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Review Article

Analysis of barriers and key enablers toward citizen ESS successful integration

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ABSTRACT

Enabling energy storage systems (ESS) is a potential aspect of the energy transition toward decarbonising the energy sector. Despite the ongoing effort to analyse distributed energy resources enablers and key barriers, several gaps need to be addressed in the literature on accelerating the implementation of ESS at the citizen level. As citizens are now at the heart of the energy transition, analysing and meeting their needs and securing potential engagement in the energy transition is of utmost importance. However, this presents many challenges as it is more complicated to model and assess rather than institutions, organisations, and companies. This paper analyses the key barriers and enablers of ESS for citizen empowerment through the ownership and operational aspects of ESS. It evaluates various types of ESS at the citizen level, exploring their suitability and distinct characteristics in this specific context and thoroughly examines the key challenges, bottlenecks, and essential facilitators required for ESS citizen empowerment. It adopts a qualitative, bottom-up analysis of barriers and bottlenecks, providing a holistic view of the ecosystem. This comprehensive methodology ensures readers gain a complete perspective on the challenges present throughout the entire ecosystem. Also, it reviews good practices, examines key enablers, and suggests actions and tailored recommendations for diverse stakeholders, facilitating the comprehensive deployment of ESS as an integrated entity to empower energy citizens toward achieving an efficient and smooth energy transition.

1. Introduction

1.1. Citizen ESS

Citizens are at heart and the key player in the European Union (EU) clean energy transition [1–3]. However, compared to the other energy sector stakeholders, citizens as target groups have many specificities. Therefore, analysing citizens' needs and potential engagement in the energy transition is more complicated than dealing with organisations, companies or institutions.

Alongside this, a communication strategy is needed to foster the energy transition and market active participation of the consumers with competitive, affordable and sustainable energy. In November 2016, legislative proposals were presented in the Clean Energy For All Europeans Package (CEP) [4], covering energy efficiency, renewable energy, security of supply, electricity market, and specific EU energy governance rules. One legislation aims to create a market framework to ease share, consume, or sell energy among consumers/prosumers and enable them to participate in demand response directly or indirectly through third parties (aggregators).

In 2019, the EU concluded a complete update of its energy policy framework beneath the CEP. The EU agreed that the member states should place substantial measures to enforce the new rights accorded to energy communities (REC and CEC) in the revised Renewables Directive [5] and the revised Internal Electricity Market Directive [6]. This has been turned into national law and considered when suggesting their National Energy and Climate Plans (NECPs). This rule will bring significant advantages from an economical, environmental and, more

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importantly, from the consumer's perspective. Accordingly, the CEP is paving the way for a substantial transition toward empowering energy citizens, initiating energy communities and consumers' active participation in the European energy markets landscape [7].

When it comes to implementing distributed energy resource (DER) technologies, energy storage systems (ESSs) are technologically improving, the cost is going down [8], and different business models are developing; thus, energy citizens' interest is increasing in participating in the actual energy transition [9–11]. Therefore, the effective integration of DERs at the citizens' premises is highly important toward achieving a smooth and efficient transition.

In 2050, it is projected that variable renewable energy (VRE) share should comprise more than 60 % of total power generation, with energy storage being a key enabler for the energy transition [12]. According to [3], the global residential energy storage market is estimated to achieve a 22.88 % compound annual growth rate (CAGR) between 2019 and 2024. The global market value is estimated to reach 17.5 billion $ by 2024, compared to an estimated value of 6.3 billion in 2019. Thus, installation of ESS at citizens' premises will be vital. At the European level, the residential storage market is dynamically evolving. According to the 'European Market Outlook for Residential Battery Storage 2021–2025' report [2], more than 100,000 storage systems were installed in Europe in 2021, reaching the GWh scale for the first time. The market soared by 44 % in 2020 [1–3].

1.2. Motivation and contribution

Recognising that ESS for citizens spans a multifaceted landscape, it is intricately linked to several interrelated domains: Energy Citizenship, Demand Response (DR), and DEG. Each of these domains possesses its unique attributes and intricacies, as elaborated upon in Section 2 of this paper. Along with this, there is lack of a generalised picture that can inform better understanding of the overall benefits of the ESS citizens (please refer to session 3).

This study offers an extensive examination of the primary obstacles, bottlenecks, and pivotal facilitators necessary to successfully integrate ESS within the context of energy citizenship. It builds upon the groundwork laid in our previous article [13], where we concisely analysed the potential role of Distributed Energy Generation (DEG) at the citizen level.

One of the primary innovations presented in this paper lies in its comprehensive and qualitative analysis of the significant barriers, bottlenecks, and crucial enablers on the path to achieving successful integration of ESS with energy citizens. We recognise a notable gap in the existing literature concerning the examination of both the facilitating factors and obstacles related to ESS at the energy citizen level. This paper makes a substantial contribution to bridging this void. Furthermore, our study introduces a qualitative bottom-up review analysis of the barriers and bottlenecks, providing a holistic view of the ecosystem. Given that ESS for citizens intersects with a multifaceted landscape, closely intertwined with domains such as Energy Citizenship, Demand Response (DR), and Distributed Energy Generation (DEG), we have conducted thorough technical, regulatory, and policy research based on the aforementioned systems. These aspects are intricately connected to ESS energy citizens.

In addition, we put forward a set of recommendations tailored to various stakeholders. These recommendations aim to facilitate the full deployment of ESS as an integrated entity, empowering energy citizens to actively participate in and benefit from the evolving energy landscape.

The rest of this paper is organised as follow; In pursuit of a comprehensive understanding of ESS for citizens, this paper proposes a qualitative review and analysis. Section 2 delves into an examination of various ESS types at the citizen level, exploring their suitability and distinctiveness within this context. Subsequently, in Section 3, we embark on a quantitative review of the barriers, bottlenecks, and potential enablers, particularly emphasising DER and, more specifically, ESS adoption for citizen empowerment. Section 4 extends this review through a qualitative, bottom-up analysis of barriers and bottlenecks to provide a holistic view of the ecosystem. This comprehensive approach offers readers a complete perspective of the challenges within the entire ecosystem. Additionally, in Section 5, our analysis expands to explore strategies for mitigating these barriers and leveraging the potential enablers. Ultimately, the objective is to furnish tailored recommendations for diverse stakeholders, facilitating the comprehensive deployment of ESS as an integrated entity to empower energy citizens. Finally, Section 6 concludes this paper.

2. ESS technology

Three main types of residential ESS technology categories are available in the market for citizen-oriented applications:

- Battery-based ESS (BESS)
- Hydrogen-based ESS (HESS)
- Thermal-based ESS (TESS)

Pumped hydro storage technologies are more related to a large scale, and Mechanical still needs to be adequate for mature residential end-users.

2.1. Battery-based ESS (BESS)

BESSs have gained increasing attention in the last decade and have been widely installed within the citizen premises [14]. They use electrochemical technologies to store energy. BESSs can provide multifarious applications for citizens locally as well as at the broader power grid [15–17].

In 2019, 96,000 systems were installed in Europe, representing 745 MWh energy capacity and a 57 % year-on-year growth. The residential BESS market is expected to achieve a low growth rate from 2021 to 2024, leading to 1 million homes installation and around 7 GWh total capacity (compared to 270,000 systems and 2 GWh at the end of 2019) [14] (Fig. 1). The "100 % Renewable Europe" conducted by LUT University and SolarEurope showed that to achieve the 2050 renewable energy target in Europe, there would be a need for 1600 GWh distributed BESS system integration [14].

Today, the market distribution between European countries is unbalanced. Only five countries monopolise the market; 90 % of the novel residential BESS in 2019, have been installed in Germany, Italy, the UK, Austria, and Switzerland [14] (Fig. 2). Germany is the undisputed leader. The German market has evolved over the years, and well-thought incentive schemes are beneficial to kick-start the BESS market until it can stand on its own feet. This difference highlights the importance of assessing different driving factors even within EU countries.

2.2. Hydrogen-based ESS (HESS)

Residential HESS is an emerging solution. Social acceptance of hydrogen-based technology is increasing [18,19]. Hydrogen is produced from electricity via an electrolyser and stored in tanks. When an electricity supply is requested, hydrogen is then used to produce electricity via a fuel cell system. Fuel cell units can be used to generate electricity—moreover, they can integrate the heating system in residential dwellings [20]. HESS-based equipment is a well-known and established technology [21]. Nevertheless, residential and building integration is still early, and market uptake is limited [22,23]. In the report published by Stafell et al. in 2019 [23], the authors claimed that only 225,000 fuel cell-based heating systems had been installed in residential houses. Many research works have assessed the potential of residential hydrogen storage and fuel cell systems. Haneda et al. [24] have evaluated the use of hydrogen energy systems for primary energy reduction potential.

