

Battery circularity for community shared energy storage system: the new city-district of Dietenbach in Freiburg, Germany

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Research Article

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Abstract

In the coming decades, the need for the end-of-life (EoL) management of retired electric vehicle (EV) batteries is projected to raise especially in the countries that have achieved a rapid market uptake of EVs. This will create a huge challenge to develop appropriate strategies for sustainable EoL management of batteries. The focus of discourses and actions has largely been on providing purchase incentives and necessary infrastructure for the use phase of EVs, lacking a battery circularity perspective to meet the environmental and safety challenges of retired EV batteries. This study will apply insights from different strands of literature to address this gap, especially in a complex context when a range of sectors are technically and physically coupled with each other. In the light of battery circularity, the energy infrastructure planning for the new city-district of Dietenbach in Freiburg is studied to provide some practical insights into the role of battery circularity in using second-life batteries (SLBs) in the community shared energy storage (CSES) systems. The results show that SLBs provide affordable and environmentally responsible energy storage alternatives and the community groups, e.g., collaborative housing groups in Dietenbach are well suited as carriers for applying the battery circularity in the CSES models, which can be used as a solid platform to initiate and develop the notion of solar-based SLBs. Then, one of the key preconditions for sustainable CSES is to establish a uniform set of standards, guidelines and regulations for safe collection and transportation and reliable use of SLBs.

Science highlights

- End-of-life management of batteries as the backbone of battery circularity.
- Upscaling household energy storage to community energy storage necessary for energy transition.
- Neighbourhood as an important planning unit to establishing a community shared energy storage.
- Social inclusion key to sustainable community shared energy storage.
- The role of territorially based factors in enabling a circular community shared energy storage.

Policy and practice recommendations

- Policy support for appropriate end-of-life battery pathway in a battery circularity framework.
- Circular community shared energy storage requires an integrated urban planning.
- Policy incentives to support safe collection, transport and use of second-life batteries.
- Policy support for a common set of standards for the second-life batteries (SLBs) industry.
- Policy framework for scaling up niche innovations of second-life batteries to mainstream market.

1. Introduction

In the framework of urban energy transitions, different energy-related sectors are becoming significantly intertwined with one another to gain cross-sector complementary and synergies, in which a complex situation arises when many sectors are coupled. As the world moves towards more renewable energy sources (e.g., solar and wind) the central role of energy storage is becoming prominent. Energy storage systems (ESS) are key to balancing the supply and demand of energy in various sectors (Global Energy Community 2023). However, a community perspective to energy storage has been largely missing, and the debate has been rather on the obstacles of the operations of individual household energy storage than the benefits of community shared energy storage (CSES).

CSES systems consist of many PV-household prosumers (both producers and consumers of electricity) connected to a local energy storage power station to feed their surplus electricity into the grid (Li et al. 2022:4–5; Shen and Wang 2025:2). This study will discuss the potentials and challenges of applying battery circularity in promoting the CSES system by providing theoretical insights into different strands of literature and practical insights into the energy concepts for the new city-district of Dietenbach in Freiburg, southwest Germany. For the scope of this study, the Dietenbach city-district is defined as a community, which as an important planning unit can provide space for collective values and actions with the aim of addressing and solving local energy storage issues. The key research questions are:

- What are the key potentials and challenges of using second-life batteries in community shared energy storage systems?
- How can the socio-spatial context of the Dietenbach city-district support a battery circularity strategy to promote community shared energy storage systems?

2. Theoretical framework

This paper will conceptualise the results of current debate on the role of retired electric vehicle (EV) batteries in creating community shared energy storage (CSES) system by zooming out beyond the single system of EV batteries, in which the transition pathways and coevolution of multiple energy systems are discussed. The existing research supports the discourses of environmental benefits to reuse and repurposing the retired EV batteries in the second life application¹. However, there is limited research about the contribution of the battery circularity concept in enhancing CSES systems as both are relatively new research fields. Therefore, in this section insights from different but interrelated concepts of sector coupling, community shared energy storage and battery circularity are provided to examine both benefits and challenges of using second-life batteries (SLBs) in CSES systems.

2.1 Sector coupling innovations

Sector coupling refers to the electrification of different energy sectors through modern technologies, e.g. the transport sector through electric vehicles or the heating sector through heat pumps. As claimed by the scholars of the sector coupling concept (cf. Münster et al. 2020; Büscher et al 2020), the key aims of sector coupling innovations are: 1) to unpack the underlying causal processes of interactions between

different urban systems related to the production and consumption of energy services including the key elements of energy system (e.g., technologies, infrastructures, actors, institutions, policies, etc.); and 2) thereby gaining cross-sector complementary and synergies for low-carbon energy transitions.

