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Community energy storage: A responsible innovation towards a sustainable energy system?

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HIGHLIGHTS

- An overview of the state of the art in community energy storage (CES) is provided.
- CES is conceptualized and analyzed as complex socio-technical system.
- Responsibility in CES design and implementation is operationalized.
- CES is not only technical but also social innovation.
- The added-value of CES go beyond economic benefits to wider societal benefits.

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ABSTRACT

The decreasing cost of energy storage and increasing demand for local flexibility are opening up new possibilities for energy storage deployment at the local level. Community energy storage (CES) is expected to contribute positively towards energy transition while accommodating the needs and expectations of citizens and local communities. Yet, the technological and societal challenges of integrating CES in the largely centralized present energy system demand for socio-technical innovation. In this article, we develop and discuss several configurations of CES. Applying system innovation and socio-technical transition frameworks and conceptualizing CES as a complex socio-technical system, different dynamics of CES in the energy systems such as coordination and interaction among actors and components of CES and the larger energy system is explored. The responsible research and innovation (RRI) framework can provide a new discourse in design and implementation of CES, facilitating the transition to a sustainable, reliable, inclusive and affordable future energy system.

1. Introduction and scope

The initial local energy systems developed by enterprises and others around 1900 evolved into the present and still dominant complex, fossil-fuel based, centralized and networked form due to various technological and societal developments, such as increasing demand, economies of scale and resource complementaries [1,2]. However, the present system is starting to lose some of its appeals, mainly due to vulnerabilities of the energy infrastructures related to geo-politics, depletion of fossil fuels and its climate change impacts as well as new developments around distributed energy resources [3,4]. Accordingly, the energy system is undergoing transformation, as can be seen in many countries around the world, but especially in Germany with its spectacular Energiewende [3,5–7].

The present energy system seems to be at a crossroad, going through rapid technological and institutional changes both at the central and the local level [8]. The energy landscape is changing from dominant vertical integration of centralized generation, transmission and distribution systems towards a combination of top-down and bottom-up systems. Although the centralized systems will have important role for decades to come, there appears to be a transition towards a low-carbon, co-operative and decentralized system, in both developed and developing countries [9]. The ongoing energy system transformation and energy transition is partly steered by and asks for a higher engagement of citizens and local communities [10].

One of main problems concerning the transformation towards a low-carbon system is the mismatch between supply and demand, which is expected to increase due to higher intermittent generation through distributed energy resources (DERs) such as sun and wind [8]. This requires serious adaptations of the energy systems, including new types

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of balancing and energy storage services [11–13].

So, two of the main challenges of the future energy system are to deal with new approaches towards balancing. i.e. with energy storage, and with engagement and involvement of local communities. One of the solution that addresses both of these challenges is community energy storage systems which are getting increased attention as potential sources of innovation for sustainable energy transition [14,15] However, it is not clear how the CES systems be developed and what can be its role in the transition of the energy system.

Similar to community energy, CES is also often treated as technical task, driven by economic incentives [16–18]. Social and behavioral aspects are not given much attention in the current literature [19,20] and institutional aspects are also largely being neglected [8,21,22]. For successful CES, it is important to satisfy the needs and objectives of local energy communities. Moreover, technological advancements and financial viability of DERs, and requirements to aggregate smaller assets make sense of community engagement. CES technologies have potential to shape future society and societal needs in terms of energy which in turn will influence their technical innovation and development. For example, CES can enable local community to be autarkic and the energy storage technologies should be accordingly adjusted to meet these new societal needs. The problems and externalities in the present centralized energy systems is fostering innovative and responsible ways to produce, transport and store energy with the engagement of the local communities [23–25].

Accordingly, the energy system transformation is starting to provide new roles and responsibilities for local communities as prosumers, and prosumagers [23–25]. These roles refers to local communities and households producing and consuming local energy, as well as producing, consuming and storing local energy, respectively [26]. As evident from the increasing number of local energy initiatives, users and citizens can play increasingly important and even essential roles in the transformation and related innovation processes [27–30]. When local energy communities adopt and use energy storage, new user-inspired innovations are possible [29,30]. Such social innovation can be on the governance and operation of the energy storage system. Sometimes, local communities can give important feedback to the technology providers regarding the further technological improvement and sustainability of the energy storage system leading to the higher acceptance and further technical innovation. In this way, the technological articulation and innovation goes on through the use of technologies in the community.

The use of CES can locally help energy system transformation in several ways such as decoupling energy demand and supply, providing different energy services, integrating the heat and electricity system for higher flexibility as well as accommodating the needs and expectations of citizens and local communities [31,32]. Accordingly, CES can drive the energy system transformation in the form of bottom-up initiatives [33]. In this process, there are opportunities and challenges for the local communities in re-organization and transformation towards a more sustainable and co-operative energy system. New local energy organizations, technologies, business models, partnerships and customer engagement programs can emerge at the changing energy landscape, further driving the energy system transformation. This transformation might result not only in socio-technological changes at the local energy system but also in fundamental shifts in the way the energy system as a whole is being organized [8].

CES might provide new options and opportunities to empower and engage local communities, as well as to foster socio-technological innovations. A careful alignment of technical and social aspects of the new energy storage technologies will be required. CES might need new enabling institutional environments for effective contribution towards energy system transformation. So, CES may lead to both system and community level dynamics. System level dynamics refers to changing roles and responsibilities of energy system actors, energy system integration including different sectors, new market design, and business models. Community level dynamics refers to new roles for local communities in ownership, governance as well as local energy markets in the form of peer to peer energy sharing.

This also means that besides demands concerning energy security, affordability, safety and soundness, other requirements and values should be taken into account, in particular with respect to sustainability and environment as well as coordination of activities and community involvement. Particularly, the sustainability of energy storage technologies and distributed energy resources is important. From a responsible research and innovation (RRI) perspective, energy system actors and local communities should collaborate to share responsibility, to become mutually responsive and to anticipate future developments to guarantee socially and technologically acceptable transformation towards an inclusive and sustainable energy system [34–36].

There are still many unanswered questions, however. What do we mean with energy storage at the local level, how many community energy initiatives are involved in CES, how can CES be shaped and organized, what are the contribution of CES in the energy transition, what are the conditions for the emergence of CES, and how can RRI be operationalized in CES?

The aim of this article is to shed light on these questions. Accordingly, the focus is not on the comparative study of CES with other distributed or utility scale application of energy storage but on the role of local communities in shaping and enacting CES. It reviews and assesses CES systems, and their different possible configurations and dynamics. To understand and analyze these systems, we will make use of the theoretical framework of system innovation, socio-technical transition and responsible research and innovation [37–41]. The rest of the article is organized as follows. First of all, in Section 2, after describing the role of storage and communities, CES is contextualized in wider energy system. In Section 3, CES is analyzed through system innovation and socio-technical transition perspectives and conceptualized as a complex socio-technical system. In Section 4, different aspects of responsibly linking CES with present energy system are outlined. In addition we will list some conditions for further development of CES. Finally, Section 5 presents and discusses our conclusions.

2. Positioning community energy storage

2.1. Need for decentralized, flexible and balanced energy system

Thanks to co-operation of different actors as well as favorable policies and regulation, DERs are being developed and embedded rapidly and widely. Accordingly, the transforming energy system also has to be more diverse and flexible to cope with increasing temporal fluctuations of demand and supply. The fluctuations in supply is growing due to increasing penetration of intermittent DERs such as solar and wind. The energy demand as well as its fluctuations are expected to rise despite the improvement in energy efficiency due to increasing electrification of the different sectors such as heating and transport in the developed countries as well as improving energy access and socio-economic conditions in the developing countries [42,43]. In addition to the traditional ways of harnessing the flexibility of supply through spin reserves, new approaches for decentralized demand and supply side flexibility is required at the local level to ensure effective system balance, to avoid local congestion and to defer the grid reinforcement.