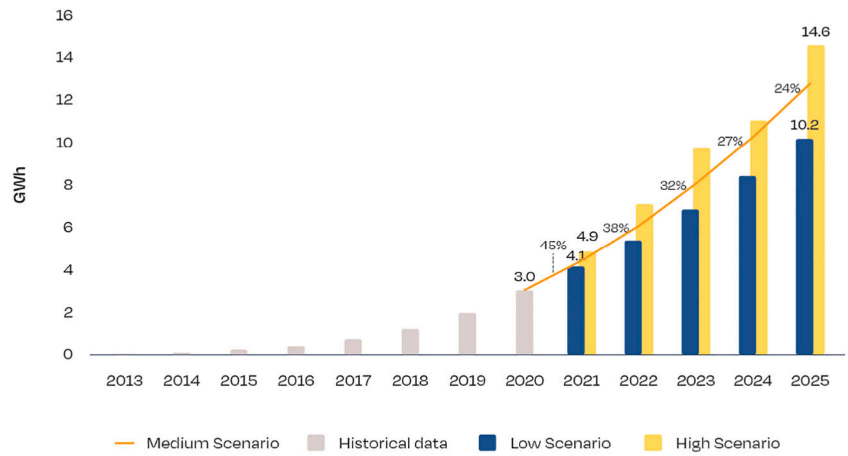

Fig. 1. Europe residential BESS annual scenarios– 2021-2025 (Europe, 2021).

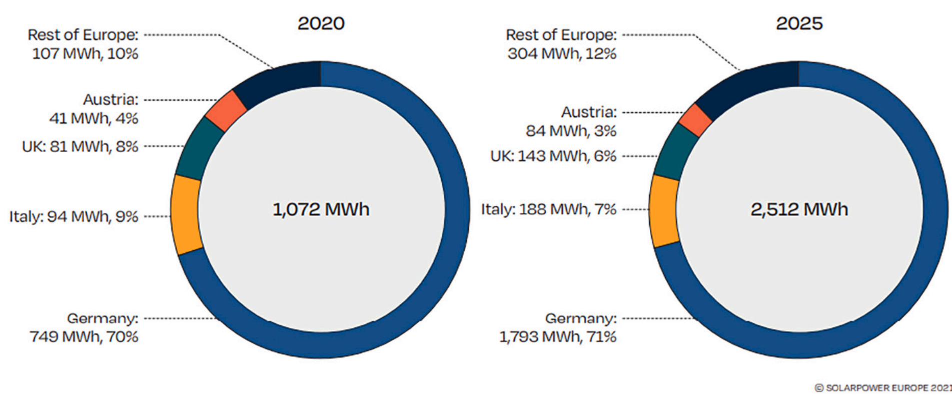

Fig. 2. Europe top 4 residential BESS markets (Europe, 2021).

Residential energy self-sufficiency has been investigated in [25]. The ‘EneFarm’ programme established in Japan presents an interesting pilot case study. Some trials have been developed in Europe to assess the performance of fuel cell systems for residential buildings. For instance, Callux (2008–2013) has integrated 560 fuel cell systems in residential houses in Germany. A larger-scale pilot has been developed through the “Ene.field” (2014–2016), integrating 1000 SOFC systems across twelve European countries.

In [26], it was pointed out that thanks to a better experience with manufacturing, the price of residential fuel cell systems is decreasing dramatically (85 % between 2005 and 2015 in Japan and 60 % between 2014 and 2015 in Germany). There are four types of fuel cells in the market: proton exchange membrane fuel cells (PEMFCs), solid oxide fuel cells (SOFCs), molten carbonate fuel cells (MCFCs), and phosphoric acid fuel cells (PAFCs). PEMFC is the most widely deployed technology for residential applications [27–30]. SOFCs have also shown a potential to integrate residential heating (1–3 kW). This technology uses high-temperature fuel cells and can be used for large industrial applications. SOFC benefits from more comprehensive fuel flexibility, high electrical efficiency, and greater fuel flexibility. However, this technology suffers from sensitive and dynamic operations issues due to the temperature requirements. PAFCs are widely used for commercial-scale heating. According to [18,31], around 400 systems were installed (85 MW) in the US, Germany, Korea and Japan. Though some demonstrations have been designed for residential [32], these systems were not brought to the market yet. MCFC is a high-temperature fuel cell technology. It is the market leader for large-scale stationary applications but inadequate for residential applications [30]. Table 1 summarises the main characteristics of PEMFC compared to SOCFC in residential applications.

Table 1
PEMFC vs SOFC for residential applications (Dodds et al., 2015).

	PEMFC	SOFC
Electrical capacity (kW)	0.75–2	0.75–250
Thermal capacity (kW)	0.75–2	0.75–250
Electrical efficiency (%)	35–39	45–60
Thermal efficiency	55	30–45
Lifetime (Year)	10	3–10

2.3. Thermal-based ESS (TESS)

TESS have a potential role in empowering energy citizen and paving the way toward decarbonising the electricity and the heating system. According to [12], buildings encompass around 150 Billion m^2, projected to reach 270 Billion m^2 in 2050. This will require an increased energy supply, and a big part of the supply will be destined for heating or cooling activities in the citizen premises. In [12], it was argued that 81 % of household energy consumption in the UK is related to heat, and domestic heating engenders 25 % of the total carbon footprint in the country. TESS technologies are well adapted to deal with the latter activities, and some technologies have been proven to provide economic benefits for citizens [12,33]. Thermal storage's main principle consists of capturing heat or cold energy from a substance (air, solid, or liquid), storing it, and releasing it when required. Three categories of TESS can be distinguished in a building: sensible, latent and thermochemical (Fig. 4). A detailed analysis of Thermal batteries using Phase-change material (PCM) technology for end-user and residential applications was presented in [12]. The report claims that, for residential heating, PCM-based TESS are a more cost-effective solution than electrochemical batteries. They can provide energy at about USD 0.05/kWh, 60–90 % cheaper than Li-ion BESS. Moreover, PCMs are well known to be non-flammable and non-toxic, which will ease their market integration in citizens' premises.

TESS holds significant potential in bolstering building energy flexibility and empowering citizens in demand-side management [34,35]. TESS Technologies can be used in conjunction with heat pumps and/or rooftop PV to electrify residential heating. Several trials have been developed. In Scotland, for example, 600 households have been involved in a pilot project where a TESS is installed in each one, and TESS have co-located a rooftop solar PV [12].

3. Overview of the state-of-the-art

Distributed energy resources (**DER**) include distributed energy generation (**DEG**), energy efficiency, demand response (**DR**), and distributed storage systems. However, variable energy resources (VER) englobes distributed and large-scale variable renewable resources. Fig. 4 shows that ESSs are a particular form of DEG and DR resources. Their peculiarities consist of their ability to perform both charging/discharging operations. In the case of charging, ESS can be considered DR; however, in the case of discharging, ESS can be considered as DEG. Thus, we propose a brief overview of the state of the art of the barriers and key enablers of DER at the energy citizens level in the first step. Then, in the second step, a deeper analysis of the literature for ESS is proposed.

3.1. DER at energy citizens' level

There is a constant endeavour to analyse the barriers and bottlenecks that inhibit the successful evolution of DER at the energy citizens' level. Literature is relatively rich, including peer-reviewed publications, project deliverables, public reports, etc. Some of the key findings are outlined below;

In [36]; the authors have identified five principal technical challenges:

- Lack of detailed DER modelling,
- Lack of interoperability norms and standards,
- New configuration and protection scheme,
- Increased control points and operation burden, and
- Stability phenomena.

The authors also emphasised the associated grid code and standards and the future role of the smart inverters to increase the DERs penetration at the citizens' level in supporting a smooth energy transition.

World Economic Forum (WEF) has analysed the prominent trends affecting the power grid, mainly electrification, digitalisation, and decentralisation [37]. This report also specifies a critical actionable framework for citizens to ensure a smooth, sustainable electricity system utilising grid-edge technologies. This framework is composed of four complementary: i) Redesigning the regulatory paradigm, ii) Deployment of enabling infrastructure, iii) Redefine the customer experience, and iv) Adopt new business models.