The literature discusses a range of coupling among EV batteries and other urban systems and technologies to save energy, to reduce environmental pollution, and to create new business models, which might transform the existing business models for energy service delivery. Pranawengkapti et al (2025:1) discuss “the challenges and opportunities of sector coupling between energy and transport to maximise renewable integration in EVs”. The key forms of interactions are grid to vehicle (G2V) for charging EV batteries, vehicle to grid (V2G) for discharging EV batteries, vehicle to building (V2B) as a substitute for grid system for powering buildings and for mitigating fluctuations from renewable energies, and solar PV-powered EVs (cf. Cao 2019; Chen et al. 2020; Minuto et al. 2021; Huang et al. 2022; Wang et al. 2023). Coupling electricity and heat sectors may occur in different constellations, e.g., end-use electrical heat pumps; district-based Combined Heat and Power (CHP) and heat pumps; micro-CHP; electrolysis-based hydrogen heating, etc. (Münster et al. 2020:19). However, emerging resource flows among different urban energy systems calls for establishing a new institutional framework to support CSES systems, which also includes integrated ‘heat-electricity production & consumption’ in many forms. The CSES system primarily requires coupling between solar panels and storage system both on household and community levels.

2.2 Community shared energy storage system

Decentralised energy generation consists of both energy generation and storage system operated either by individual households or community members using a shared energy storage system, which can play a vital role in stabilising the grid system. However, the research has been largely focusing on enhancing the operations of household energy storage than developing the notion of community shared energy storage (CSES), which usually decrease the operational cost of photovoltaic electricity generation for the households. Research on household energy storage has not adequately addressed the benefit of sharing costs of battery usage despite the fact that shared energy storage, due to economies of scale, provides multiple prosumers with a lower capital and operational cost. In addition, shared energy storage systems are “easy to install and maintain, better fit into smart grid, and reduce power loss and energy costs” (Chang et al. 2022:2).

Khojasteh et al (2024:3415) define community shared energy storage (CSES) as “a solution to alleviate the uncertainty of renewable resources by aggregating excess energy during appropriate periods and discharging it when renewable generation is low”. Shen and Wang (2025:1) state that “CSES is the integration of the sharing economy concept into energy storage models. In CSES system, multiple community members jointly use the energy storage system, share its benefits, and jointly bear both the investment and maintenance costs”. Nevertheless, Li et al (2022:1) highlight that prosumers are unwilling to install energy storage systems (EES) when the initial investment cost for the installation of EES is high. Therefore, it is necessary to integrate the sharing economy notion in the energy storage field to share both benefits and costs. So, CSES consists of multiple household prosumers, who are sharing

an energy storage system based on renewable energy sources, e.g., solar and wind. However, renewable energies present some challenges due to their inconstant and variable supply because of factors such as weather conditions. So, renewable energies need to be stored by using ESS technologies.

The main benefits of ESS are: 1) to integrate renewable energy sources (e.g., solar and wind) into the grid; 2) storing (charging) excess energy during off-peak hours and releasing (discharging) it during peak demand hours to balance the supply and demand of energy and thereby contributing to grid stability. For instance, “residential energy storage involves storing excess solar energy during the day and using it at night or during power outages” (Global Energy Community 2023).

As highlighted by Mar et al (2024:13) “ESS can optimize energy usage, reduce costs, and enhance grid reliability”. Also, the study by Li et al (2022:20) shows that the prosumers in the community shared energy storage system can achieve 6.09% reduced cost compared with household energy storage system. In addition, the self-sufficiency rate of renewable energy is increased by 5.21%, and the profit is allocated fairly, which all confirm the feasibility of the CSES system from the economic, environmental and social aspects of sustainability. Furthermore, the comparative case study results of the cities of Ennis (Ireland) and Waterloo (Canada) show the advantage of using CSES regarding cost savings (related to both the energy storage utilisation and operational expenses) compared to household energy storage (Chang et al. 2022:1). Also, communities (including households, business entities and public organisations) in Chinese provinces of Guangdong, Hunan, and Qinghai have played a central role in achieving sustainable development and energy transitions goals. In 2021, the Chinese national government initiated the county-wide photovoltaic installation of community rooftop in 676 areas. An increasing number of residents have acted as electricity prosumers to install both photovoltaics and small-scale wind power, leading to the emergence and development of CSES systems in residential areas (Shen and Wang 2025:17). Barbour et al (2018:496) conclude that in community energy storage, compared to household energy storage, the total amount of deployed storage devices is decreased and consequently the energy self-sufficiency of local communities is increased without relying on third-party suppliers.

However, as emphasised by Barbour et al (2018:496) “due to the system-wide benefits of community storage”, specific market mechanisms need to be developed in favour of community storage deployment, particularly in the neighbourhoods with high proportion of households using rooftop solar panels. In addition, there are some socio-technical obstacles to emerging CSES systems, largely driven by place-specific factors. For instance, Yong et al (2023) illustrate a range of barriers to the development of CSES systems in the Chinese context classified as economic (e.g., high initial investment), technical (e.g., storage and maintenance of shared data), policy (e.g., lack of regulatory framework) and business model (e.g., unclear mode to benefit sharing).

2.3 Battery circularity

Electric vehicle (EV) batteries have gained standing for their role in promoting sustainable transportation and energy transitions. In the next decades, the number of EV batteries for the end-of-life (EoL)

management is projected to raise enormously, especially in the countries like Norway with a large market for EVs. This will create a huge challenge to put appropriate regulations and infrastructure in place. Many scholars support the notion of 'battery circularity' with the aim of achieving sustainable EoL management of EV batteries (cf. Casals et al., 2019; Baars et al. 2020).

