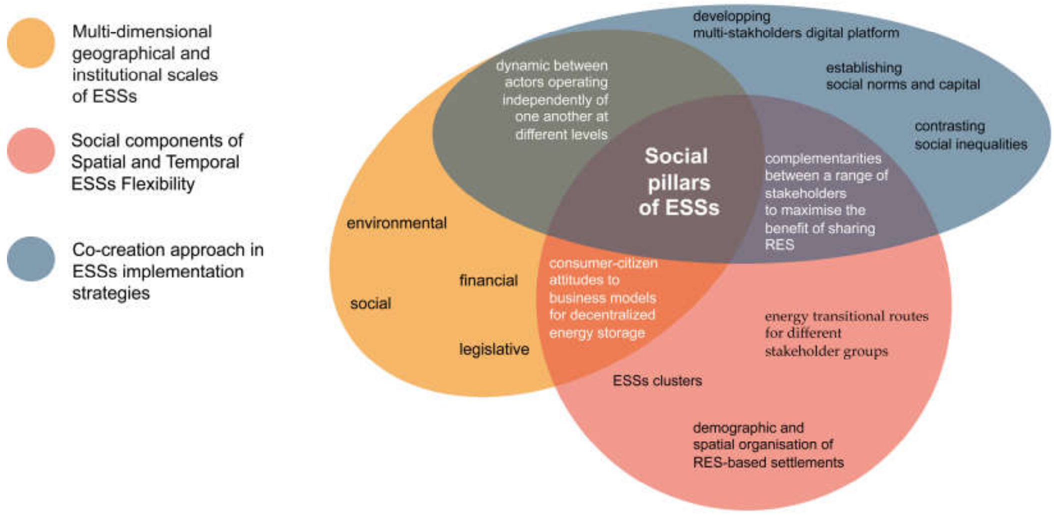

Figure 1. Integrated social pillars of Energy Storage Systems.

3.2. Implications

In this section, we present the implications of each pillar in relation to the literature examined.

Firstly, in line with Schelly et al. [60], it is essential to explore how each aspect of social factors of ESSs is related to the geographical and institutional scales (from local to national). As Huckebrink and Bertsch [34] argue, studying the socio-economic and socio-political dynamics that characterise a specific local context and how these affect the capabilities of specific target groups is fundamental to understand why local communities reject or accept ESSs. It is also vital to integrate various factors influencing the perception and the exploitation of ESSs at the local level and draw several policy recommendations from these results, which is essential for the sector's progress in line with Baur et al. [62]. While the literature paid attention to the above-mentioned topics, their holistic integration from the different stakeholders' perspectives remains challenging.

By contrast, the first pillar promotes a multi-dimensional geographical and institutional scale concerning the social acceptance of ESS implementation. The proposed pillar stresses the need to focus on actors operating independently of one another at different levels (local and national) within the same energy infrastructure, integrating "top-down" and "bottom-up" viewpoints [10,21] in order to take into consideration the complex dynamics between technological and social innovation over time. Operatively, this calls for analysing various societal groups, while remaining aware of the potential application of innovative technologies at macro, meso, and micro scales, exploring the dynamics between various decision-making levels and intertwined policy areas, including both public and non-governmental actors and their strategies as described by Ambrosio-Albala et al. [67].

Secondly, as suggested by Hoicka et al. [49], operationalising technological innovation at the multi-dimensional geographical and institutional scales requires attention to the peculiarities of a local context rather than the one-size-fits-all approach. The main problem is including such peculiarities within a new energy planning framework. In this regard, it is expected that attention should be paid to advanced multi-criteria techniques supported by digital platforms to select the most promising portfolio of energy technologies, as stressed by Adams et al. [50] and Bauwens et al. [52]. So far, the spatial and temporal flexibility of ESSs is a topic mainly confined within the technical and technological silos with a particular emphasis on digital platforms to manage real-time flows of information and energy related to market mechanisms. However, such digital platforms do not guarantee a socially-driven and equitable low-carbon transition.

This is a crucial social aspect. Indeed, despite the benefits of ESSs, the potential social implications of their development and use should be considered. One implication is that developing and implementing ESSs could exacerbate social and economic inequalities. For example, wealthy households or geographical regions may have greater access to ESSs, enabling them to benefit from energy security and renewable energy sources. In contrast, low-income households may need more resources to invest in such technology. This inequality could lead to energy poverty and marginalization of low-income households and vulnerable populations. In line with Knox et al. [68], applying a comprehensive framework to illustrate the cross-over between sector-based perspectives (i.e., social, environmental, financial, and legislative, among others) is crucial. Therefore, digital platforms dedicated to educating stakeholders on the benefits of EESs, promoting strategies to implement social partnerships, and integrating social components into spatial and temporal flexibility are critical future perspectives.