The International Energy Agency (IEA) report “Distributed energy resources for net-zero: An asset or a hassle to the electricity grid?” pointed out that, in addition to grid digitalisation, all other aspects of the power system require changeover for fostering valuable and beneficial DERs integration into the energy system [38]. Delloite Centre of Energy Resource [39] has also analysed the DER and VER integration challenges. It also described ten categories of solutions to encounter the integration challenges; i) Redesigning markets, ii) Accessing dispatchable centralised generation resources, iii) Improving forecasting, iv) Deploying energy storage, v) Tapping into dispatchable DER, vi) Optimising/planning DER location, vii) Boosting regional coordination, viii) Expanding transmission, ix) Testing new technologies, x) Modernising the grid.

3.2. ESS energy citizens' level

In parallel to DER barriers and key enablers analysis, there is a growing body of literature for regulations and policymakers analysing the role of ESS in the energy transition and the role of different stakeholders in smoothing an effective integration of ESS technologies in the energy citizen. However, the reviewed literature commonly points out that there are more viable solutions than ESS for a single residential application [9,10,33]. To address this gap, a few studies analysed removing market barriers and different policy interventions' impacts on residential ESS economic viability.

The residential ESS aggregation impact has been analysed in [40]. Authors in [33] have assessed the TESS potential in residential houses and concluded that multi-family homes could exhibit better scale efficiency and increase the financial offering than the case of single-family houses. The authors in [41] pointed out the role of the aggregator in maximising the value of residential energy storage systems; moreover, they showed that residential storage coordination could financially benefit consumers without the battery even more than battery owners themselves. The role of multiple grid services revenue stacking has also been highlighted in many works. For instance, in [42], a deep analysis is performed to identify the potential benefits of ESS from participating in the different market segments in Germany. The benefits of ESS coordination at the community level have also been assessed in [43]. The potential economic profitability provided by two different types of Li-ion battery technologies through an ageing model when used in a residential PV application has been analysed in [44].

To support ESS and ESS energy citizen efficient integration, a part of the literature has addressed policies and potential recommendations to engage citizens in the energy transition better and improve the value of energy storage at their premises. The authors in [45] discussed the regulations and barriers hindering ESS deployment. They proposed a novel regulatory classification of ESS as a “Flexible resource” to ease ESS integration in the power system. The role of policies in the EU, Canada, and US for enhancing ESS viability has been outlined in [46]. In [33], the authors have assessed the potential of the residential TESS solution. The authors claimed that these solutions are coequal performant to batteries for increasing house self-consumption. The authors also identified that there are now many financially mature and viable market-ready solutions available for citizens. In [47], the authors assessed the impact of different policies on PV-ESS financial viability for residential prosumers in the U.K. The authors have analysed potential approaches that can break down the barriers hindering ESS deployment in grid multi-service provision. In [48], the authors identified 16 investment barriers hindering the efficient integration of ESS technologies in the electricity market. Policy recommendations have been proposed toward removing bottlenecks for facilitating such a concept. In [41], four main policies have been recommended for the EU member states; 1) Actively promote a smooth and sound implementation of the provisions of the CEP in all member states to remove market distortions and to create a level playing field for ESS. This recommendation especially holds for the “active customer” framework with residential ESS. The member states must establish simple energy market participation forms for small-scale customers. 2) Leverage Next-Generation EU funds to enhance and prioritise ESS deployment, such as direct and indirect subsidy schemes. It should be supported through the establishment of industrial ecosystems that cover the whole value chain: from the establishment of processing raw materials, manufacturing cell and battery modules, to sale and install at the local level. 3). Acknowledge the pivotal role of distributed ESS in the energy transition. European and national policymakers should recognise this vast potential and promote distributed storage in their energy and climate plans. 4) Modernise the grid for storage to fulfil its full potential in providing flexibility to the energy system.

The authors in [49] discussed how redirecting feed-in tariffs toward residential battery storage can help reduce storage system costs. Moreover, they propose seven policy principles that should be considered while designing battery incentive policies to maximise the storage of social welfare. In [26], the authors suggest that policymakers should consider hydrogen storage in low-carbon heat policy analysis and propose to provide dedicated support to fuel cell and hydrogen based-storage technology, providing appropriate market design, support for innovation and industrial development of hydrogen technologies, and investment for keeping future technology options. In reference [50], the authors have enumerated four barriers hindering the use of hydrogen for residential applications: 1) electricity cost for powering the electrolyser, 2) lack of subsidies, 3) lack of production and distribution infrastructures investment, and 4) safety. The author also suggested developing a novel energy market paradigm where the oil price does not fix the electricity/energy cost. Creating a novel framework for incentivising emerging cross-sectoral technologies has also been proposed in [51]. Also, the authors in this paper suggested that policymakers introduce or strengthen CO2 levies to enable more integration of hydrogen energy systems.

The preceding examination of the current state-of-the-art literature reveals a predominant emphasis on the analysis of Variable Energy Resources (VER), Distributed Energy Resources (DER), and Energy Storage Systems (ESS) at a level higher than what is ideally required. A noticeable gap exists in the literature when it comes to the scrutiny of the factors that facilitate and hinder these technologies, particularly regarding ESS at the level of individual energy citizens.

In the subsequent sections of this paper, we embark on an exhaustive bottom-up analysis. We focus on meticulously investigating the primary barriers and bottlenecks while expanding our study to gain a deeper understanding of the critical facilitators and enablers essential to reaching a successful ESS energy citizen integration.

4. Barriers and bottlenecks - A bottom-up analysis

This section assesses the main barriers and bottlenecks hindering energy citizens from employing ESS in their facilities (Fig. 5). While adopting a bottom-up analysis, the technology maturity can be pulled out as the first barrier. On top of this, integration barriers are to be analysed. The integration issues will define the codes and standards to be implemented and should consider the cybersecurity issues. Thus, code and standards and cybersecurity barriers have to be examined. The citizen awareness of all the above and the benefits that can be gained from the residential ESS in the energy market is also critical barriers that should be looked over. Finally, and at the top level, comes policy barriers.

4.1. Technology maturity

The technology maturity of the ESS for energy citizens presents one of the main factors hindering the ESS deployment at the citizen premises. Our state-of-the-art analysis shows that The BESS is one of the most mature ESS technologies in the market. The technical merits are well known and established; however, the economic viability deployment on the citizen side is still questionable. Most of the recently reviewed literature concludes that BESS is still not profitable under the actual market conditions. Moreover, there is still a lack of understanding of the life cycle degradation phenomena, limiting BESS's full-value deployment. The HESS and TESS technology show less maturity for direct market uptake. As shown in Fig. 3, only a few TESS have reached the commercialisation scale (TTS, Solid-state, Ice). Other interesting TESS technologies are still in the demonstration or prototyping phase. The technology readiness levels (TRLs) for chemical storage-based and low-temperature PCMs TESS for heating/cooling citizen-oriented applications are still relatively low. Scaling down some TESS technologies, such as borehole thermal energy storage (BTES) and aquifer thermal energy storage (ATES), for small-scale applications is one of the challenges and can impact the storage unit's efficiency and performance [52]. The residential HESSs also suffer from low maturity. Currently, many HESS citizen-oriented products are at the prototyping and demonstrating stage. Despite implementing many HESS pilots at the citizen level, many pending challenges hinder the large-scale commercialisation of citizen-oriented HESS. LCOE is still high and has not yet reached the market competitive level. Hydrogen technologies' uncertainty and complexity still hinder representing of these hydrogen-based systems in the energy system models [53]. There is also a gap in assessing the full life-cycle cost and a lack of HESS efficiency analysis. For instance, it is to be noticed that PEM electrolyser efficiency is around 60 %, while PEM fuel cell efficiency value is between 40 and 60 %, which results in a 24 % to 36 % PEM cycle efficiency ratio; this can vary depending on the operating temperature and output power [12,54].

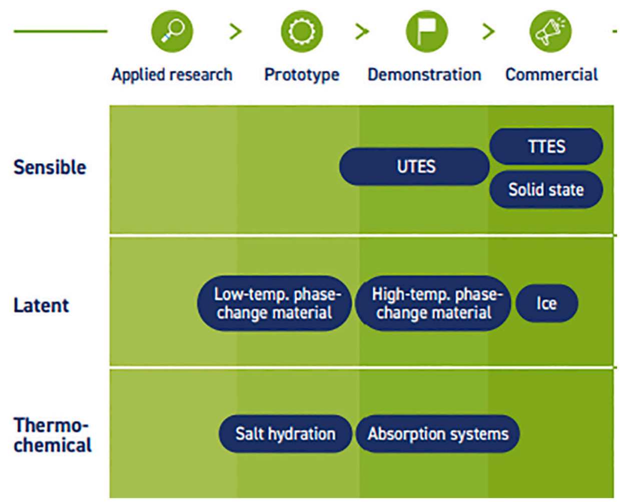

Fig. 3. TES technology status in the buildings sector (IRENA, 2020).
UTES: Underground thermal energy storage.
TTES: Tank thermal energy storage.