Fig. 1 presents the five key ways such flexibility could be harnessed in the present energy system namely supply side flexibility, demand side flexibility, energy storage, energy conversion as well as interconnection and grid reinforcement [31,44]. Supply side flexibility can be harnessed through ramping up and down of traditional spin reserves and curtailment of renewables [45,46]. Demand side flexibility can be harnessed through demand side management and demand response and requires tremendous amount of consumer engagement [21,47]. Energy storage in the form of electricity and heat can minimize supply and demand mismatch [48–50]. Energy conversion into other forms such as

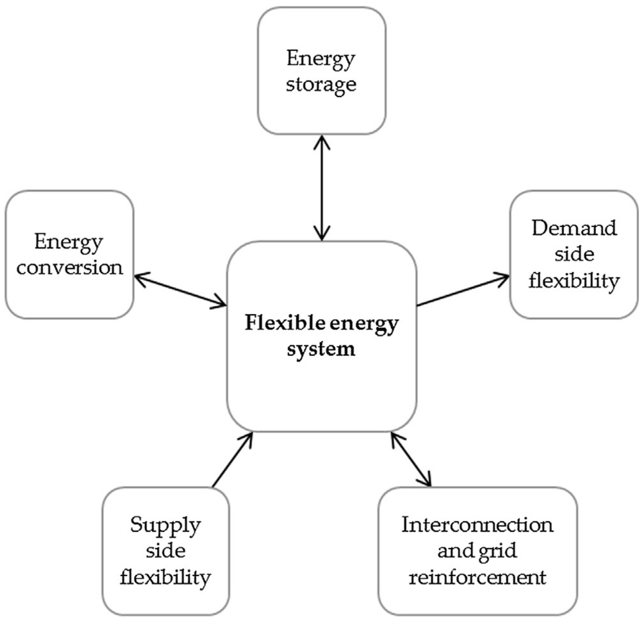

Fig. 1. Five key blocks of the flexible energy system.

power to gas also helps to ensure flexibility in the energy system [25,26]. Grid interconnection and reinforcement absorbs supply and demand mismatch over wide geographic regions with the aid of national, regional, international and super grid [31]. The flexibility of future energy system depends on integrated and synergized operation of these key options.

Energy storage is one of the key blocks for the flexible energy system and it can enable integrated and synergized operation of these several flexibility options as well as different sectors such as heat, electricity and transport [51]. There are many different types of energy storage technologies being used and developed which can be classified based on materials used, form of energy stored, their functions, response times and storage durations. Broadly, energy storage technologies can be categorized into mechanical, electrochemical, electrical, thermochemical, chemical and thermal energy storage [22,52–55]. According to the United States Department of Energy, Global Energy Storage database, pumped-hydro is the most deployed stationary energy storage technology worldwide followed by electrochemical and thermal energy storage, as summarized in Table 1 [53].

Lithium-ion batteries are the fastest developing energy storage technologies, thanks to its fast pace of development for electric vehicles, as well as residential and utility scale applications [51,56]. Electric vehicles batteries can be used for both transport as well as stationary storage purposes subjected to suitable business model and consumer acceptance. In practice, there are some distinction between stationary and mobility oriented energy storage technologies, as batteries are systems rather than just the battery packs. In fact, the batteries used in the electric vehicles are still suitable for a second life in the stationary energy storage application such as residential and CES systems [57]. This second reuse refers to the battery packs but a different balance of system components might need to be designed as further discussed in Section 4.1.

Table 1
Global status of energy storage deployment [53].

Technology	Rated power (GW)
Pumped hydro	185.2
Electro-chemical	4.7
Thermal	4.03
Electro-mechanical	2.65
Hydrogen	0.022

Several scholars provide review and study on energy storage technologies and its applications [22,52,54,58–62]. Gallo et al. (2018), review energy storage technologies in the context of energy transition [55]. Aneke and Wang provide overview of energy storage technologies with the focus on real-life application [60]. Luo et al. provide an overview of the electric energy storage applications and their potential application in power system operation [52]. Hadjipaschalis et al., Chen et al. and Diaz-Gonzalez et al. also perform a comprehensive review on different energy storage technologies [63–65]. Koohi-Kamali et al. study the emergence of energy storage technologies for the smart energy systems [66]. A review of stationary energy storage technologies for wind power application is provided in Díaz-González et al. [65]. Similarly, Parra et al. [67] compare lead-acid and li-ion energy storage application for time shifting of energy from solar photovoltaic system. Lund et al. provide an overview of different energy storage applications for the flexibility provision [31]. Kousksou et al. provide a review of different applications and challenges of energy storage in general [16].

It is not well known yet, if energy storage will have similar dynamics as renewable energy and which policies and regulations are adequate, but initial studies show that energy storage has similar learning curves and cost reduction as solar photovoltaics and wind [17,51]. According to Gallo et al. (2018), most important barriers for energy storage deployments are related to economic feasibility and regulatory environment [55]. Kyriakopoulos and Arabatzis [54] review energy policies, regulatory regimes and technology innovation required for electrical energy storage systems. Whittingham et al. highlights limitation of electrical energy storage such as cost, energy performance requirements and preference for environment friendly materials [18]. The authors highlight necessity for major advances in naturally abundant new materials, cathode materials of higher storage capacity, safer and low cost anode and stable electrolytes [18]. Liu argues that although material science and material chemistry play a key role, energy storage is also a system problem involving many issues such as energy system integration and actors engagement [19].

The cost of energy storage tends to decrease. Increasing demand for local flexibility, to avoid local congestion and to defer grid reinforcement, is opening up new possibilities for energy storage systems deployment at the local level [12]. The need for local energy storage is expected to grow in the future in line with increasing DERs penetration, and to meet increasing demand for flexibility as well as self-sufficiency [51]. This is also evident by the large number of local demonstration projects on energy storage being implemented worldwide [20,53,68,69]. For example, there are more than 80,000 residential energy storage system in Germany, and every second newly installed residential PV system is combined with an energy storage [70].

The centralized design and regulation of the energy system present challenges for the implementation of CES. On the one hand, CES has to meet different expectations and objectives of local energy communities such as local balancing, energy costs reduction, energy security, independence as well as social cohesion and community engagement [71–73]. On the other hand, the energy systems actors such as system operators and aggregators could also have different expectations from the CES such as peak shaving and ancillary services [37,58,74]. For example, households want low-cost local energy from CES while aggregators seek to maximize the flexibility value of CES in various energy markets [42]. CES needs to align these often conflicting expectations in order to contribute towards energy system transformation in an acceptable way for all stakeholders [38–40,74]. These conflicting interests and expectations can be managed with the aid of methods such as value-sensitive design and value case method, as further discussed in Section 4.5 [34,41]. Recently, value-sensitive design is applied in the design of solar and wind systems [75,76].

2.2. Energy communities

The increasing involvement of citizens the energy production and management can be seen in the rapid growth of local energy co-operatives [23,24]. The diminished role of households and local communities to that of passive consumers in the centralized energy systems is changing to active prosumers. With these developments, the future energy system is going to be combination of centralized and decentralized energy system working in synergy with each other.

Cities and communities around the globe are starting to drive the transformation of the energy system [11]. When consumers have more control and options, they tend to self-organize and co-operate to initiate a community energy system [77–85]. In some cases, the need to adjust local energy system seems to be more urgent than the regional and national level. Some prominent examples in this regard are the recent growth of local energy co-operatives in Germany and 'van gas los' discussions in the Netherlands [86,87]. In the recent years, more and more distributed energy resources (DERs) have been installed at the household and the community level [7,33]. Organizing local energy collectively often makes sense for economic and logistic reasons as well as for effective resource mobilization [81]. With further facilitation from the smart grid development and the drive for energy independence, more local communities are expected to engage themselves to match their supply and demand locally.

Table 2 provides an overview of local energy initiatives wide-spread in the present European energy landscape. In Europe, there are more than 2800 local energy co-operatives of which around 1000 are in Germany and around 400 are in the Netherlands [7,25,88]. Increasing numbers of local communities are engaging themselves in generating, conserving, sharing, consuming and exporting energy locally thanks to the recent developments such as the implementation of suitable policies, cost reduction of renewables, the emergence of information and communication technologies (ICTs) and internet of things (IoT) as well as environmental awareness and community objectives such as grid independence [89,90]. Local communities are well-placed to identify local energy needs, take proper initiatives and bring people together to achieve common goals such as self-sufficiency, resiliency, and autonomy. Technical innovation in distributed renewable energy technologies and social innovation in its governance are leading to the surge of local energy collectives that generate and manage energy in a decentralized, democratic and distributed way [11].

The local energy initiatives are emerging with varying numbers, success rate and strategies in Europe [91]. The diversity in the success of these community initiatives could be partially attributed to prevailing structural, strategic and biophysical conditions [81,91]. For example, in Germany, the motivation so far has mainly been the mixture of environmental awareness and economic incentives facilitated by enabling policy frameworks. With the recent changes in the market conditions and support incentives in terms of feed-in tariffs co-operatives now have to compete with the centralized generation with economies of scale, highlighting the obsolescence of current business models [23]. In this context, self-consumption, local balancing and CES become increasingly important.