Thus, in line with prior studies [55–57], the second pillar endorses an integration of social components into the spatial and temporal flexibility of ESSs, encouraging: (i) "ESSs as social-clusters" exploring complementarities between a range of stakeholders to maximise the benefit of sharing and exchange of renewable energy locally; (ii) relationships between the demographic and spatial configuration of settlements and their renewable energy generation potential, to maximize investments in new forms of energy infrastructure such as positive energy districts and energy communities; (iii) inclusion of diverse stakeholders, such as vulnerable and low-income consumers, to ensure a just, socially-orientated energy transition.

This second pillar aims to foster the exploration of how such social factors can be integrated into energy system models, suggesting the perspective for a framework to illustrate the consequences of different energy transitional routes for different stakeholder groups. This will open a new season of co-production approaches, allowing local communities to promote their socio-economic preferences about energy system transformation pathways. By doing so, it will be possible to develop more critical and reliable energy transition models, including capturing the social realities of the energy transition.

For this reason, this perspective emphasises a specific social pillar on co-production approaches to ESS implementation strategies. One of the key benefits of co-creation and co-design approaches is that they enable stakeholders to work together to identify the most suitable and effective energy storage solutions for their community. According to Nguyen and Batel [13], this collaboration allows for a more holistic and comprehensive approach to energy planning, leading to more sustainable and efficient energy systems, contrasting social inequalities and passive participation.

One example of co-creation and co-design in PEDs is the involvement of residents in developing community energy storage systems and establishing social norms and capital, as stressed by Haque et al. [26]. According to Trivedi et al. [43], this approach allows residents to have a say in the type of energy storage technology used, as well as the location and design of the system. By involving residents in the design process, the resulting energy storage system is more likely to meet the needs and preferences of the community, which can lead to greater acceptance and support for the system.

Another key benefit of co-creation and co-design approaches is that they can help build trust and cooperation between stakeholders, supporting the definition of the concept of "community" in this context, which is currently unsettled [52]. By working collaboratively, stakeholders can develop a shared vision and understanding of the energy system, which can help to foster a sense of ownership and responsibility for the system's success. This can lead to more robust support for the system and increased cooperation in its operation and maintenance.

Thus, in line with Krug et al. [51], for a successful application of ESSs at the local level, the future research agenda must be directed toward new forms of collaboration and partnership between various stakeholders, including residents, businesses, and local authorities, to design and develop energy systems that are tailored to meet the needs of the community.

4. Conclusions, Limits, and Future Research

Novel approaches in ESSs should impose the emergence of technological transitions based on what a community considers a priority rather than aligning the community aspirations to the techno-economic possibilities. The main goal of the current study was to determine the factors required for the social implementation of ESSs at scale, and future research perspectives to operationalise such factors. In this regard, a conceptual framework was elaborated and organised around three main social pillars concerning ESS implementation strategies. Our findings stressed the significance of the negative perceptions concerning ESSs, which may cause significant delays in their implementation. We pointed out that addressing these concerns through increased community engagement, education, and awareness programs can significantly change citizens' attitudes towards ESSs. In addition, our findings emphasised the social dimension in managing the spatial and temporal flexibility of ESSs. This dimension enables community ownership and participation and supports innovative business models to reinforce emerging paradigms such as Positive Energy Districts and Positive Energy Blocks as feasible and reliable energy infrastructure that could shift the energy system towards a more sustainable and equitable future. Finally, our findings promoted the implementation of co-creation approaches in ESS implementation strategies. Co-creation approaches are instrumental in creating a platform for dialogue and collaboration between stakeholders that enable the introduction and development of ESSs.

While this study made contributions to the current debate, it has limitations. The three pillars proposed here are incomplete, but they contribute to fostering in-depth socio-technological approaches to implementing ESS. Thus, they pave the way to dealing with a critical challenge to establishing a low-carbon society. ESSs present numerous socio-technical benefits, including enhanced energy resilience, demand response capabilities, community engagement, and economic opportunities, which undoubtedly require more sophisticated conceptual models and an extension of the literature analysis. However, overcoming the existing social barriers is essential, promoting collaborations between governments, utility companies, community members, and various stakeholders to pave the way towards a cleaner, more resilient, and sustainable energy future based on a citizen-centred energy model.

Therefore, future research must incorporate co-creation approaches to deliver platforms for dialogue and collaboration between energy experts, researchers, policymakers, and the local community to optimise the implementation of ESSs. A possible research path is to exploit knowledge graph (KG) techniques. A knowledge graph is a structured representation of knowledge that models real-world entities and their interconnections non-linearly, allowing for rich and flexible data representation [69]. They emphasise the interlinking of data to create comprehensive and dynamic databases, with promising interactions between KG and AI techniques [70]. Such digital multi-stakeholder platforms could be a solution for an equitable distribution of ESSs' benefits, ensuring that the interests of all stakeholders are considered, ultimately increasing the likelihood of successful implementation of ESSs. They can also foster community engagement by providing opportunities for residents and organisations to participate in the energy management process. In conclusion, developing these types of digital platforms will promote a new season of collaboration between engineering and social science research.

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