Battery packs of retired EV batteries present technological, economic and environmental opportunities to improve both material efficiency and energy system of tomorrow. The scholars agree that about 80% of original capacity of EV batteries can be used for secondary purpose. Lastoskie & Dai (2015:162) state that "the energy storage capacity of the battery pack decreases linearly over its cycle life, such that at the end of its cycle life, the pack retains 80% of its original capacity". Also, Li (2023:896) states that "as the battery cycles increase, it becomes unsuitable for EV use and needs to retire when its maximum available capacity decays to 80%. Furthermore, the car manufacturers believe that batteries "are not useful for traction purposes as they reach a state of health of 80%" (Casals et al. 2019:99). Driving style and frequency directly impact the first service life of EV batteries. Hasty driving and high-frequency deep cycling would lead to faster capacity loss, while responsible driving and moderate use would extend battery life.

Different terminologies about the scope and boundary of the EoL phase have been discussed in the literature. For instance, Richa et al (2017:717) provides a management hierarchy framework for the EoL battery pathways: reusing, remanufacturing, recycling, incineration, and landfilling, which are largely shaped by the context of battery industry and regulations. There are assumptions about both positive and negative outcomes of each EoL pathway in the literature. For the scope of this study, only the three pathways (reuse, repurposing and recycling) are discussed here.

Reuse & Repurposing

The key aim in both reuse and repurposing pathways is to extend the life of retired EV batteries for secondary use. In the reuse pathway, the battery pack is reused for smaller cars that require less horsepower, e.g., in a FIAT 500X Hybrid. Cusenza et al. (2019:340) state that "reuse is preferable to recycling", which is consistent with battery circularity principles and the waste management hierarchy. In the repurposing pathway, the battery pack is repurposed for a new application, e.g., for domestic energy storage (Philippot et al. 2022:2). As discussed, about 80% of primary capacity of EV batteries can be used for secondary purpose, which can be used in other applications, e.g., energy storage stations in residential and industrial areas to stabilise the grid system. For instance, grid-connected PV power plants generate electricity only during daytime, from sunrise to sunset, and in many countries, in addition to daily peak demand, the demand for electricity is high at night hours, which justifies the use of stationary battery storage.

The literature present cases of repurposing EV batteries in a range of contexts. Lee et al (2021:8) show the successful results of a range of demonstration projects in different countries (Germany, Netherland, France, Spain and United States) aimed at repurposing second-life batteries (SLBs) as an energy storage system (ESS) in a range of applications. Retired EV batteries can be reused in stationary applications as

part of a smart grid to provide ESS for both residential and commercial use, as Ahmadi et al (2017) shows in the context of Canadian electricity mix production. Also, Zhao and Baker (2022), as part of the UK future energy scenarios by 2050, present an opportunity to shift peak demand through vehicle-to-grid (V2G) application or alternatively repurposing retired batteries as a storage system, as a means of extending the useful battery life. In addition, Ioannidis et al (2019) examine the environmental impact of repurposing a Lithium Iron Phosphate (LFP) battery in Spain, which can no longer be used in an EV but still fulfils the requirements as an energy storage unit in a building powered either by solar PVs or Spanish electricity mix. Also, a 1-MW grid-connected PV power plant in Arak city in Iran has been studied for which the repurposed EV batteries have been evaluated based on different tariffs and scenarios (Mirzaei Omrani and Jannesari 2019).

Casals et al (2019:99) discuss the potentials to provide a second life to the retired EV batteries in buildings, in which the 'prosumer' business model plays an important role in engaging citizens who both produce and consume energy, and take an active part in energy service generation and delivery. However, Lee et al (2021:15) discuss the challenges of repurposing SLBs, among others, the absence of a common set of standards to evaluate batteries if they fit into the stationary storage application. They believe that actors from different societal sectors should agree on establishing a uniform set of standards, guidelines and regulations, which takes account of different measures for the safe transportation and reliable use of SLBs.

Recycling

As mentioned, batteries can be recycled after a primary use in electric vehicles once their capacity declines to 80%, or when they are damaged. However, it is preferred that retired EV batteries before recycling enter into a second life in the form of reuse or repurposing (Lee et al. 2021:2). In places with weak or no recycling system, the recycling of batteries might not be cost-effective "due to the lack of collection systems, high recycling costs and low lithium value" (Mirzaei Omrani and Jannesari 2019:3), which justify the reuse and repurposing pathways to extend battery life. But, by the end of second service life of batteries (after reuse/repurposing), recycling creates an excellent opportunity for recovering substantial amounts of critical minerals (e.g., lithium, cobalt, copper, lead, etc.). By manufacturing new EV batteries, the reliance on extracting new raw materials is decreased, which are largely mined in Global South where most environmental and social impacts occur (cf. M. Wang et al. 2022:10; Noudeng et al. 2022: 5; Mahzouni and Velden 2026). The extraction of new materials particularly in the mining sites of the Global South often involves both environmental degradation practices (e.g., habitat destruction, water pollution and soil contamination, etc.) and social justice issues (e.g., child labour, gender discrimination and indigenous rights violations, etc.) (cf. Nkulu et al. 2018: 499).

In addition, retired EV batteries usually contain chemical substances that cause "potential hazards to the environment and human health and safety" (Prates et al. 2023:1). Also, Zeng et al (2015:1761) address potential environmental and health risks during the unsafe disposal of retired EV batteries in China.