These existing local energy initiatives may provide fruitful ground for the development and implementation of CES. For example, the energy community of Feldheim, Germany has recently added CES in their mix of technologies [20]. CES stores the excess local heat and electricity that cannot be consumed locally when produced and make it available later when it is needed. The stored energy can be used for different purposes depending on the local conditions such as resource availability and consumption patterns. In this way, CES can enable effective matching of local renewable energy supply and local energy demand. It not only allows higher penetration of local generation such as renewables, but also facilitates energy sharing and local self-consumption of locally generated renewables. At the same time, CES can provide different energy services to the neighboring communities as well as the larger energy systems. For example, it can provide ancillary and balancing services to the larger energy systems. In other words, CES can enhance synergies between local energy initiatives and the larger energy system.

Table 2
Emergence of local energy initiatives in Europe.

Country	Number of local energy initiatives	Number of members	References
Europe	2800	–	[25]
Germany	1000	180,000	[23]
The Netherlands	392	65,000	[24]

2.3. Community energy storage: Concepts, definitions and scope

There are multiple but not precise definitions of CES in practice and the definition varies a lot among the scholars [48,67,92–97]. Parra et al. refers it as energy storage located at the consumption level with several applications and positive impacts to end users and network operator [95]. Roberts and Sandberg suggests CES as an intermediate solution between residential energy storage and utility-scale distributed energy storage for balancing local intermittent renewable supply and dynamic demands such as heat pumps and electric vehicles [94]. In essence, both these definitions are limited to the location of energy storage and do not provide attention to community engagement, virtual communities, ownership as well as benefits. van der Stelt refers it as energy storage systems located at the consumption level with the ability to perform multiple applications to manage demand and supply with a positive impacts to both consumers and the system operators [92]. This definition brings along interesting dynamics to CES as energy systems actors such as system operators as well as program responsible parties who are not the owner might also get the benefits. Barbour et al. define it as energy storage introduced for community that can be shared between members who are typically but not exclusively located in the local community, opening up the possibilities for virtual CES [48].

In this review article, CES is defined as *an energy storage system with community ownership and governance for generating collective socio-economic benefits such as higher penetration and self-consumption of renewables, reduced dependence on fossil fuels, reduced energy bills, revenue generation through multiple energy services as well as higher social cohesion and local economy.* This definition excludes purely residential and utility scale application and theoretically, CES lies between these two applications.

2.4. Studies on energy storage and communities

Recently, energy storage and community energy receive increasing attention in academia [48,58,92]. Fig. 2 presents increasing trends of research articles on the topics of energy storage, community energy as well as residential and CES, as can be found in Scopus® database [98]. CES seems to get more attention than the residential energy storage. This could be attributed to size, economy of scale of CES as well as its potential applications in the energy systems.

Many authors argue that CES will have an important role in creating a more efficient energy system [31,66]. Barbour et al. concluded that CES is more effective option than the residential energy storage [48]. Similarly, Parra et al. analyzed the performance and economic benefits of CES for time-shifting of solar photovoltaic energy [67]. The community application is demonstrated to reduce the life-cycle cost of energy storage as high as 37% over the individual household application [67].

Some authors, however, report that CES are not yet feasible [92]. For example, Van der Stelt et al. compared techno-economic feasibility of residential and CES scenarios using optimization and dynamic

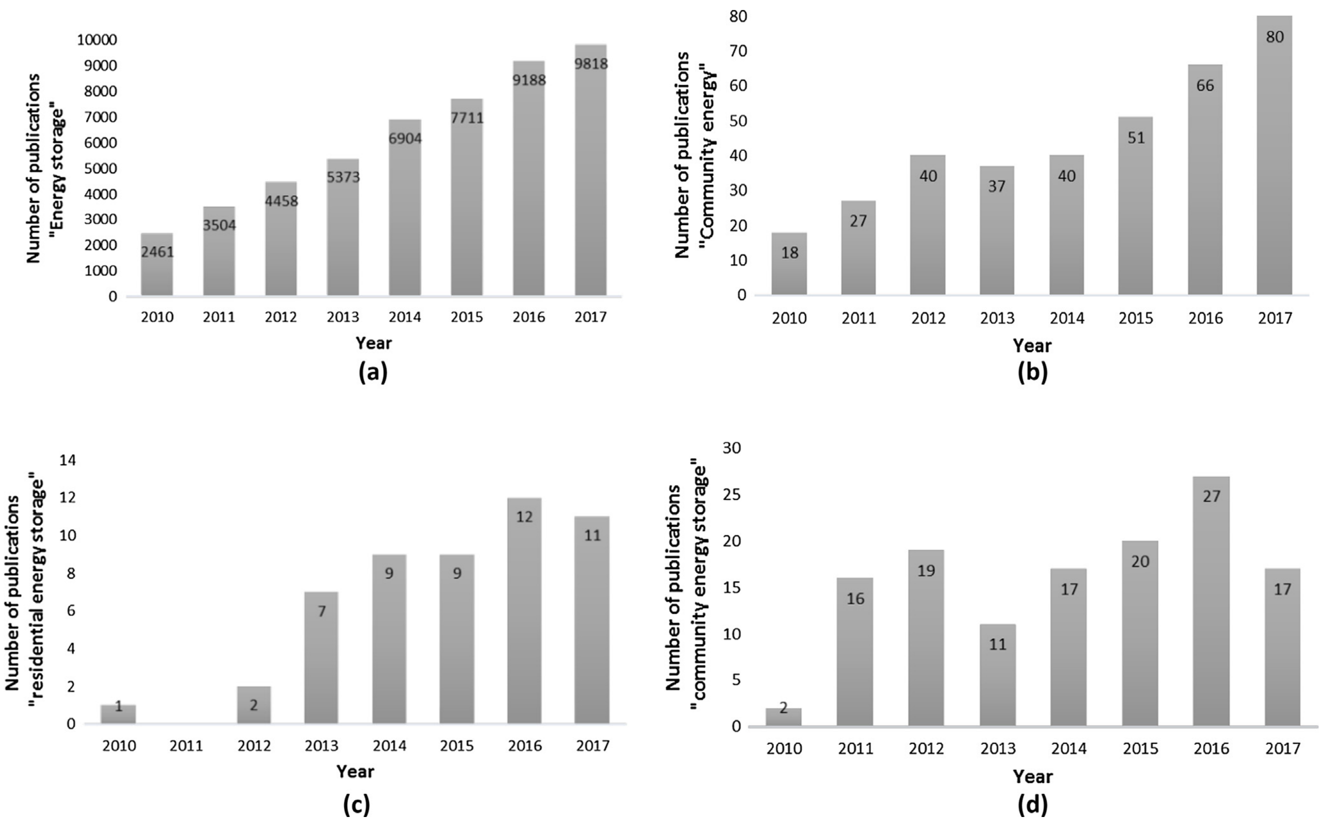

Fig. 2. Occurrences of search phrases in Scopus database (a) "Energy Storage" (b) "Community Energy", (c) "home energy storage" OR "residential energy storage" OR "household energy storage" and (d) "CES" OR "local energy storage"

pricing and concluded both residential and CES to be economically infeasible under current investment costs [92]. Nevertheless, both configurations of energy storage led to increase in self-consumption of PV and decrease in annual energy costs by 30%, approximately [92]. Nevertheless, van Melven et al. reports economic and social viability of CES when the multiple-values such as local balancing, peak shaving, grid services and avoided costs of grid-reinforcement are stacked [99].

Some other scholars focus on control, energy management and market aspects of CES [93,97,100]. Arghandeh et al. presents control strategy to maximize the revenue from CES considering crucial uncertainties in price and load forecasts as well as transformer loading, reserve capacity and feeder losses [93]. The authors presented a market based optimization algorithm to realize additional benefits of CES in the competitive energy market [93]. Sardi et al. proposed strategy for optimal allocation of CES using all possible costs and benefits [100]. The costs considered are capital costs, operation and maintenance costs as well as replacement costs whereas the benefits considered are arbitrage, peak support, loss reduction, grid re-enforcement deferrals, emission reduction as well as grid-support services [100]. Onar et al. models the control and application of CES based re-purposed electric vehicles batteries and highlights its potential application in grid support and ancillary services [97].

Although Parra et al. reviews the challenges and perspectives on CES with emphasis on techno-economic, social and environmental assessment as well as end-use application [58], most of the research on CES so far deals with techno-economic aspects [58,67,92,97,101]. There is limited attention on societal, institutional and environmental aspects. The attention on these aspects can bring along new opportunities for CES such as citizen participation and community engagement, sustainability as well as awareness on energy consumption and environmental aspects. Gaede and Rowlands identifies political and socio-technical factors to enhance transformation capacity of energy storage and conclude that its transformative potential depends on complex interactions between actors and institutional factors [102]. Building upon existing reviews and research on CES, this review focuses on how energy storage is being shaped and enacted in local communities. Based on current developments in the energy landscape, several configurations of CES are identified and discussed. Different dynamics of CES in the energy systems as well as within the local community such as co-ordination and interaction among actors and components of CES will be explored. This review also benefits from the application of responsible research and innovation (RRI) framework in design, implementation and integration of CES.