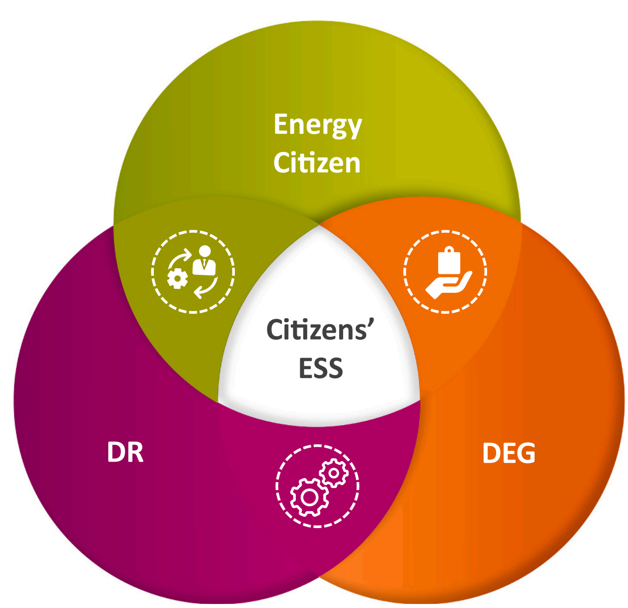

Fig. 4. Particularity of citizen' ESS relative to DR, DER and energy citizen.

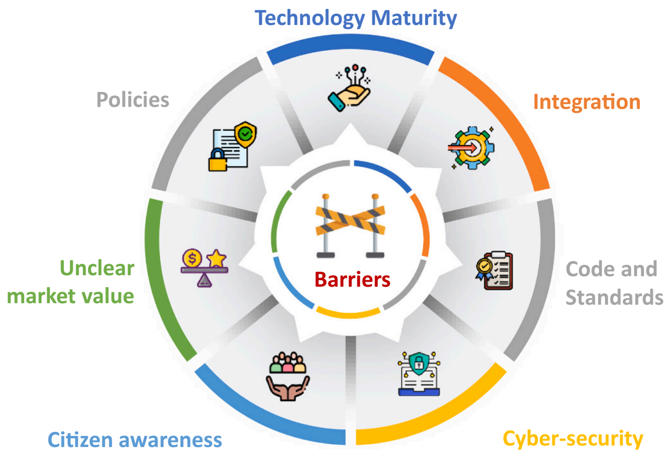

Fig. 5. Main citizen ESS deployment barriers– Relationships and structures.

4.2. Integration

Many challenges hinder ESS integration at the citizen level. The challenge of limited observability of ESS from the grid operator's perspective is a significant hurdle in achieving comprehensive visibility and ensuring its efficient operation within the distribution network [55]. Moreover ESSs at the citizens' premises are generally viewed as a net constant power load [36]. Power electronics converters are used to interface these ESSs with the low voltage distribution network (LVDN). The widespread use of these systems in the LVDN depends on the adequate understanding of their dynamics and the LVDN capability to incorporate a vast number of smart inverters to maintain the grid-supporting functionalities. It is also observed that with the proliferation of inverter-based ESS connected to the LVDN, the short circuit current issue can become more sensitive, requiring careful attention and monitoring [36]. To overcome this problem, the grid protection system, including sensitive sensors and relays, should be better-developed to enable and support a secure grid operation [36,56]. Another challenge associated with this mass integration of ESS is the harmonics induced by power electronics and switching dynamics. An unstable operation can happen at super-synchronous harmonics frequency. The impact of this unstable operation on the power grid and the root causes are still unknown. Thus, designing a consistent grid super-synchronous harmonics frequency stability analysis framework [36] is of paramount importance.

Along with the abovementioned challenges, the LVDNs are designed initially to support unidirectional power flow. With the high penetration of DER/ESS and depending on their functionalities, a bidirectional power flow can happen. Moreover, consumers' participation in the energy market could also lead to unstable operating conditions, impacting the ESS/DER deployment/integration and high penetration of clean energy at the citizen end.

4.3. Code and standardisation

Actually, there is an ongoing effort to develop and upgrade grid code for enhancing DER grid integration and interoperability as IEEE1547 [57], IEEE 2030 [57], and IEC 61850-7-420 [58]. The IEC 61850 and IEEE1547 constitute the preliminary documents for grid integration and required specifications for grid code and operation. These also contain some details on flexibility and choices. Some other standards have been envisioned for enhanced integration. Indeed, the IEEE 2030 and IEC 61850-7-420 suggest an enhanced framework for intelligent grid integration of DERs. The latter defines realisation and interoperability for associated ICT and IoT technologies [59]. The variety of integration and connectivity models, as outlined in the previous standard documents, is leading to the development of different industrial protocols. Specific connectivity measures, national/regional regulations and technical requirements might also be considered from the service providers' perspective. The co-implementation of the different protocols may become very challenging, especially in the case of cost/expenditure and cyber-security issues and thus deserve further research and innovation

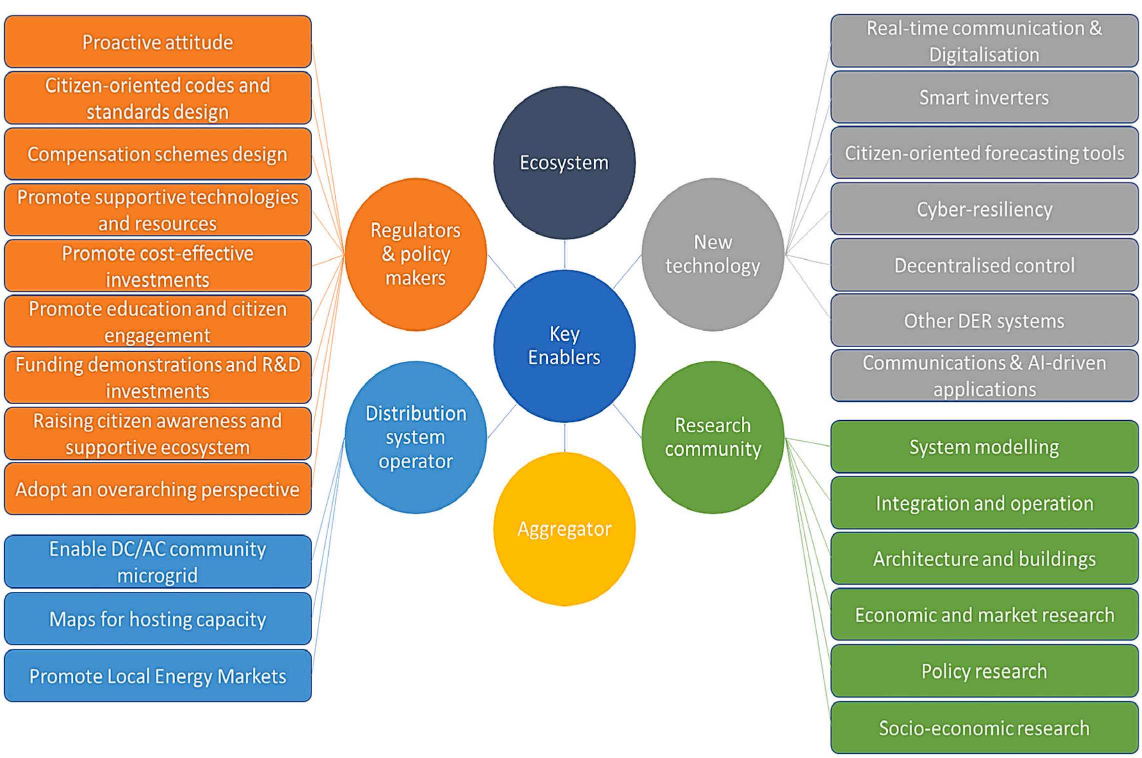

Fig. 6. Presentation of the interplay between essential enablers and players toward empowering citizen ESS deployment.