Extensive literature addresses the need to safely collect, transport, and handle retired EV batteries, which usually contain hazardous materials (cf. Richa et al. 2017:725; Grandjean et al. 2019:204; Reinhardt et al. 2019: 441; Kumar et al. 2021:4; Sultana et al. 2022:23; Prates et al. 2023:9).

Currently, battery recycling for recovery is highly resource demanding, requiring both a capital-intensive investment and expertise in the chemical and metallurgical fields and (Colarullo and Thakur 2022:3). The battery circularity is enhanced when SLBs provide maximum use before resource the recycling takes place.”. Repurposing retired EV batteries for second-life applications can decrease “the overall environmental impact of the battery pack by 25–40%” (Nazim and Madurai Elavarasan 2026:26) through avoiding the production of new storage devices, decreased materials use requirements, and delayed recycling (cf. Machín et al. 2024; Ullah et al. 2025).

2.4 The contribution of second-life batteries to a circular CSES system

Scientific research about the benefits and challenges of second-life batteries (SLBs) is nascent. This study relies on four recently published review papers (Freitas Gomes et al. 2020; Shahjalal et al. 2022; Machín et al. 2024; Nazim and Madurai Elavarasan 2026), which all provide a comprehensive overview of the present state of SLBs. Here, some synthesised results on the crucial role of SLBs including technical, economic and environmental aspects are presented from an interdisciplinary and battery lifecycle approach.

Benefits of second-life batteries

Strong electric vehicle (EV) market uptake will lead to an increased amount of SLBs in the next few decades (Freitas Gomes et al. 2020; Colarullo and Thakur 2022:3). So, in the near future we will be overburdened with a large amount of retired EV batteries due to the rapid growth of the EV market, which is alarming (Lee et al. 2021:1). Nevertheless, according to Shahjalal et al (2022:1), energy storage solutions will be highly demanded in the near future when more renewable energy sources (RES) are incorporated into the power grid. Retired EV batteries usually contain about 80% of their original remaining capacity, which can be used in less-demanding applications, e.g., as stationary energy storage systems (ESS). So, using second-life batteries (SLBs) in a battery circularity context will lead to decreasing both environmental impacts and the total costs of producing new ESS (Lee et al. 2021:14). That is to say, when a retired EV battery is used as an ESS, the costs of ESS can be reduced by “up to 25%, creating a viable pathway to low-cost ESS” (Nazim and Madurai Elavarasan 2026:28). In addition, the retired EV batteries contain critical materials, which can be recycled for manufacturing new batteries and therefore reducing waste, avoiding battery mineral extraction and enabling a circular and sustainable energy system.

The study by Y. Wang et al (2022) indicates that if all retired batteries are reused before they enter into their recycling phase, the delay in mining critical materials and using energy and other resources for manufacturing new batteries might reduce a large amount of greenhouse gas emissions. In addition,

Colarullo and Thakur (2022:3) state that reducing the demand for manufacturing new batteries through recovering important materials can enhance energy communities and thereby contributing to greater energy sustainability and battery circularity (Colarullo and Thakur 2022:11).

Extending the useful life of retired EV batteries offers a “unique intersection of technological, economic, and environmental benefits”. The repurposing of retired EV batteries “enables wider access to energy storage solutions in grid stabilization, renewable energy integration, and off-grid applications where cost sensitivity is high. Environmentally, SLBs contribute to resource conservation by delaying the energy-intensive recycling process, lowering raw material demand, and reducing waste generation” (Nazim and Madurai Elavarasan 2026:25–26). Here, the contribution of SLBs to grid stabilisation and renewable energy integration is discussed.

Grid stabilisation

Retired EV batteries can be repurposed within about 4–5 months compared to 12–18 months for acquiring new ESS, causing both environmental risks and additional costs because new produced ESS require “raw material procurement, cell manufacturing, and international logistics” (Nazim and Madurai Elavarasan 2026:27). So, the quicker access to SLBs enables grid operators in accelerating the integration of renewable energy sources into the grid and then avoiding environmental impacts (Casals et al., 2019).

In addition, second-life batteries (SLBs) are capable of providing a variety of services when coupled with the grid system, e.g., through peak shaving schemes, which helps charging during low-demand hours and discharging during peak hours, thereby reducing electricity expenses and large-scale ESS capital investment costs. Put differently, peak shaving “involves charging batteries during off-peak periods of low electricity prices and discharging batteries during periods of increased prices”. Furthermore, once “an EV plugs in for a fast charge, the high-power demand is supplied primarily by the SLB, not the grid. This peak shaving capability smooths the power profile, and avoids costly grid upgradation fees (Nazim and Madurai Elavarasan 2026:21–22). Besides, coupling SLBs with solar panels can decrease the CO₂ emissions of electricity generation by about 56%, contributing to the decarbonisation of electricity sector (Ahmadi et al. 2014).