2.5. Categorization, configuration and cases of community energy storage

Several electrical and thermal energy storage technologies have potential application in the local energy communities. For electrical energy storage at community level, electrochemical energy storage technologies such as lithium-ion, sea-salt and lead-acid batteries as well as flow batteries are suitable [49,58,59,103–105]. Despite high capital cost and low efficiency, hydrogen energy storage can play important role in CES [106,107]. Not all the electrical energy storage technologies outlined earlier are suitable for community level application. For example, pumped hydro and compressed air are often not suitable for application at the community level due to their size as well as geographic requirements [51,58]. Technologies such as super-capacitors and flywheels are not capable of meeting the specific energy and power requirement for the community level applications [51,63].

For the thermal application at the community level, sensible and latent heat storage technologies are suitable for daily and seasonal storage [108–114]. The few examples of sensible heat storage medium are water, aquifer, pit, rocks and bricks [58,111]. The aquifer based thermal energy storage technologies are common in the Netherlands, whereas as pit thermal storage technologies are common in Denmark [58]. Latent thermal energy storage consists of phase change materials and are used for more compact storage applications [58,112].

The technical and social innovation in electric and thermal storage system can enable its new application at the local level. Community values such as sustainability, safety and energy security are increasingly being embedded in the design of CES as evident in new energy storage technologies such as DrTen® and Ecovat® [105,108]. Local energy communities are also the location where electric and thermal energy storage can be integrated providing multiple benefits such as higher flexibility, reliability as well as energy security [31,58].

In the rest of this article, the focus is on electrical CES, although most of the discussion will be valid for thermal energy storage as well. CES are considered intermediate solution between residential and utility scale energy storage application [58,94]. The increasing penetration of intermitted renewables as well as decreasing costs of DERs has led to a broader implementation of CES of various size and scales [67]. With the digitalization of energy system, such as through advancement in information and communication technologies and energy management systems, residential energy storage, however, could also be shared and used for CES applications [115]. Moreover, the community can be distinguished between localized and virtual community [116,117]. Feldheim energy community provides a typical example for the localized CES whereas SonnenCommunity® serves as an example for the virtual CES [20,115]. As presented in Table 3, shared residential energy storage, shared local energy storage and shared virtual energy storage are three promising CES configuration [92]. Each configuration presents different socio-technical dynamics which will be discussed further in Section 3.

CES is being deployed worldwide, Germany, US, Japan, China and Korea being the market leaders [51,70]. Different countries have different social such as governance and legal as well as physical conditions for the development and implementation of CES. Existing and new local energy initiatives offer a strong platform for the deployment of the thermal and electrical energy storage systems [20]. Yet, very few local energy initiatives are engaged with energy storage, as CES is still in its infancy. There are still very few operational and demonstration projects being implemented worldwide in different forms and applications [118]. Some of these initiatives are local whereas others are virtual. In this Section, examples of initial projects on different CES configuration are provided.

2.5.1. Shared residential energy storage

There are very few cases of shared residential energy storage in practice and several pilot projects are being implemented worldwide to demonstrate this configuration. However, it is going to speed up with the digitalization of energy sector through advancement in information and communication technologies, micro-grid technologies, energy management platforms and internet of things [119]. For example, in a 47 household energy community in Heeten, The Netherlands, 24 households are being equipped with 5 kWh residential energy storage [68]. The households can optimally share energy storage for the collective benefits such as peak shaving, higher self-consumption of local generation and lower energy costs. One of the several pilots being implement in US is the Sacramento Municipal Utility's Anatolia III solar smart home community home project consisting of 15 residential batteries of 7.7 KWh each [120]. However, this pilot is utility owned and controlled and local communities have no roles and responsibilities except being able to monitor their daily electricity consumption as well as export. In Bangladesh, Solshare® interconnects solar home systems (SHSs) and energy storage through peer to peer energy trading platforms [121].

Solshare® has partnered with Gramin Shakti, a micro-credit enterprise for financing of solar panels and energy storage. It utilizes mobile payment systems which is also a prime example of south-south technology transfer which was first launched in Kenya and Tanzania [122]. The bottom-up swarm electrification and energy storage approach allows each villagers to become energy entrepreneurs and take control of their energy system. Solshare is the evidence of the undergoing energy transformation in developing countries and co-operation among different actors towards decentralized, decarbonized, democratized and digitalized energy systems. This innovation is seen as an important steps and contribution towards providing universal access to energy [123].

2.5.2. Shared local energy storage

Shared local energy storage refers to collective energy storage in a localized community. Although utility scale application of bulk energy storage is common, shared local energy storage are emerging in the energy landscape. For example, since 2015, Feldheim energy community owns 10 MWh CES.

Feldheim energy community is a pioneering example of self-sufficient energy community [20]. It achieved its energy independence through local generation, energy storage and even private energy network. The energy system is gradually increased to the size of 81.1 MW_p Wind, 2.25 MW_p Solar PV, 500 kW_e/ KW_t biomass plant and 10 MWh energy storage [20,82]. The energy community meets all its energy demand locally and sells surplus generation to the national grid. In fact, Feldheim energy community had to build its own parallel electricity network, after the initial attempt to lease the network from the incumbent utilities failed. Hence, it owns a community electricity and heating network and is independent on demand side from the national electricity network. This alternative arrangement led to one third lower energy prices which is independently determined by the energy co-operative irrespective of the retail prices at the centralized energy system.

In 2015, the German wind turbine manufacturer, Enercon, and German wind developer, Energgiequelle and Feldheim energy community jointly developed a 10 MWh energy storage for local balancing and to stabilize the electricity network of German transmission system operator 50 Hz [20]. In other words, this CES provides frequency regulation for the transmission system operator. The co-ordination and interaction between energy systems actors and the energy community led to this new business model and application. This case is a good example for the potential role of local energy initiatives and energy system actors to develop CES.

Table 3
Different configurations of community energy storage system.

Storage type	Descriptions
Shared residential energy storage	Network of residential energy storage of size up to 20 kWh installed behind the meter and EV batteries in consumer premises which can be shared among the community members of a specific location via the local physical grid. Example: Gridflex Heeten [68]
Shared local energy storage	Energy storage of size tens to hundreds of kWh installed in front of the meter and behind the transformer in the local neighborhoods with community ownership and governance as well as shared via the local physical grid. Example: Feldheim energy community [20]
Shared virtual energy storage	Network of decentralized stationary and mobility oriented energy storage installed at different locations with independent ownership and governance which can be aggregated and virtually shared at national and international level via the main grid based on the market design and regulation. Example: SonnenCommunity® [115]. The size of the individual energy storage units is identical to that of residential energy storage or local energy storage. The range of virtual energy storage depends on the capability of the digital networking platform. For example, in Germany, growing number of more than 10,000 end-users are associated with the SonnenCommunity®

2.5.3. Shared virtual energy storage

Due to liberalization and restructuring of the energy sector, there are number of virtual energy storage networks being developed worldwide [115,124–127]. For example, in Germany there are already few commercial practices in virtual energy storage such as Sonnen-Community®, Lichtblick – Schwarmbatterie® and Nextkraftwerke®. Similarly, Storenet project in Ireland and virtual power plant project in Adelaide are demonstrating this CES configuration [124,125].

SonnenCommunity® is a growing network of above 10,000 end-users in Germany who produce, store, use and share energy [115]. Independent of the established utilities and location, it is a community of producers, consumers and energy storage owners who can supply each other with self-generated as well as stored electricity. In this way, SonnenCommunity® function itself as a utility. The surplus electricity that cannot be consumed or stored at virtual community members' premises is shared online among the members of the Sonnencommunity® all over Germany and beyond. Distributed generation, energy storage technologies and digital networking are the three basic building blocks of the SonnenCommunity®. A robust, self-learning software platforms connects the members of the Sonnencommunity® with each other and ensures real-time optimal energy balance within the virtual community network and minimizes the balance responsibility [128]. Similarly, The Lichtblick-Schwarmbatterie® are interconnected via the smart platform Schwarmdirigent®, enabling energy sharing between member consumers [126]. The locally produced energy can be stored and consumed when there is need. The NextKraftwerke®, virtual power plant, connects producers such as biomass, wind and solar power plants as well as energy storage with the consumers [127]. It digitally aggregates distributed units and the power and flexibility from these networks is valorized in different energy markets. For example, Nextkraftwerke® has total networked capacity of 4200 MW and can even balance frequency fluctuations of the grid.