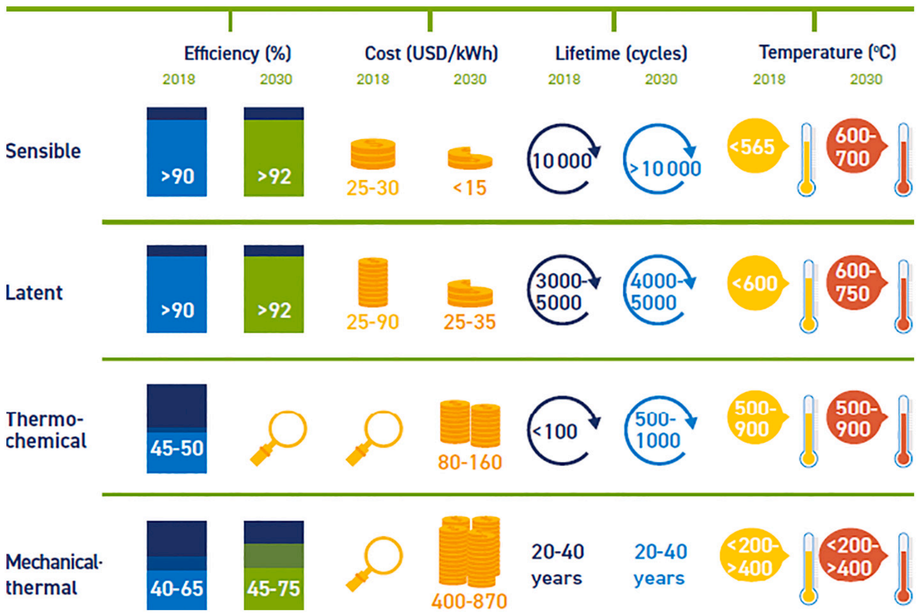

Fig. 7. TESS technology targeted performances (IRENA, 2020).

activities. Despite the development and maturation of integration, interconnection and interoperability standards, the market uptake of plug-and-play solutions for citizen-oriented ESS technologies requires a common standard [36,56,60].

The development of grid code and standards for DR and DEG has a direct impact on the ESS implementation. The safety standard is well developed, and the BESS is widely integrated at the citizen premises. However, additional barriers are raised in the case of TESS and HESS. In the case of TESS, there are still no common regulations for heat or cold. Moreover, there is a lack of building codes empowering non-fuel-based heating systems. Similarly, there is a lack of HESS citizen-oriented application codes, regulations, and standards, as well as interface technologies operating procedures ensuring safety and public acceptance of this technology.

4.4. Cybersecurity

The distributed ESS solutions at the citizens' premises and their communications for better operation to accomplish the desired function may increase the vulnerability of the main power grid [56]. In the analysis presented in [61], the authors claimed that over 70 % of DER devices might contain vulnerabilities, operator-side data leakage, insecure data transfer, and poor data breach response. Despite implementing the local cyber-security procedures and technologies, the distributed nature of ESS, their control and communication and the heterogeneity of cyber-security approaches can affect the security of the whole electricity system. Hence, the coordination among the cyber-security protocols and the event attack localisation are among the primary concerns of the grid network operators.

4.5. Citizen awareness

There is a lack of public awareness of how ESS can provide individual economic benefits and community and environmental benefits. In [49], the authors performed a study to analyse comment barriers for citizen BESS deployment. 23 % of respondents mentioned that BESS does not make financial/economic sense, 26 % claimed to lack knowledge about storage, and 14 % expressed concern about BESS's durability. On the other hand, and even compared to BESS, the public awareness of the potential of TESS and HESS on decarbonising the building sector is very low. There is less understanding of heating and cooling residential energy systems. In addition to the above, many social/demographic factors hinder ESS citizen deployment. In the previously mentioned study performed by Esplin et al. [49], the authors pointed out the impact of citizen demography and household structure. The authors pointed out that higher energy consumption households have more tendency to and willingness to install residential storage. For instance, single-parent households are less likely to deploy storage on their premises. Only 5 % of single parent household respondents expressed their interest in purchasing a BESS in the next three years compared to 13 % in the case of couples with children [49,62,63].

Last but not least, house renting also presents one of the main barriers to ESS energy citizen empowerment. Citizens are less likely to invest in residential storage in case they are not household owners. In the study [49], 35 % of respondents cited this barrier for not investing in household battery storage.

4.6. Unclear market value

The concept of energy citizens is still relatively new. Hence, the energy market framework for citizens still needs to be well established. Recently, transactive energy frameworks and several transactive management strategies, including peer-to-peer, were developed to allow citizens, especially prosumers, to actively trade the produced energy locally and optimise their DER social welfare output. Despite the vast potential of residential ESS, no clear market framework for residential storage has yet been established. As a new approach, the aggregation concept offers many opportunities for citizens to maximise ESS's value in the wholesale and ancillary market. However, this is coordinated through a centralised strategy.

The citizen market framework for decentralised/distributed ESS is also not yet established. Transactive energy and the local energy market are still in their early stages, and the complete value of citizen ESS in the market space is still to be unlocked. In the review paper [64], the authors have examined Peer-to-Peer, Community Self-Consumption, and transactive local energy market models. In broader space, five research gaps have been identified that require further analysis: i) physical/technical constraints of ESS integration into market mechanisms, ii) scalability and replicability of the market models, iii) market operation in a holistic approach, iv) security of information, and v) privacy.

4.7. Policy

Energy resources and their integration in the whole integrated energy systems are encountering an extensive and rapid revolution. The energy citizen concept is still new in the ecosystem environment. The entire value chain here needs to be well-known. The conventional energy/electricity systems and regulatory structures were designed around a well-known and static energy ecosystem where consumers' power delivery is guaranteed via centralised generation assets and unidirectional power flow in the grid. New players, such as aggregators, local electricity market operators, etc., are merging in the value chain, and the position of traditional stakeholders is thus altering. Responsibilities for most of the upstream generation systems (security of supply, grid stability, etc.) will be assigned to the distributed and local energy generations. This transition is made possible by leveraging the capabilities and functionalities of smart inverters and participating in citizen-driven programs such as Demand Response.

Network and market operators will have to deal with such new entrants. Therefore, the conventional regulatory structure is not sufficient to sustain this transition. It is also to be noted that there is siloed thinking among policymakers on how to promote each ESS category independently of the other one. Furthermore, there is a gap between the residential heat sector decarbonisation policies and the energy citizen sectors. This has created some unbalanced ESS citizen-oriented markets that can set a complex cost-competitiveness environment for some technologies. What is more, some conflict and a lack of harmonisation in policy design exist. For example, the low retail electricity price in some counties presents a major barrier to the residential BESS business take-off [65,66]. For instance, the electricity price for household consumers for the first half of 2022 is around 0.06 EUR/kWh in the Netherlands compared to 0.45 EUR/kWh in Denmark [65]. The cheap gas price in many EU countries affects TESS and renewable heat demand.

5. Key enablers and recommendations

New infrastructure, regulation, new business models, and customer engagement present one of the primary enabling factors for dealing with ESS citizens' empowerment challenges and unlocking the potential ESS/DER deployment opportunities. This requires stakeholders' (private and public sector, institution, technology providers, etc.) contributions and complimentary engagement in an ongoing effort in the coming days [59].

The relationship between the barriers and key enablers for ESS to empower energy citizens is presented in Fig. 6. The key enabling points and how they assist in suppressing the barriers are assessed further.

5.1. Role of new technologies

5.1.1. Real-time communication system and digitalisation system

The fast evolution of real-time communication and digitalisation systems (such as 4G, 5G) and their efficient market deployment present a potential opportunity to empower energy citizens. An effective communication system is the backbone of the energy transition. The development of digital twins and advancement in big-data management system technology also plays a key role in empowering energy citizens. At the same time, these offer efficient solutions for handling the vast data supporting the IoT and different user interface systems [67].

5.1.2. Smart inverter

The smart inverter in general, provides voltage and reactive grid support and incorporates fault ride-through control schemes. Its functionalities are needed to support more citizen ESS/DER integration and thus support increasing the grid hosting capability [68]. Hence, the latest version of IEEE Std. 1547–2018 outlines that inverter-based DERs are required to deliver autonomous control and protection functionalities and grid-supported communication-based operation [36]. A review of the trend of future smart inverter functionalities is described in [69], suggests that they should provide five principal functionalities:

1. Integrated system control functions (e.g., grid forming/feeding/supporting)
2. Integrated system protection functions (e.g., fault current blocking)
3. Distributed system stabilisation functions (e.g., virtual inertia, power quality)
4. Integrated sensing and measurement functions (e.g. phasor measurement unit (PMU))
5. Integrated cybersecurity functions

5.1.3. Citizen-oriented forecasting tools

Citizens have been active in participating in energy trading and markets. Hence, incorporating simple and adequate local energy generation and demand forecasting tools in the citizens' local energy management strategies is paramount to engaging citizens in managing ESS/DER technologies and energy trading activities. These tools are well-developed for larger VER/DEG/DER/energy market players. However, more adequate citizen-oriented, friendly-user tools should be designed.