SLB-based ESS can act as ‘battery-buffered EV charging’ to bridge the gap between grid limitations and charging demands, where all chargers have access to a pool of energy storage for direct current (DC) fast-charging (Power-Sonic 2024). Salek et al (2022) modelled an EV charging station incorporating solar panels and SLBs in a residential context and found that the incorporation of SLBs with solar panels substantially increases grid stability. To sum up, the high initial investment cost of ESS has limited prosperity, and SLBs deal with this challenge by providing affordable and environmentally responsible ESS alternatives to avoid fluctuations and stabilise the grid system. SLBs can contribute to sustainable grid stabilisation and management. Furthermore, SLBs provide a reliable solution for home ESS, where cost is a major factor (Ambrose et al. 2014), and thereby saving a large quantity of electricity costs (Rallo et al. 2020).

Renewable energy integration

According to Casals et al (2019), coupling second-life batteries (SLBs) with renewable energy sources (RES) is one of the most crucial pathways for promoting sustainable energy transitions and battery circularity. RES, e.g., solar and wind are naturally intermittent, and their large-scale operation requires adequate and efficient energy storage systems to ensure the balance between energy generation and demand. So, SLBs facilitate the integration of renewable energy sources into the grid system by providing cost-effective storage solutions and enhancing the reliable and flexible integration of renewable energy into the grid system. Also, Colarullo and Thakur (2022:1) state that SLBs contribute to the establishment of community storage by saving high storage costs and by lowering energy bills, especially in the contexts when a solar generation system is coupled with a storage solution.

Challenges of upscaling and adoption of second-life batteries

As discussed, the application of second-life batteries (SLBs) extends the life of batteries, decreases the need for manufacturing new batteries, supports battery circularity initiatives, and generates new business opportunities (Shahjalal et al. 2022). However, the literature also addresses the safety concerns of SLBs (cf. Lee et al (2021; Adejare et al. 2025). As discussed by Nazim and Madurai Elavarasan (2026:1), large-scale adoption of SLBs are limited by safety risks and the lack of standardised repurposing procedures, which hinders the integration of renewable energy sources in the grid systems. Furthermore, they are listing a range of other obstacles by arguing that the “successful mass implementation requires effective collection, safe storage, and effective recycling. Challenges related to the historical use of data, differences in battery chemistries, and non-uniform aging characteristics create ambiguity for the evaluation of the health and reliability of spent batteries [...] These challenges must be overcome in order for SLBs to achieve their economic, environmental, and social advantages and establish themselves as a core component of sustainable energy infrastructure.” (Nazim and Madurai Elavarasan 2026:2).

The repurposing of EV retired batteries for second-life application includes safety concerns, which “arise from degradation, heterogeneity, incomplete usage history, and repacking complexities” causing thermal runaway and increased internal reaction. In addition to safety risks, “historical data from the first life is often missing when assessing those batteries as SLB, which includes exposure to mechanical abuse, overcharge events, or prolonged high-temperature storage” (Nazim and Madurai Elavarasan 2026:26). There is a lack of a common set of standards to evaluate and test the retired EV batteries to ensure their relevancy for second-life applications, which could influence the feasibility of the wide use of the SLBs in CSES systems. Thus, providing a uniform set of standards to evaluate the retired EV batteries for second-life application will reduce the potential safety risk and ensures safe use of SLBs, which all depends on the previous use and degradation status of the batteries.

In addition, the potential risk of toxic gas emissions caused by malfunctioning EV batteries cause a substantial threat, especially in enclosed environments e.g., in aircraft or in a home equipped with ESS. Thus, to ensure a high safety, SLBs should be monitored through battery management system (BMS) to

take necessary measures for enhancing the cooling system aimed at avoiding overcharging and preventing thermal event that usually causes battery fire. But it would be difficult to handle retired EV batteries especially when their previous usage conditions are unknown. In this case conducting appropriate evaluation methods is crucial “to identify the damaged cells to be removed from the battery pack” (Lee et al. 2021:15), ensuring a safe use of SLBs.

2.5 Socio-technical approach to community shared energy storage system

Energy transition is highly place-based as practices and activities are initiated and developed in a particular socio-spatial context, in which the energy infrastructure shapes and is shaped by society. Socio-technical system includes not only the element of technological artifacts but also social elements such as actors, practices and regulations, which is supported by sustainability transition scholars (cf. Rip and Kemp 1998:334; Geels 2004; Smith et al. 2005:1493; Loorbach 2010). Energy system is not only about technological artifacts but also a constantly ongoing social organisation to address inefficiencies in the “material production, communication, information and control” of the system (Edwards 2002:222). Therefore, there is a need to take an interdisciplinary integrated socio-technical approach as an overarching framework to analyse the challenges and opportunities of socio-spatial factors including planning infrastructures for CSES systems (Fig. 1).

Actors

The notion of the CSES involves active collaboration among a range of stakeholders e.g., PV-household prosumers, community organisations, energy utility companies, grid operators, housing companies, municipal authorities, regulatory bodies, etc. The actors should be able to actively collaborate on the four pillars of onsite renewable energies: generation, trading, distribution, and use (cf. Mar et al. 2024:1; Li et al. 2022:4–5; Shen and Wang 2025:2). The main actors in CSES systems are multiple household prosumers and the storage operator. Besides households, business entities and public organisations might play a vital role in supporting CSES systems. Consistent with Büscher et al (2020:18), sector coupling supports the convergence of different existing and new infrastructure, which brings about a higher complexity in planning and implementation when a large number of actors are involved.