2.5.4. Initial projects in CES

Several pilot and commercial projects are being developed worldwide in order to demonstrate the added value of the CES, Table 4 [20,69,129]. For example, in the Netherlands, distribution system operators are installing CES in collaboration with local communities with the aim of maximizing self-consumption of local generation as well as to identify suitable conditions for operation of CES [69,129]. Recently, bottom-up initiatives through local energy communities on energy storage can also be seen in the Dutch energy landscape, such as Gridflex Heeten [68]. In Feldheim, CES provides primary frequency regulation for transmission system operator, as discussed earlier in this Section [20]. Within the framework of sustainable community energy networks (SCENe) project, a largest CES in the United Kinddom has been installed with the aim of optimizing energy storage use for grid services as well as self-consumption within local communities [130]. SonnenCommunity® enabled by distributed generation, energy storage and digital networking, is a virtual community of 10,000 members in Germany which even functions as a shadow utility. SonnenCommunity® is rapidly expanding to other countries such as Austria, Italy, The Netherlands, Switzerland, United States as well as Australia.

2.6. Applications of CES

Based on techno-economic and energy system perspectives, CES can have different applications for the local communities and the larger energy system, as summarized in Table 5. These applications range from local balancing to integration of variable renewables, grid support and ancillary services. CES combined with demand side management can lead to higher self-consumption of local generation and reduce grid imbalance of supply and demand [92]. The added value of community energy storage include improved operation of energy systems, reduced network investments, reduced primary energy consumption, energy security and reduced environmental impacts [16]. Often, these added values needs to be stacked to have a viable business case for CES [32,99]. New social, environmental and institutional added values never envisioned before could emerge through interaction and co-ordination between actors in CES. For example, CES might lead to social cohesion and community trust as well as enhance sustainability, resiliency and autonomy.

CES is gaining attention in the transitioning energy system. CES technologies are gaining maturity thanks to rapid pace of electrification of transport sector and decarbonization of the energy sector. The changing energy landscape also favors the emergence of CES. Yet, design and implementation of CES is a social learning process. As pointed out earlier, most of the research have limited focus on techno-economic aspects such as energy system balancing, arbitrage and grid services. The added value assessments also focus on techno-economic gains for the traditional energy system actors. It is also important to understand the social, environmental and institutional dynamics of introducing CES in the energy system as well as added value to the local communities, as discussed further with the aid of boarder frameworks in Section 3.

3. Understanding the dynamics of community energy storage

3.1. System innovation and socio-technical transitions frameworks

Given the focus on energy system transformation and energy transition, several socio-technical transition and innovation theories, in particular the Technological Innovation Systems (TIS), Multi-level Perspective (MLP) and Strategic Niche Management (SNM) frameworks might help to better understand the interactions and dynamics of CES, Table 6 [30,131–133]. Several scholars have successfully applied these theories in community energy as well as sustainability transition research, demonstrating their potential application for CES [132,134]. In practice, the theories and methods that are applicable to community energy systems in general are also applicable to CES and vice versa. Often, CES forms the part of the wider community energy systems with local generation and demand-side management. These theories are heuristic and are continuously being evolved with ongoing research as

Table 4
Initial projects in community energy storage.

Location	Size/number of households/configuration	Year	Objective	References
Rijsenhout, The Netherlands	128 kWh/35/shared local	2017	Maximizing self-consumption of local generation	[129]
Etten-leur, The Netherlands	230 kWh/200/shared local	2012	To identify the conditions of reliable, affordable and sustainable energy supply through CES	[69]
Heeten, The Netherlands	120 kWh (24 households with 5 kWh each)/47/shared residential	2017	To develop an innovative business case for a local energy market	[68]
Feldheim, Germany	10 MWh/10 MW/37/shared local	2015	Primary reserve for transmission network operator (50 Hz), local balancing	[20]
Trent Basin, United Kingdom	2.1 MWh/120 Households (greenfield)/ shared local	2018	Optimization related to grid services and community consumption	[130]
SonnenCommunity®, Germany	Virtual community of 10,000 members with 2 to 16 kWh energy storage units / shared virtual	2013	Share self-produced and stored energy with other community members	[153]

Table 5
Different applications of CES in local communities and larger energy system.

	Applications	Explanations
Local communities	Higher self-consumption and integration of variable distributed energy resources	Reduce mismatch between local supply and demand as well as to increase local renewables self-consumption [96]. The impacts are local balancing, security of supply, reduced energy dependence and lower emissions
	Peak shaving	Peak shaving community energy demand or supply [96,177]. The impacts are reduced network and energy costs, deferral or prevention of grid reinforcement
	Economic incentives	The local communities can benefit from arbitrage, i.e. the price fluctuations in the energy markets [178,179] or avoid peak prices, regulated costs, surcharges and taxes
	Seasonal storage	Long term energy storage with reduced energy dependence on fossil fuels [151]
	Emergency services	CES can provide energy for essential services during disaster or emergency
	Sustainability, self-governance and autonomy	Self-governance and ownership of CES leading to sustainable and autarkic local energy system
Larger energy system	Energy and network services	Grid support, ancillary services, operating reserve flexibility provision and congestion management [97]. For example, Feldheim energy community provides grid services to a transmission system operator through its 10 MWh energy storage [20]
	Network reinforcement deferral	Defer network investment due to local matching of supply and demand

well as practices and are not based on a single discipline but draw concepts and insights from multiple disciplines and practices. Moreover, these theories appreciate non-linear nature of socio-technical innovation, rather than traditional linear technology-push model of innovation and give adequate importance to key elements such as actor networks, institutions, social practices, businesses as well as socio-economic and technological characteristics.

The TIS framework is traditionally used to study the emergence and growth of new technological fields and industries [132]. It focuses on understanding the dynamics of innovation based on the performance of the surrounding technological system. The key structural elements of TIS framework are actors, institutions, interactions and infrastructures. Its key functions include knowledge development and diffusion, market formation, goal formation, resource mobilization as well as entrepreneurial activities [135]. This approach monitors key structures and functions to identify weakness and improve them. Some critiques of TIS are limited attention to external structures, its delineation, not enough coverage of geographical issues, its usefulness in analyzing transition, marginal role of policy as well as normative issues and policy recommendations [132]. Recently, some scholars discuss the prospects of TIS approach in analysis of socio-technical transition [132].

The MLP framework includes a broader societal context than the TIS framework and is widely being used to study socio-technical transitions [136,137]. This framework recognizes the co-evolutionary development of technologies, institutions as well as social and economic systems. According to MLP, socio-technical transition emerge through interactions at three structural levels, namely socio-technical landscape (macro), regime (meso) and technological niches (micro) [30,131]. Landscape level consists of macro-economic and political developments as well as deep cultural patterns and it is changes in this level which exerts pressure on socio-technical regime and technological niches, stimulating further socio-technical transition. Regime level is made of current practices and routines including dominant rules and technologies and often presents barrier to new technological and social innovation. The niche level is loosely structured and is less influenced by market and regulatory structures, hence, providing favorable conditions for experimentation and radical innovation as well as interaction among the actors of socio-technical innovation.

MLP serves as an useful framework to study CES as it considers interactions between niche innovations and existing regimes [138]. In other words, it conceptualizes technological change as process of niche innovation competing with incumbent socio-technical regimes [131,139]. It helps to better understand socio-technical transitions, emergence of innovation as well as shift of the incumbent regimes towards sustainability [134]. It is also concerned with transformative societal processes and focuses on prospects and dynamics of boarder

Table 6
Comparative analysis of TIS, MLP and SNM frameworks.

Frameworks	Key characteristics	Limitations	Relevance to CES
Technological innovation systems (TIS)	Innovation occurs in the context of entire systems consisting of actors, institutions, interactions and infrastructures. Focuses on dynamics, system functions and prospects of a particular innovation and its diffusion.	Technology is judged based on the performance of TIS. Cultural and demand aspects are marginalized. System functions are more important than system changes and dynamics. Neglect smaller actors such as grassroots initiatives, local communities and citizens.	Relevant for the innovation in energy storage technologies as well as understanding different system actors and functions but limited attention on societal aspects. Innovation dynamics of CES depends on the performance of community energy system in which it is embedded.
Multi-level perspectives (MLP)	Socio-technical transition emerges through interaction at landscape, regime and niche level. Broader societal context than TIS as it recognizes co-evolutionary development of technologies, institutions, as well as socio-economic systems. Focuses on dynamics of variety of innovation and transition processes.	Overstates the stability of regime and landscape level. Neglects the role of geo-spatial factors Collaboration between niche and regime actors is not sufficiently considered.	Considers interactions between different niche actors as well as transformative societal processes. Changes in landscape and regime can enable emergence of CES. Classification of CES as niche innovation does not help to understand community level dynamics as well as collaboration with other energy system actors.
Strategic niche management (SNM)	Focuses on niche level of MLP and highlights importance of protected space and user engagement in early stage of technology development. Enables new technology pathways to penetrate regime level. Process oriented and gives importance to demonstration, experiment and learning.	Too much focus on internal niche processes at expense of external niche processes. Most SNM experiments are local-context specific and have not scaled-up.	CES can be steered by range of actors including citizens and local communities. Can generate learning about needs, business models, operation as well as technology imperfections of CES and strategies to overcome them.

transition processes and varieties of innovation. Yet, there are several critiques of MLP such as lack of agency, operationalization of regimes, overstating the stability of regimes, neglecting the roles of geo-spatial factors, bias towards bottom-up change models as well as socio-technical landscape as residual category [140,141].