5.1.4. Cyber resiliency

Protecting equipment and devices from likely cyberattacks is of paramount importance. Resilient cybersecurity tools and solutions are being developed to prevent complex cyberattacks. The new tools should be incorporated to the extent of ESS/DER systems. Rules and protocols have to be well defined for different types of ESS/DER in the citizen premises to guarantee the system security and safe and resilient operation of equipment and devices in case of cyberattacks.

5.1.5. Decentralised control

Compared to centralised control, decentralised control alleviates many computation, communication, and cybersecurity issues. It decreases the computational load, facilitates control implementation, and makes it feasible. On the other hand, it requires a high communication bandwidth. Overall, it reduces the required investment for computing and communication infrastructures.

5.1.6. Other DER system

There is a strong relationship between DER technologies. DEG, energy efficiency, and demand response (DR) potentially enable ESS at the citizens' level and vice versa. Pairing solar PV with batteries in citizens' premises increases self-consumption, reducing electricity imports from the grid [41]. Moreover, the ESS allows them to enhance the value of the DEG's value through participation in energy and balancing markets while exercising adequate control, including grid services.

5.1.7. Communication and AI-driven applications

Energy digitalisation is essential to integrate modern technologies, including information and communication technology, into the energy sector. Data-driven AI technologies can be a great tool to enable communication between smart grids [70], smart meters [71] and the internet of things [72]. However, to maintain the whole system's integrity, it is essential to develop a smart communication network that follows data authentication and information exchange at multiple points across the whole infrastructure with end-to-end encryption keys [73]. In addition, new communication protocols should be explored to facilitate the synchronization of existing and new equipment.

With the decentralised power system structures, inverters enabled with AI can provide a range of functionalities (grid feeding, grid forming, and grid supporting) [74] in the integrated system. Smart inverters can be efficiently used for reactive power control [75], grid stability and autonomous operation [69].

In recent years, AI has emerged as a potential tool to provide better and more accurate forecasts. AI techniques for forecasting provide insights into future circumstances and thus can be applied to automate and improve the performance of the smart grid. Neural network-based algorithms for local energy demand [76], day-ahead load profiles, renewable energy production [77], energy market prices [78], and energy storage operation [79] have been recently developed and are proved more accurate compared to classical methods.

With advanced computing and communication networking technologies, the exchange of data containing confidential information has become much easier. However, it is vulnerable and subjected to many cyber threats. AI can play a pivotal role in identifying, detecting, and alleviating cyber-attacks in the system. In recent years, AI has been implemented for malware identification [80], false data injection detection [81], intrusion [82] and energy theft detection [83] in smart grids.

Considering large shares of stochastic-natured DERs and uncertainties associated with them, effective controlling becomes very critical for the reliable operation of the whole system. The system complexities, communication requirements, level of control and energy resources, and hierarchical control scheme for different functionality is developed. Integrating AI techniques with existing control schemes can bring accurate and effective control and operation of the system. A whole range of AI applications in decentralised control schemes is discussed in [84], including energy storage state of charge (SoC) control [85,86], frequency stabilisation [87], power sharing [88], optimal control for hybrid storage systems [89] etc.

5.2. Role of distribution system operator

5.2.1. Enable DC/AC community-based microgrids

Community-based microgrids can play a key role in empowering energy citizens. Microgrids can deliver multiple services to the citizens, microgrid management/operator and the electric grid. It can improve citizen engagement and facilitate citizens' local generation exchange. The DC community microgrid can be a part of this transition also while facilitating the exchange of DC-generated power among citizens within the communities. Therefore, the distribution network's architecture must be developed to support the new community-based microgrid concept. This requires potential support from the distribution system operators (DSOs) [60].

5.2.2. Provide valuable and public access maps for hosting capacity

One of the main barriers that hinder citizen ESS/DER roll-out is the need for more information about the distribution network and its hosting capacity. Therefore, determining grid hosting capacity is essential for ensuring DEG's (including ESS) safe integration into the grid [90]. For a particular feeder, the hosting capacity index defines the maximum DEG generations that can be hosted or accommodated without adversely affecting the safe operation and reliability of the grid [91].

5.2.3. Promote local energy markets

To date, distribution networks are facing increasing challenges (poor power quality, voltage fluctuations, grid congestion, losses, etc.) due to the rise of DER, mainly PV self-consumption and electric vehicle penetration [92,93]. This will continue to intensify in the coming years. In fact, while the European '2030 climate and energy framework' seeks to reach at least a 32 % share of renewable energy consumption [94], countries such as Denmark aim to cover 100 % of demand with renewable generation by 2050 [95].

Therefore, local energy markets (LEMs) were proposed in order to face these challenges in geographically limited areas of the grid (neighbourhoods, small cities, towns, etc.) [96]. As explained, these competitive markets allow small-scale energy users to exchange energy with the grid to restore the balance between supply and demand in return for financial compensation. These LEMs have been developed in some European countries such as Germany, the Netherlands, Norway, Sweden and the United Kingdom [97]. Other countries are also considering proposals to introduce LEMs, such as Spain, Greece and Portugal, some places with the greatest potential for self-consumption installations [98–100].

Despite being at an early stage of development, the growth of these types of markets is clearly undeniable. Moreover, they are crucial not only for the energy transition but also for the development of smart grids [101]. Therefore, ESSs at the citizens' level are completely indispensable to assuming the role of LEMs suppliers because of their location in the distribution network. For this purpose, the DSO has to promote these LEMs markets among citizens and relax requirements for suppliers, increase transparency and coordination between the different stakeholders (transmission system operator (TSO), aggregator, suppliers, etc.) [67], and allow both centralised bids from aggregators and decentralised bids as in peer-to-peer energy-trading (P2P) [102] to increase citizen participation [103].

5.3. Role of aggregator

Aggregators are already established in the energy ecosystem and are important in promoting ESS/DER integration. They are the mediators between the consumers/citizens and the different energy market segments. Aggregation control mechanisms for the geographically distributed ESS/DER can mitigate some network constraints. Moreover, the functionality of the aggregator can increase competitiveness while stacking revenues from participating in different energy and flexibility markets. Furthermore, efficient coordination with the local network conditions can be enforced. Also, the economy of scale feature they show relieves the marketing cost. For instance, aggregated ESS/DER producers (such as VPP) allow the integration and implementation of advanced artificial intelligence optimisation techniques that help maximise ESS/DER benefits and social welfare. Also, with the fading of Feed-In Tariff scheme support, the aggregator will be at the centre of the energy market in promoting ESS/DER at the citizens' level. Therefore, competitive market frameworks should be designated for independent aggregators. The latter should also integrate mechanisms for conflict resolution.

5.4. Role of the research community

The research community will have a potential role in promoting ESS energy citizens via performing technical, economic, social and policy-oriented research to increase the maturity of the technologies [104]. A lot of work is required to develop more advanced and economic TESS and HESS materials and processes in order to keep down the manufacturing costs and LCOE. In the report [8], IRENA set a technical and economic improvements directory for different BESS technologies for 2030. A 2030 TESS maturity indices target has been proposed in (Fig. 7), also defining the next generation of residential TESSs [12]. Moving toward achieving the energy transition targets requires a skilled research staff as well as a good support research infrastructure. Moreover, a key role of the research community here is to build pilot and demonstration projects to prove the viability of newer technologies and methods and disseminate results to all citizen energy stakeholders.

5.4.1. Modelling

There is still a lack of knowledge of technology modelling and dynamics. ESS ageing is still an open research field. BESS ageing is one of the hot research topics today. Though being driven by other applications, accurate ageing modelling will enable unlocking the full value of the ESS for different applications [105,106].

5.4.2. Integration and operation

Efficient integration of the ESS within the citizen energy environment (Grid, DEG, DR, VER, other ESS, load) is highly important for deploying the ESS's full potential in the citizen premises. Appropriate sizing methods and energy management strategies have to be defined to fit citizen needs as well as to maximise the ESS's social welfare. This will also require developing methodology and appropriate tools to perform ESS valuation.