Technological artefacts

The hard elements of community shared energy storage (CSES) system consist of storage devices (either second-life batteries or new energy storage systems); electricity generation devices (e.g., solar panels, electricity grid system, and building envelopes) (cf. Minuto et al. 2021:3; Nishanthi et al. 2023:12; Alam et al. 2023:4; Mar et al. 2024:2; Shen and Wang 2025:3). Mar et al (2024:1) examine “the positive impact of incorporating a storage system into an energy community” to ensure the access of community members to energy in case of grid failures. Then, in case of coupling between the energy and transportation systems, the elements of Electric Vehicles (EV) charging facilities are added. In addition, digital platforms and energy community services provide clear rules for communities to define and

implement their specific sharing. For instance, the WeShareEnergy platform enables individuals and organisations to directly share and trade renewable energies (e.g. solar energy) with each other, and manage utility contracts and billings (WeShareEnergy 2026). Smart energy management systems are key to control and optimise energy generation, storage, and consumption. It allows for real-time tracking and state-of-charge monitoring, coordinating power plants and energy storage systems to meet real-time electricity demand, and thereby stabilising power grids.

Energy community practices

An energy community “is a social collective with shared interests, comprised of users who can actively engage in either energy consumption or production” (Mar et al. 2024:1), which is enabled by collective values of citizens for energy transitions at the local level (Tidwell and Tidwell 2018). In an energy community, household prosumers are engaged in storing and sharing renewable energies, making it accessible within the community if needed (Mar et al. 2024:2). Pooling resources allows the community to amortise high upfront infrastructure costs over a broader base and time period, making projects economically viable for local community members.

In 2021, the EU-funded SERENE and SUSTENANCE projects set out to develop sustainable energy system for local communities by creating “more efficient, integrated, cost-effective and customer-centric solutions that could enhance communities’ energy autonomy” (CORDIS 2025). The outcome of the two projects shows how this approach can promote decarbonisation in European countries with relatively different socioeconomic and political systems. The results from the SERENE project confirms that opportunities and challenges of local energy systems transition is highly context-based (Ibrahim et al. 2025). So, community shared energy storage (CSES) systems are shaped by “spatially embedded visions of the future city and energy system”, in which the places provide “a shared, protected experimental space” that enable actors to shape their own energy transition (Engels and Münch 2015:35).

The core element of energy community is the active participation of local citizens in community projects, which would bring about greater public awareness and acceptance of renewable energy technologies. However, the increased share of renewable energies in the energy mix demands higher stability and reliability of the grid system. In a battery circularity context, using SLBs will contribute to lowering costs of establishing and maintaining an energy community, which will not only facilitate the community access to energy but also contribute to sustainability and circularity. So, onsite decentralised energy production and consumption based on local resources reduces both “transmission, distribution, and conversion losses”, and emissions and thereby contributing to a circular energy economy (Colarullo and Thakur 2022:12).

Regulations for using second-life batteries

One of the key barriers to developing market for second-life batteries (SLBs), is the lack of standardised and consistent global regulations. Currently, the European Union (EU) is the pioneer “to adopt policies and mechanisms to aid the market of SLB as well as a proper waste management plan for battery

disposal". One of the key acts implemented by the EU is the end-of-life vehicles (ELV) directive aimed at preventing waste from retired EV batteries and to promote the safe collection, transportation, reuse and recycling of their components for environmental protection. The aim is to ensure that the EVs are designed in a way to facilitate efficient reuse, repurposing and recycling of retired EV batteries (Lee et al. 2021:15).

3. Methods

This study applies a qualitative case study methodology (Yin 2009; Merriam 2009) to analyse the challenges and potentials of establishing community shared energy storage (CSES) system in the particular socio-spatial context of the new city-district of Dietenbach in Freiburg. Miles and Huberman (1994) define a 'case' as "a phenomenon of some sort occurring in a bounded context", and Yin (2009:18) defines a 'case study' as "an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident". The socio-technical CSES system including the element of second-life batteries (SLBs) in the new city-district of Dietenbach is defined as the 'main unit of analysis' and the energy infrastructure planning as the 'embedded unit of analysis' to enable CSES systems (Yin 2009:31). Both units are studied within socio-spatial context (including the historical and urban planning) of Freiburg. A socio-spatial context refers to the combined impacts of social dimension (e.g., community networks, organisations, cultural rules, etc.) and spatial dimension (e.g., the physical layout, built & natural environments, etc.).

As part of desk study, the information sources have been research articles, reports, local newspapers and policy documents. XXX has lived in Freiburg for many years and observed the sustainability events in Freiburg very closely by participating in numerous public events on the development and the planning process in Dietenbach, about which she has acquired deep knowledge. Thus, the reliability of obtained information has been cross-checked through the active observation of XXX, which helped to prove the obtained qualitative data. In the next section, the case study results are presented.