The SNM framework suggests that sustainable innovation journey can be facilitated by appropriately designed technological niches which allow experimentation with the co-evolution of technology, user practices and regulatory structures [133]. SNM emerged partly from MLP with policy, normative and governance oriented focus, therefore, pay specific attention to the role of visions, development of actor networks as well favorable conditions for niche innovations and strategies for up-scaling niche innovations.

CES might be subjected to complex and manifold of influences under changing energy landscape with multiplicity of technical, socio-economic, environmental and institutional interactions with the energy system [42,82]. They have to emerge in changing energy landscape with rapid technological and institutional developments and consists of several interacting systems of socio-technical innovation. In this context, the collaboration between energy system actors and local communities is important to ensure continuity of energy supply. It is not clear yet whether CES will become mainstream in the energy system. As many regime actors are now also engaged with energy storage, one possible scenario is that they will take over CES. Yet, new energy policies and regulations focuses on empowering citizens and giving them more control on energy systems [10]. In such scenario, CES will be an important building block of the future energy system.

3.2. Community energy storage: A complex socio-technical system

Building upon above mentioned system innovation and socio-technical transition frameworks, CES can be broadly aligned in the energy system through three layers namely physical system, actor network and external environment including wider socio-technical context such as legislation and beyond, as illustrated in Fig. 3. There are complex and non-linear interaction and dynamics among different layers, actors as well as the technological components of CES [142]. The socio-technical configurations of CES differ in different types introduced in Section 2.5, namely shared residential, shared local and shared virtual CES. It depends on the energy storage technologies, digital platforms, energy management systems, actors and geographical scope as well as the corresponding social, political, market and regulatory conditions [143]. The technologies invested and topologies chosen collectively by the local communities as well as market and regulatory conditions are expected to determine the configuration of the CES. The availability of numerous distributed technologies, different social preferences, different energy consumption patterns, policies, as well as the existing institutions, make the design and implementation of CES rather complex. Accordingly, there are different ways to engage and involve different actors and institutions in the different configurations of CES, leading to interactions and dynamics in physical system, actor network as well as external environment layers

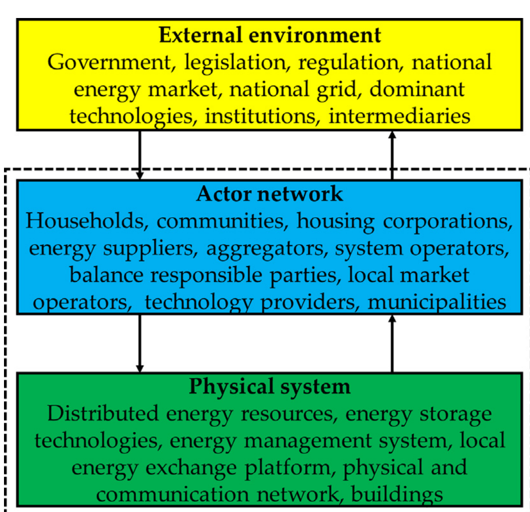

Fig. 3. Community energy storage as complex socio-technical system.

3.2.1. Physical system

The physical system of CES consists of storage technologies, the energy management systems as well as cloud services embedded with the community energy system consisting of distributed energy resources and physical networks. The physical system is likely to differ among different CES configuration introduced in Section 2.5. For example, the sizing and location of shared residential and shared local configuration are limited by the grid capacity and often contributes towards local energy balance and grid relief. The virtual shared CES does not necessarily consider this as limitation as it is the responsibility of distribution system operators to provide sufficient transport capacity according to the energy regulation. Moreover, the first two configurations are local whereas the third configuration is virtual and is dependent on wider physical energy network and deregulated energy sector.

The interoperability between energy storage technologies and the balance of the systems is crucial for the CES. In other words, the energy storage technologies and balance of the systems such as charge controllers, inverters and energy management systems needs to be compatible with each other. This demands for standardization as several different technology developers are engaged in research and development of the energy storage system components. Recently, more decentralized energy storage technologies and energy management systems have become affordable, further driving household and community investment in energy storage [144]. Furthermore, the technological configuration also needs to be adapted as the societal needs regarding energy storage changes such as electrification of transportation and heating as well as resiliency.

3.2.2. Actors network

The actors network of CES consists of different societal actors such as households, communities, housing corporation, local and national government as well different energy systems actors such as prosumers, energy suppliers, energy co-operatives, aggregators, system operators, energy service and technology providers, regulators as well as local and energy market operators. Similar to physical system, the actors network differ among the various configuration of CES introduced in Section 2.5. For example, for shared virtual energy storage, more actors from larger energy systems such as transmission system operators and balance responsible parties are more relevant to ensure energy balance in virtual communities than for shared residential and shared local configuration of CES.

These actors perform different activities such as production, storage, charging, discharging, balancing, trading and distribution and have variety of interests and functionalities. For example, CES can be used for local balancing through the physical network of community grid or distribution system operators depending on the grid ownership. At the same time, the surplus energy could be traded to the different energy markets through the aggregators. Yet, the actors are inter-dependent in the realization of their goals and different actors might have different expectations from the CES. For instance, households want low-cost and local energy at their disposal while aggregators seek to maximize the value of flexibility in the various energy markets. It is important to manage these conflicting interests and expectations. Moreover, the interaction and co-ordination among societal and energy system actors is important for the CES design and implementation.

3.2.3. External environment

CES is a decentralized and bottom-up initiative positioned in the socio-technical regime and landscape [131,133]. These socio-technical innovation are influenced not only by the local conditions but also by external environment consisting of different regulatory and market conditions, dominant technologies and institutions. These systems are governed by different national and regional energy policies which needs to be adequately considered to ensure its economic and effective operation. Different actors of CES and external environment interplay to steer and transform the activities of CES. The CES activities are influenced by technical attributes of external environment such as available technologies and grid capacity as well as attributes of community in which actors and actions are embedded and institutions which guide and govern the actors behaviors. This leads to patterns of interactions and outcomes which could cause different socio-technical issues in different types of CES. For example, the ownership model of the local grid as allowed by the energy regulation will affect strategic operation of shared residential and shared local CES in maintaining local energy storage. At the same time, if local grid is owned by the local communities, virtual CES might not get access to this local grid. Moreover, as political, social, economic and institutional structure are different, CES implemented at different place and time will have different impacts and need further analysis.

To summarize, CES is unique decentralized solution in the sense that it continuously has interactions and collaboration with other energy system actors and has to function in a multi-level institutional environment. The complex socio-technical representation of CES into physical, actor and external environment layers helps to understand different inter and intra-layer dynamics of CES. The functioning of CES depends on available generation and demand resources in the physical system and interaction between them guided and governed by the actor network. The external environment and the local conditions jointly determine the operational basis for CES. Hence, CES could have wider techno-economic, environmental and social impact in the energy system. In the following Section, we further analyze design and implementation of CES from the responsible innovation perspective to enhance the positive impacts and to minimize the negative impacts.

4. Operationalizing responsible innovation in CES

Including the demands of different actors at different societal levels, and different types of values such as affordability and sustainability asks for what is called responsible research and innovation (RRI). In other words, RRI aims at improving alignment of technological innovation and societal demands and values [34]. It aims to identify the imperatives and anticipate incompatibilities of societal and technological determinism and to counter unwanted effects. Stilgoe defines responsible innovation as taking care of future through collective stewardship of science and innovation in the present with the aid of its four dimensions, namely anticipation, reflexivity, inclusion and responsiveness [35]. Anticipation involves system thinking and recognizes complexities, uncertainties, and risks of science and societies [35]. It also shapes desirable futures and organizes resources towards them [145]. Reflexivity asks to include wider moral obligations in the roles and responsibilities of different actors. Inclusion refers to moving beyond engagement of stakeholders to the wider public. Responsiveness is the ability to change shape or direction with changing actors and public values as well as changing circumstances [35]. RRI asks for integrating and embedding these dimensions in the governance of CES.