5.4.3. Architecture and building

Classic building architecture approaches were not adopted to such a transition in the energy citizen. With the development of different citizen-oriented application ESS technologies, many research questions have been raised: How should the novel building approach consider ESSs integration into the citizen premises? How should the building architecture approaches evolve to optimise the added value from different types of citizen ESSs?

5.4.4. Economic and market research

Another important research topic to consider is–how to evaluate the potential of ESS energy citizens within the different energy market segments? This will define the ESS citizen market priority and give recommendations to policymakers. Moreover, research should come up with a novel market framework approach to better adapt the energy system to a novel status where ESSs at the citizen level are a key resource in performing a secure electricity supply.

5.4.5. Socio-economic research

Performing citizen-oriented social research and defining potential interests and future trends within the different citizen categories is of utmost importance. This will inform regulators of public interest and align policies with citizens' interests. This is very important for successfully implementing novel policies. For example, the literature review mentioned that older people are less likely to use ESS in their houses [49,62,63]. This points the finger at the lack of social research in this field. Such a gap should be considered, and no one should be left behind.

5.4.6. Policy research

Policy research is pivotal in defining the optimal way to hinder technical barriers, aligning new technologies with novel codes and regulations, and considering policy objectives.

Modelling future policy scenarios and their potential impacts on ESS citizen energy is also of utmost importance. A proactive policy research approach should be adopted to keep policymakers and regulators informed and aware of the impact of their decision-making. For instance, research should suggest possible scenarios for future scenarios, explore the potential technical and economic of ESS citizens' integration, and report to regulators and policymakers on future trends/perspectives and recommendations.

5.5. Role of regulators and policymakers

To market uptake of ESS for citizen empowerment, regulators have to establish a strong legislative framework for energy citizens and communities as well as efficient support mechanisms. Aligning citizens' interests with total system costs cut-down is of high importance while designing policies (as proposed in Table 2). Through the solution, they suggest, regulators' guidance for program administrators, manufacturers, and market distributors, influencing and tracing consumer choices and perspectives. Measures include but are not limited to:

5.5.1. Proactive attitude

To empower the citizens and new technologies deployment, regulatory organisations and institutions should be more reactive and even proactive. Moreover, they should reinforce their communication links with conventional and new stakeholders in the energy system through the overall value chain. It is to be noted that here, citizens will be the leading players in this transition.

5.5.2. Citizen-oriented codes and standards design

To accommodate the new and advance technologies into the grid and

Table 2
Example of barriers to the exploitation of enabler vs. related gaps in financial support.

	Barriers to the exploitation of enabler	Related gaps in financial support
Policy	Siloed thinking among policymakers on how to promote each ESS category independently of the other one.	Policymakers should adopt a long-term view on citizen empowerment while taking into account the whole systems approach, enabling a cost-effective and smooth energy transition. Strategies should be implemented as part of a clear, integrated energy policy to avoid any conflicting measures and help realise higher benefits.
	Gaps between the residential heat sector decarbonisation policies and the energy citizen sectors.	There is a gap between the residential heat sector decarbonisation policies and the energy citizen sectors. There is less understanding of heating and cooling residential energy systems. This has created some unbalanced ESS citizen-oriented markets that can set a complex cost-competitiveness environment for some technologies. In [23], the authors suggest that policymakers should consider hydrogen storage in low-carbon heat policy analysis and propose to provide dedicated support for fuel cell and hydrogen based-storage technology.
	Conflict and lack of harmonisation in policy design.	Policymakers should define potential interests and future trends within the different citizen categories. Moreover, an overarching approach should be adopted to unlock the full value of ESS at the citizen premises.
	ESS forefront cost is still high	The necessity of establishing a robust legislative framework, as well as efficient support mechanisms. Aligning citizens' interests with total system costs cut-down is of high importance while designing policies.
	Lack of common code and standards for ESS-citizen	Policies should propose a common code and standards framework for ESS-citizen. Establishing a building code for ESS installation in the residence premises will enhance market uptake of the ESS solution and inform the citizen of the safety and reliability of their storage facilities. Moreover, there is a lack of building codes empowering non-fuel-based heating systems. Similarly, there is a lack of HESS citizen-oriented application codes, regulations, standards, and interface technologies operating procedures ensuring this technology's safety and public acceptance.
	The complete value of citizen ESS in the market space is still unlocked	Policies should be formed around transactive energy and local energy markets. These concepts are still in their early stages, and a solid regulatory market framework should be defined.
Regulatory	Building code and architecture	Classic building architecture approaches are not adopted to

(continued on next page)

Table 2 (*continued*)

	Barriers to the exploitation of enabler	Related gaps in financial support
		the energy citizen transition. Regulations and codes should define novel building approaches while considering ESSs integration in the citizen premises and how to optimise the added value from different types of citizen ESSs in this case. In the case of TESS and HESS, there are still no common heat or cold regulations.
	Uncertainty and complexity of the ESS	The uncertainty and complexity of some ESS technologies are hindering the representation of these systems in the energy system models [47]. There is also a gap in assessing the full life-cycle cost and a lack of systems modelling and analysis. Promoting demonstration and R&D is critical to show the viability of advanced citizen ESSs and pave the way for the non-delayed market uptake of the next technology generations.
Social	No clear idea about the full value of ESS	ESS energy citizen benefits, and support mechanisms, should be effectively communicated across all stakeholders. Different media types should be involved to mobilise all citizen categories to enable a cost-effective and successful energy transition. In [49], 23 % of respondents mentioned that BESS does not make financial/ economic sense, 26 % claimed to lack knowledge about storage, and 14 % expressed concern about BESS's durability.
	House ownership	House renting present also one of the main barriers to ESS energy citizen empowerment. Citizens are less likely to invest in residential storage in case they are not household owners. In the study [49], 35 % of respondents cited this barrier for not investing in household battery storage.

ease their integration and development, the existing grid code and standard must be updated to suit energy citizen empowerment. Tailored grid code can ease the use of new technologies, facilitate integration, and avoid any complexities at the citizen premises. The design should consider reducing additional construction costs and the complexity of populating these solutions/technologies into the market with improved functionality. A common code and standards for ESS-citizen will reinforce technical reliability and ensure manufacturing quality to bolster consumer confidence. Designing Grid code should consider not only actual energy citizens and grid infrastructures but also anticipate future requirements for integrating and decarbonising the whole energy systems. Establishing a building code for ESS installation in the residence premises will also enhance the market uptake of the ESS solution and inform the citizen of the safety and reliability of their storage facilities.

5.5.3. *Compensation schemes design*

Adequate compensation schemes could be introduced at the national/regional level to encourage citizens to engage efficiently in the energy transition. Rebates, grants, and incentives stimulate the market and can also encourage citizens to own ESS at their premises. Compensation schemes have a significant role in aligning the interests of energy citizens with the grid requirements and regulatory objectives. It will encourage citizens to locate and operate their ESS resources efficiently [107]. Support mechanisms can be developed to promote the commercial viability of early-stage technologies [107]. This strategy might not stimulate innovation but will facilitate the integration of new technology into the grid and align implementation to the required grid code and standards. Two types of compensation schemes can be adopted: Direct incentives and indirect incentives (Fig. 8).

a) Direct incentives/compensation scheme

ESS forefront cost is still high. Direct incentives and compensation schemes are necessary to encourage citizens initially to purchase ESS and reduce upfront citizen investment costs. Generous subsidies have allowed the Italian residential BESS market to achieve high development. The latter became the second-largest residential BESS market in Europe in 2016. Such Direct incentives/compensation schemes can include the following mechanism:

- Grants: Grants/rebates are classic mechanisms used to reduce the CAPEX of the storage asset. It is a direct and effective tool since it directly impacts citizen ESS investment decisions.
- Depreciation: Depreciation consists of a tax advantage scheme that can be allocated to citizens for ESS investment. A part of the investment cost can be deducted from a tax obligation. Although this minimises direct costs and is easy to implement, the visibility of the grant for citizens here can be lower and can be less effective than direct grants.
- Investment tax credit: This scheme presents an extremely effective approach for bringing down capital costs and reducing exposure to capital risk. Previous research has assessed the impact of ITC for storage in the US over ten years and concluded that, with a possible 20 % federal Investment tax credit value, the total ESS capacity could triple in contrast to no Investment tax credit being applied [104].

b) Indirect incentives scheme

Indirect incentive schemes will indirectly impact the profitability of ESS at the citizen level, even by maximising the revenue or creating market barriers for competitors in a carbon footprint framework.