4. Enabling factors for community shared energy storage in Dietenbach

The Dietenbach construction area lies in the west of the Freiburg city centre, which is surrounded by residential buildings to the south (Rieselfeld city-district) and to the north (Lehen city-district), and major roads both in the east and the north. It requires a particular infrastructure planning for major services, e.g., energy supply, mobility, etc. The planned city-district on the greenfield of Dietenbach will offer 6,900 apartments for up to 16,000 people in an area of 110 hectares by 2040 (Amtsblatt 2024). Key enabling factors for establishing and maintaining the CSES in Dietenbach include both hard and soft elements of socio-technical transitions (Fig. 1), which are discussed here.

4.1 Energy planning policies and practices

The new city-district of Dietenbach, considered as one of Germany's largest climate-neutral city-districts, which has been planned from the ground up and will be constructed gradually. The first construction phase 'Am Frohnholz' has already started in mid-2026, in which dense urban neighbourhoods concentrate energy demand. The master plan for the Dietenbach city-district and local conditions enables community storage solutions by envisioning an enormous photovoltaic area of approximately 142,000 m² on roofs and facades, for which central energy units are planned for each construction phase. Since the buildings are highly insulated, a massive electricity surplus is generated especially in the summertime (City of Freiburg 2026a; City of Freiburg 2026b; Transsolar KlimaEngineering 2026). However, planning for massive PV expansion in Dietenbach requires neighbourhood energy storage. Instead of each household installing a small home storage system, community shared energy storage (CSES) can be integrated directly into the planned infrastructure nodes to ease the regional grid system operated by municipal utility company Badenova. CSES allows multiple household prosumers to pool their resources aimed at lowering per-unit costs and maximising the use of local renewable energy sources, especially by using SLBs as an affordable and environmentally friendly energy storage system.

4.2 Technological artefacts of heat supply

As part of the energy concept for the Dietenbach city-district, the City of Freiburg has developed four heat supply variants, in which different sectors are coupled (Nusser et al. 2021:20).

Variant V1 – Coupling between decentralised heat pumps and seasonal storage with ice storage.

Variant V2 - Dietenbach Plus: Decentralised heat pumps for heat generation at construction site level.

Variant V3 - Deep geothermal energy: Central heat supply via local heating network with heat from deep geothermal plant outside the Dietenbach area.

Variant V4 - Dietenbach Klyn: Central heat pumps for heat generation from wastewater heat and groundwater as well as use of electrolysis waste heat.

The first three listed variants include decentralised air-to-air heat pumps with ice storage and wastewater heat retention as well as central geothermal energy for a water-based heating system. Variant 4 is based on a low-temperature local heating network to supply heat to the entire district. An energy centre at the Mundenhof Zoo in the west of the Dietenbach greenfield accommodates a central heat pump system and an electrolysis plant for the production of green hydrogen. The waste heat from the electrolysis covers around 20% of the heat demand, and the remaining heat demand is covered by central heat pumps based on wastewater and groundwater heat. The combination of emission-free waste heat, renewable heat and the production of green hydrogen enable high system efficiency and a climate-neutral energy transition in Dietenbach. The energy concept for Dietenbach envisions cold district heating networks and large decentralised heat pumps for parts of the Dietenbach city-district (Endura kommunal 2018; Badenova Freiburg 2026). So far, there is no planned infrastructure for using SLBs, but both the master plan and energy infrastructure planning for Dietenbach provide an enabling environment for establishing community shared energy storage (CSES) systems. Furthermore, the CSES

systems can provide reliable electricity to all four variants. A CSES system, which uses solar-based second-life batteries to temporarily store inexpensive solar power from midday to cover the electricity demand of the heat pumps for space heating and hot water in the evening and at night in a CO₂-neutral manner.

4.3 Actor constellation

Historically, there are solid platforms for partnership building and networking at the local level in Freiburg, e.g., in the form of collaborative building groups (co-building groups and cooperatives). City of Freiburg promotes the creation of co-building groups (Baugemeinschaften) and cooperatives (Baugenossenschaften) in Dietenbach by drawing on success stories in other city-districts in Freiburg, e.g., Vauban and Rieselfeld (Mahzouni 2017). The City of Freiburg will award land plots to groups of people who intend to build together in Dietenbach. Co-building groups and cooperatives who intend to apply for a land plot in the first construction phase 'Am Frohnholz', must fulfil some criteria set by the City of Freiburg's evaluation committee, among others to provide a model project for neighbourhood electricity generation. Those who submit an innovative and collaborative energy concept for their multi-story building/neighbourhood, will increase their chances of being awarded a land plot. Initiatives, like the Grünhof Freiburg network with its GeBauT series, support co-building groups and cooperatives (GeBauT Dietenbach 2025). The planned community-oriented housing projects, e.g., the 'FreiRäume' co-building group or the 'Bienenstock' cooperative in the first construction phase 'Am Frohnholz' are ideally suited as carriers for a community shared energy storage (CSES) model. The Bienenstock cooperative aimed at achieving 40 to 50 residential units in multi-story buildings with a high proportion of natural materials, primarily wood, straw and clay and the FreiRäume co-building group is intended for "planning, building, and living together in a fair and cooperative way" (City of Freiburg 2026; Bienenstock 2026; FreiRäume 2026).

4.4 Energy Community practices

Freiburg is home to many green energy pioneers and entities, which have supported the energy community notion with their expertise, which can play a vital role in supporting the CSES notion, e.g.