Although the concept of RRI is not new, the ongoing energy system transformation towards decentralized, digitalized, sustainable and cooperative energy system is asking for its application to this domain. Only few scholars have applied this concept in the energy domain and found to be not yet influenced by RRI approach when considered globally [34,36,146]. However, detailed analysis do suggest more correspondence as RRI framework and socio-technical considerations share the same theoretical background [36]. According to Carbajo and Cabeza, the key RRI dimensions for energy system transformation are science education, public engagement, social justice, gender equality, ethics, governance, open access and sustainability [36]. Stigka et al. concludes that the responsibility approach in energy system is moving its focus from energy economics such as efficiency and circular economy towards social and behavioral approaches [36,146]. Innovation in CES can be regarded as shared and collective responsibility of its actors. The dynamics of interaction between its actors and the collective nature of innovation process in CES make it complex and unpredictable [147]. In the remaining of this Section, five different aspects of CES namely socio-technical innovation, markets and business, policies and regulation, roles and responsibilities as well as values are discussed where the concept of responsible innovation could be operationalized.

4.1. Socio-technical innovation

There are several socio-technical innovations undergoing in the CES due to its relevance for the energy system integration. These innovations are mainly driven by the development of the smart grids, cross-sector energy system integration, need for energy storage as well as decentralization in the form of local energy initiatives. In addition to these developments, different technical, socio-economic and political issues drive the socio-technical innovation in CES. Based on energy policy objectives, energy system integration requirements as well as grassroots energy initiatives, the key socio-technical innovation issues in CES are sustainability, interoperability, affordability, long term energy storage, energy system integration, energy system performance improvement such as through local energy balance and energy efficiency as well as relationship to the local communities [82,148–150]. The synergies, frictions and disruptions arising from these issues will shape the CES and the future energy systems. (Self) governance and ownership will lead to social innovation in CES.

The type, size and need for CES differ based on long-term and short-term demand to store energy. Short-term energy storage is important to achieve energy balance and higher energy efficiency, long-term seasonal energy storage will be essential for energy security and sustainability. The thermal energy storage research till date has focus on technology development and building integration and its application for local community has been given little emphasis [151]. Recently, there are some technical innovation for seasonal storage of heat, however, long-term electricity storage is still technologically challenging. Moreover, further technical innovations are desirable for harnessing the flexibility through integrated operation of heat and electricity storage systems. Other major issues in energy storage technologies in general are the limited availability of the raw materials, increasing demand for rare earth materials, limited production capacity, technologies for seasonal storage as well as the cost. Batteries used in energy storage will be the main contributor to environmental impact and faces recycling issues [57]. Significant improvements in materials use, sustainability, performance and costs are needed for CES to contribute in the energy system transformation. Moreover, considering responsible innovation perspective, human values such as safety, privacy, justice, access, equality, and sustainability also needs to be adequately considered in CES [36].

There are numerous attempts to improve energy storage technologies based on technological and societal (including economic and environmental) requirements. For example, with increasing volume, the sustainability of the materials used in the energy storage is increasingly becoming important. As discussed earlier in Section 2.5, two Dutch innovations in thermal and electric energy storage, namely Ecovat® and DrTen® are already embedding sustainability and economic values in their design. The subterranean thermal energy storage of Ecovat® has good storage capacity and long lifespan. The initial results of 10% losses over 6 months are promising for Ecovat® to become affordable seasonal energy storage [108]. It has potential to serve as the missing link in sustainability transitions of the local energy systems. Similarly, DrTen® sea-salt battery is considered to be a cheap and clean source to store energy due to the cheap, clean and abundantly present materials used in its production [105]. It has sea-salt as electrolyte and carbon as electrode. Its potential application are stationary household or community level storage as well as at the charging station for the electric cars. A charging and discharging cycles of more than 7000 cycles has been demonstrated. The main advantages of DrTen® sea-salt batteries are full discharge, clean and very low capital and operation cost [105].

From the actor network perspective, the reuse of electric vehicle batteries into CES has different implications in the socio-technical system, innovation pathways as well as design of battery packs. For examples, anticipating and envisioning the second life, the electric vehicle batteries packs can be designed to suit both mobile and stationary applications.

4.2. Markets and business

It can be anticipated that the changes in the external environment such as digitalization of the energy sector, coupling of electricity, transport and heat sectors as well as system integration can enable necessary conditions for CES. CES can synergize energy system integration and sector coupling leading to a more flexible local energy systems. Decentralized markets for flexibility, ease of market participation as well as community empowerment are expected to create better conditions for its implementation. For example, CES might provide grid balancing services for the energy system operators and earn additional revenues through the arbitrage. According to Mengelkamp et al., other promising applications includes grid-strengthening and management, network balancing, solving capacity issues, and autarky [152]. The market design of future energy system may provide an enabling environment for CES considering its characteristics to participate in these market segments.

In addition, community participation is essential in design, decision making as well as operation and management of CES. At the same time, introduction of energy storage with community participation may stimulate socio-technological changes in the energy system [150]. For example, CES might affect the program responsibility with higher self-consumption of local generation [153]. Program responsibility refers to the responsibility of the energy system actors on their programs for production, transport and consumption of electricity. Program responsible parties are expected to act in accordance with these programs which they provide to the system operator and face penalties if they do not comply with their submitted schedules. In addition, the local balancing enabled through CES might defer the investment required for the gird re-enforcement or CES might be utilized to mitigate local congestion [58]. New business and governance models may evolve reflecting upon these changes.

For the emergence of CES, business model innovation is a prerequisite [154,155]. These new business models need to tap and stack different value streams into a functional business case [32,156]. Moreover, these models needs to continuously evolve with the changing energy landscape [155]. As far as financing is concerned, CES will require customized approach and can be funded through several collective as well as public-private partnership such as local communities, municipalities, local co-operatives and banks [74,157].

Local energy markets and energy sharing platforms are important for the implementation of CES which in turn can substantially enhance their efficiency [74,152,158,159]. The local energy price determined through the local energy markets has to reflect all the capital costs, operation and maintenance costs as well as local network costs. The local energy exchange could take different forms such as peer to peer exchange further enabled by innovative and transactive blockchain based technologies [160,161]. At the same time, blockchain can bring security and trust among those involved and create concerns among those who are not the part of the system. There are already some platforms which enables peer to peer energy trading. For example, the Dutch platform Vandebron®, which means 'from the source', allows Dutch consumers to buy their electricity directly from the independent renewable energy producers [159]. Other examples for the peer to peer trading are Brooklyn micro-grid in United States, OpenUtility® in United Kingdom and SonnenCommunity® in Germany [115,160,162].

4.3. Policies and regulation

Energy policy and regulation have an important role in creating enabling conditions for CES. For example, CES cannot emerge in the environment where it is regulated similar to other sources of energy generation and consumption [163,164]. CES needs bidirectional energy and information flows as well as interactions among its several actors. In the centralized energy system with unidirectional flows this can be complicated. For example, energy sharing or trading with neighbors is difficult and grid access for CES can be long, complex and costly [74]. Although, annual residential net-metering in the Netherlands contributed towards higher uptake of rooftop solar PV, it is counter-productive for the adoption of energy storage. An energy policy for location-based net-metering in the other hand can incentivize higher self-consumption and local balancing, leading to higher adoption of shared residential and local CES [74]. Ideally, for both cases, the local communities need to own the community grid with distinct point of common coupling. Similarly, energy policies and regulation promoting virtual power plants and virtual energy communities lead towards higher adoption of virtual CES. This option rely on the main grid and in the deregulated energy systems system operators should ensure sufficient transport capacity. However, this is an important issues from the RRI perspective as it ask for fair and reasonable cost allocation for the use of the main grid.

New regulations are being developed around the world to promote energy storage. Some of these new regulations such as in the United states consider energy storage characteristics and provide enabling conditions for the emergence of CES [164,165]. In Switzerland, a new policy was released for community self-consumers [166]. In the Netherlands, postcode regulation (*postcoderoosregeling*), allows energy sharing among households within a postcode [167]. Spanish self-consumption regulation however, hinders energy storage and community energy storage is not possible to implement as energy sharing is not allowed [168].

Furthermore, the legislation needs to be flexible for the experimentation and development of socio-technical models specific to the local, social and physical conditions. A wide range of models for community ownership, participation, investment and governance needs to be permitted by the legal framework for experimentation. For example, it might be more responsible and less complicated to promote CES to deal with local congestion than the costly and time-consuming re-enforcement of the local grid. In the Netherlands, experimental regulation is in place to allow demonstration projects such as gridflex Heeten [68,169].