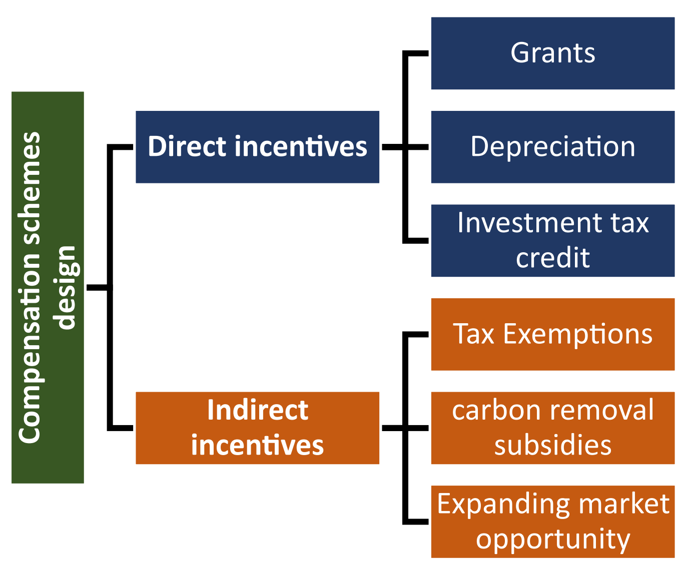

Fig. 8. Compensation schemes design for ESS' citizens empowerment.

- Tax Exemptions for citizen ESS application: Besides direct support schemes, tax exemption on electricity self-consumption or other ESS citizen-based applications can impact citizen decisions by more investment into ESS.
- Introducing a price on carbon and removing fossil fuel subsidies: This kind of indirect incentive scheme will create more barriers for fuel-based applications at the citizen premises. Thus, it will improve ESS storage, especially for heating and cooling applications.
- Expanding market opportunity: Encouraging novel electricity tariff mechanisms (as dynamic tariff) and incentivising citizen demand-side flexibility can create a novel opportunity for ESS citizens to maximise the value of their storage system. Another approach is to promote energy markets with larger auctions per day and shorter energy products, such as the continuous intraday energy market proposed in the XBID project [108]. These types of markets increase the gap between off-peak and peak-time prices [100,109] to create more room for citizen ESS to maximise their energy trading in the distribution network. The regulator can also prioritise energy services that match ESS citizen applications. Promoting transactive energy in the local energy market will play a potential role in unlocking the full potential of citizen storage facilities. Allowing citizens to capture the full value of their storage flexibility in competitive markets is of utmost importance to enhance citizen engagement and empower energy citizens.

5.5.4. *Promote cost-effective investments*

Reducing the investments is very important for sustainable development. It is crucial to consider that the market uptake of new technology will need various promotion forms to increase the network operation and the contestability of the electricity market.

5.5.5. *Promote education and citizen engagement*

Empowering energy citizens must engage all types of consumers, classes and categories and leave no one behind. Disadvantaged communities can benefit from such technologies and must rebuild a role in this transition. This has to be also accompanied by aligning and funding new education and behavioural support programs to educate and engage end-users about the urgent needs of the environment and enlisting their endeavour to support cleaner energy transition [56,110].

5.5.6. *Funding demonstrations and investing more in R&D*

As discussed earlier, the research community is called-out to invest a considerable effort to empower ESS citizen integration. Accordingly, regulators, on the other hand, have to define activities and programmes to encourage and promote research in this field. Moreover, in order to show the viability of ESS-based citizen solutions, increase citizen awareness, and demonstrate the low investment risk, further focus should be given to developing more pilot and demonstration projects. This should be done in parallel with promoting R&D and research activities funds. As discussed in the previous section, research for citizen-ESS includes such diverse areas. Promoting demonstration and low technology readiness level (TRL) R&D side by side is critical to validate research outputs in a real-life environment, show the viability of advanced citizen ESSs and pave the way for the non-delayed market uptake of the next technology generations.

5.5.7. *Promote supportive technologies and resources*

The full value of citizen ESS can only be deployed if it is efficiently deployed within DEG and DR resources within the citizen premises. Along with promoting citizen ESS, policymakers encourage the twining of ESS with other resources. Continuous development of residential PV should be considered. Heat pumps also present a potential DR system associated with different ESS categories, especially TESS. Supporting the development/penetration of DEG and DR resources will directly impact citizen ESS empowerment.

5.5.8. *Raising citizen awareness*

ESS energy citizen benefits and support mechanisms should be effectively communicated across all stakeholders. Different media types should be involved to mobilise all citizen categories to enable a cost-effective and successful energy transition.

5.5.9. *Providing a supportive ecosystem*

One main challenge is preparing and forming a qualified workforce to ensure a smooth energy transition. In addition, a proper ecosystem should be established by creating an adequate industry sector that can support this. The technologies' prompt change and evolvement need a continuing education and training scheme for highly specialised staff and engineers to support the implementation of the systems, protection, management, and maintenance. Moreover, the End of Life Cycles of the supporting devices should be well-defined [107].

5.5.10. *Adopt an overarching perspective*

Policymakers should adopt a long-term view on citizen empowerment while taking into account the whole-systems approach, enabling a cost-effective and smooth energy transition. Strategies should be implemented as part of a clear, integrated energy policy to avoid any conflicting measures and help realise higher benefits. Proposed policies and measures should have a clear spatial-temporal framework to avoid any uncertainties. Direct and indirect incentives/subsidies should be integrated and consistent, emphasising the ESS energy citizen's financial, environmental and pro-social benefits. All citizen dimensions should be considered when targeting citizens: social, economic, demographic, etc. The needs of older citizens are different from those of younger ones. Subsidies and support schemes should be tailored for the household owners as well as renters. Renting should not be a barrier to empowering energy citizens, and proper measures and policies should be adopted for this that will impact the whole chain from technology maturity to market value.

5.6. *Trustworthiness of AI*

In many developed countries, AI and its associated technologies have been in use for communication and management between smart meters, internet of things devices and smart grids. Though these technologies bring better management, improved performance, better utilisation of assets, and increased dependency on AI entail risks. AI algorithm complexities, huge dependency on data and the likelihood of unexpected behaviour of AI-based technologies require framework and methodologies that can guarantee technical robustness, transparency, explainability, privacy and accountability, non-discrimination and fairness. These elements are essential to understand and establishing trust in AI-based systems [111]. Therefore, responsible AI technologies should be developed and adopted carefully. Moreover, AI facilitates multiple service provisions, data, communication and operating systems, and security becomes crucial. Considerable research to resolve plausible vulnerabilities arising from the rapid uptake of AI technology is needed.

6. Conclusion

Moving toward a 100 % renewable European energy system has placed the citizens at the heart of the energy transition. Citizen-owning and operating ESS is the backbone of this. The efficient integration of the ESS at the citizen level is highly important. The ESSs at the citizen premises will benefit end-users and ensure a pivotal role in securing the grid's power supply and stability. The whole transition is still at an early stage due to many challenges, barriers, bottlenecks and knowledge gaps of a wholistic structure of ESS at the citizen level.

This paper introduced a qualitative bottom-up review analysis of the barriers and bottlenecks, taking into account a holistic view of the ecosystem. Seven main categories of barriers have been identified: integration barriers, codes and standards, cybersecurity, citizen awareness, unclear market value, and policy barriers. Each category has been thoroughly assessed, and key enablers to deal with hindering barriers and bottlenecks have been discussed for each stakeholder in a structured way. Moreover, we come up with recommendations for different stakeholders, such as the research community and policymakers, aiming to catalyse the full deployment of ESS as a holistic entity in empowering energy citizens throughout the energy transition.

While this study highlights that BESSs present one of the most mature solutions for citizen integration, it underscores that the complete value of ESS for citizens can be fully exploited only if all categories of citizen ESS are deployed in a synergistic and efficient way. It emphasises the need for proactive measures and coordinated efforts to achieve a cost-effective transition, enabling increased renewable integration and reduced citizen carbon footprint. Thus, this study calls for future endeavours to establish a unified framework for diverse citizen ESS technologies.

CRediT authorship contribution statement

Mohamed Bahloul: Conceptualization, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing, Formal analysis. **Rohit Trivedi:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Javier Cardo-Miota:** Conceptualization, Methodology, Writing – original draft. **Christina Papadimitriou:** Methodology, Writing – original draft, Validation. **Venizelos Efthymiou:** Funding acquisition, Validation, Writing – original draft. **Alireza Nouri:** Validation, Writing – original draft. **Shafi Khadem:** Funding acquisition, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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Data availability

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