4.4. Roles and responsibilities

With the implementation of CES, the role of societal and energy system actors also changes. For example, as discussed in Section 1, the roles of citizens and local communities change from passive consumers to prosumagers. Local energy communities could even practice new roles such as aggregators, flexibility provider, energy service providers as well as network owner. The roles and responsibilities of energy system actors needs to be adapted for the management and operation of CES. The actors need to be anticipative, reflexive and responsive towards changes in the energy systems. In other words, actors interests also evolve and change overtime as new development such as new technologies, regulation and market mechanism gets established [42].

CES challenges existing centralized energy structures as well as regimes and creates opportunities for self-governance [170]. In the context of CES, (self-) governance refers to economic and administrative practices such as rules of collective decision making among its members [170,171]. The robustness of self-governance in commons has been previously demonstrated and its viability for CES depends on local energy communities' ability to co-ordinate with different governance circles as well as social and technical complexity of the energy storage technologies implemented [172,173]. For example, local communities often lack the technical skills for operation and maintenance of energy storage systems, providing roles for energy service companies or technology service providers. However, the management role still lies with the energy communities.

The ownership of CES is affected by different financing requirements, social welfare issues as well as the risk perceptions [116,174]. CES could be fully community owned or may be developed in partnership with public and private sectors [116]. Given the unbundling requirements, there are key discussions in Europe whether the system operators can own the energy storage facilities in future [10]. In such case, energy communities have important responsibility in ownership of energy storage facilities. Different social and energy system actors can co-ordinate and interact to co-create a smart local energy system. In this context, community ownership and governance of energy storage systems becomes very relevant. Yet, there can be resistance from the incumbent grid operator in providing grid access and for leasing or selling the physical network to the local communities operating CES.

4.5. Values

CES provides a range of values, for instance concerning technology, environment, responsibility and governance related to the local communities and the energy system [42].

The value streams in economic terms could probably be realized through collaboration with different energy system actors which in turn might lead to benefits never envisioned before. Sometimes multiple value streams such as local balancing and flexibility to larger energy system can be simultaneously harnessed which demands for interaction and co-ordination among different relevant actors [156].

But CES being unconventional ways to store energy may confront resistance from local communities and other energy system actors, which may have different values, concerning for instance ownership, profitability, safety or sustainability [34]. It can be helpful to consider varieties and dynamics of actor's values and interactions in (re) design of the technological system and the societal context for CES. The actors values might also be affected by the local context and the process through which CES is initiated. By this approach conflicting values can be identified early in the CES implementation and embedded in the socio-technological design through anticipatory actions and modifications, avoiding public controversy and resistance.

Several methods such as value sensitive design (VSD) and value case method (VCM) has been developed to align economic and non-economic values of multi-actor and multi-value system such as CES [34,41,175]. The ultimate aim of value case method is a decision for collective action with adequate consideration of multiple values of different actors and is implemented in four iterative steps namely, value identification, value quantification, value sensitivity and value alignment [41]. With respect to RRI, VSD offers a framework for stakeholders to express their values as well as design operational criteria to respect and include these values [34]. It facilitates consensus-building in CES through participation and thereby might increase its social acceptance.

5. Discussion and conclusions

In the changing energy landscape, CES is emerging as a decentralized socio-technical innovation. The way society perceives energy consumption, production and storage is changing with the deployment of distributed energy resources such as CES. With increasing generation through DERs and changing consumption patterns, the need as well as challenges for better alignment of supply and demand will grow and become increasingly difficult. CES has the potential to be part of the solution to confront the various challenges of the present energy systems. It might not only provide competitive energy prices and investment returns but also helps in fighting climate change, developing co-operation among neighbors and providing added-value to the local economy.

Yet, there are technological as well as social challenges at regime and landscape level for the integration of CES in the present energy system. The system innovation and socio-technical transition frameworks such as Technological System Innovation (TIS), Multi-level Perspective (MLP) and Strategic Niche Management (SNM) help to understand and study socio-technical dynamics in CES but cannot provide comprehensive assessment. Especially, categorizing CES as niche innovation is not sufficient to understand community level dynamics as well as collaboration between energy system actors and local energy communities. In the other hand, conceptualization of CES as complex socio-technical system helps to outline the co-shaping dynamics of actor networks and community level dynamics as well as important role of various technical and societal elements, such as governance, market structure, division of responsibilities as well as legislation. A socio-technical approach to CES development might lead to the systems that are more acceptable to end users and deliver better values to its actors.

Based on current developments, three configurations of community energy storage, namely shared residential, shared local and shared virtual, can be identified. Shared residential and shared local configurations are local specific, whereas shared virtual configuration has no location specificity and can expand to national level and beyond. Further development of these configurations depend on local conditions, policy framework, system of regulations as well as market conditions.

In Section 1, several unanswered questions surrounding community energy storage (CES) were raised. These questions were, what do we mean with energy storage at the local level, how many community energy initiatives are involved in CES, how can CES be shaped and organized, what are the contribution of CES in the energy transition, what are the conditions for the emergence of CES, and how can RRI be operationalized in CES? The rest of this Section summarizes how these questions are addressed in this article.

5.1. Local energy initiatives and CES

Despite, the increasing number of local energy initiatives starting to engage also with energy storage, there are very few examples of operational CES in practice and a few demonstration projects are being implemented. However, the growing number of local energy initiatives and the ongoing energy system transformation indicate a future in which CES could be prominent. Local pilot demonstration projects are crucial to show how CES works in practice, learn on new business and governance models as well to improve its public perception, acceptance and boarder participation. Energy storage at the local level also means more participation and control as well as responsibilities for the local communities.

Local communities can use and articulate energy storage in different ways depending on their objectives, as well as local, physical, market and governance conditions. Articulation and alignment of technological, social and normative aspects of both the communities and the energy storage goes on in design, implementation and operation of CES. Through CES and local energy initiatives, the transformative role of the local communities can be further enhanced, leading to the transition towards a sustainable, decarbonized, inclusive and decentralized energy system.

5.2. Energy transition and CES

CES is the missing link in the energy transition. It can provide effective means for energy system integration, flexibility and community engagement. It not only empowers local communities but also improves efficiency and strengthens the security of supply. CES can link local energy initiatives and centralized energy system, enabling the low-carbon transformation of the overall energy system. In this way, CES also helps to achieve climate and energy policy objectives.

CES operate in the changing energy landscape, where new technologies will become available, new institutions and actors will emerge and roles and responsibilities of the actors continuously change. Its contribution to energy transition should be assessed not in isolation but in terms of its interactions, dynamics and exchanges with the energy system and the local or virtual communities. Therefore, innovative value streams in synergy with the requirements of both the energy system and the local or virtual communities is required for CES to enhance ongoing energy transition.

5.3. Institutional pre-conditions for the emergence of CES

Current socio-technical configurations, including governmental, financial and regulatory systems at the regime level do not yet anticipate on the implementation of CES. New market structures, enabled through digitalization such as local energy markets where consumers can directly share or transact energy is leading to emergence of virtual CES. Furthermore, implementation of local CES might benefit from new energy policy as well as new legislation and tariffs structures such as time of use tariffs and location-based net metering. New organization and business models as well as coordination and interaction among community and energy system actors is prerequisite for the CES.

New roles and responsibilities will emerge with the emergence of CES. For example, the roles of local communities change from consumers to prosumagers. New actors such as intermediaries or energy service companies can help local communities regarding different CES configurations as well as comparison of their relative merits. They could play an important role in empowering households and local communities and may takeover tedious technical task from local communities.

To summarize, as both local and virtual CES configurations are gaining maturity, adjustments in all three levels namely physical, actor as well as external environment including regulation, legislation and culture is necessary. Enabling technical, regulatory, policy and market environment as well as suitable conditions for collaboration between social and energy system actors needs to be developed. In essence, the process of gaining maturity is a social shaping as demonstrated in existing pilots. These factors together will determine the emergence of community energy storage towards mainstream socio-technical innovation in the energy system.

5.4. Operationalization of responsible innovation in CES

Responsible innovation, including processes of value sensitive design as well as concepts of circular economy may provide a helpful approach to link various values such as affordability, safety, reliability, inclusion and sustainability in CES development. The RRI approach provides new discourse through community engagement and value considerations in design and implementation of CES.

This study focused on energy storage being shaped and enacted by the local communities. However, to see whether CES is a responsible innovation towards sustainable energy system may require further comparative investigation and review of alternatives such as utility scale energy storage. This study could be used as a basis to develop analytical framework to quantify the performance indicators for such comparison. Such assessments of CES should not be limited to economic benefits but also to wider societal and ethical aspects.

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