- Elektrizitätswerke Schönau (EWS), which actively supports citizen energy projects and cooperative storage solutions and can serve as a partner for any project related to local energy transactions (Nordic Energy Research 2023:112)
- The Fraunhofer Institute for Solar Energy Systems (ISE) is a world leader in research on smart grids and battery storage. Many local neighbourhoods in Freiburg (e.g., Vauban and Gutleutmatten) have utilised the ISE expertise to establish their innovative energy concepts (City of Freiburg 2014; Fraunhofer ISE 2026).
- Badenova Netze, which as the regional distribution network operator forms the interface for the feed-in and is responsible for coordinating the network connection and the installation of smart metering systems.

The actor constellation in Freiburg indicates promising pathways for collaboration among a range of actors from public, private and civil society sectors to enable the use of SLBs in CSES systems. However, it might also present a range of techno-economic and regulatory challenges because of the difficulty to bring the interests and preferences of different actors together (Mahzouni 2025:2).

4.5 Multi-level regulations

Fair electrical grid access would ensure that all energy market actors (municipal-owned utilities, business entities and renewable energy communities) can physically connect to and transmit power through the grid on a transparent and non-discriminatory grid tariffs basis. This enables community shared energy storage (CSES) to operate by multiple household prosumers, including collective self-consumption and peer-to-peer trading. As stated by Lee et al (2021:15), “the lack of uniform global and regional policy is one of the critical barriers to develop the market for SLBs”. The European Union (EU) has launched the end-of-life vehicles (ELV) directive, which entered into force on 13 August 2026 to promote the safe collection, reuse and recycling of retired EV batteries, and thereby preventing waste and maximising the efficient use of resources (Hossain et al. 2019). Then, in Germany the framework for CSES systems is strongly influenced by the Renewable Energy Sources Act (EEG).

5. Discussion

In this section, the discussion of results from previous section will be extended to address the two research questions listed in the introduction section mainly by reflecting on the theoretical and analytical framework and the case study results. It also includes two main challenges: safety of repurposing second-life batteries and social exclusion from the community shared energy storage (CSES).

What are the key potentials and challenges of using second-life batteries in community shared energy storage systems?

The environmental and social impacts of electric vehicle (EV) batteries are found throughout their entire life cycle, from raw material extraction through end-of-life (EoL) treatment. In particular, mining of the critical battery minerals is very energy-intensive and causes a range of environmental risks (e.g., soil erosion, water contamination, greenhouse emissions, etc.) and social risks (e.g., child labour, gender discrimination, modern slavery, etc.). Second-life batteries (SLBs) deal with these challenges by extending the lifespan of batteries before they enter into their recycling phase.

The literature shows that coupling among different technologies e.g. between PV and EV system will be a key strategy for energy system decarbonisation, in which residential SLB-based energy storage system (ESS), when applied in CSES systems, will play a key role in accelerating local energy transitions (Englberger et al. 2019). The literature emphasises the role of SLBs, as socio-technical system, to create a range of couplings and synergies both at the use and end-of-life phases in different contexts. There are many benefits to establish a sustainable circular battery value chain globally as the EV batteries entre

into their EoL when they reach 80% of their initial capacity. So, in the near future, there will be a large number of batteries with useful potentials to be used to store renewable energy sources.

However, there are some challenges to using SLBs in the CSES. As part of the 'sustainable batteries' concept, European Commission (2020a) supports the sustainable management of EoL of EV batteries that are safely collected and handled for reuse and repurposing in a battery circularity framework. However, the SLBs are beneficial under certain conditions, depending on the battery chemistry, first use conditions and energy mix production for remanufacturing retired batteries (Philippot et al. 2022:1). In particular, user safety and environmental protection have been recorded of high concern due to the fire risk or explosion and the use of toxic or hazardous materials in some battery technologies (Global Energy Community 2023). As stated by Lee et al (2021:16), usually the EV manufactures have no direct access to the retired EV batteries because they are dispersed globally that creates a challenging task to ensure safe collection and transportation of batteries, which might be an obstacle to market uptake of SLBs. So, enhancing the regulation, standardisation, and end-of-life management of batteries should be given a priority to ensure safe and reliable collection, transportation and use of SLBs. The national policymakers can contribute to uptake of SLBs by enacting and implementing appropriate incentives, e.g., tax credits, grants, etc. Nevertheless, as highlighted by Nazim and Madurai Elavarasan (2026:27) "SLBs' true value proposition lies not in competing on pure cost metrics against the new low-cost batteries, but in delivering circular economy benefits".

How can the socio-spatial context of the Dietenbach city-district support a battery circularity strategy to promote community shared energy storage systems?

Energy sharing practices and activities are highly place-based and they are defined in particular socio-spatial settings, e.g., in a certain neighbourhood as an important planning unit for implementing sustainable shared production and consumption (prosumer). This study shows that community shared energy storage (CSES) projects can present a solid platform for residents in Dietenbach to take an active role in local energy transitions, which relies on several intersecting factors. The successful use of SLBs in community shared energy storage (CSES) would depend on many territorial and socio-technical factors such as battery design, battery state of health, recycling infrastructure, governance system and institutional structure. The master plan and energy infrastructure planning for Dietenbach will provide an enabling environment for establishing CSES in form of building solar panels on roofs and facades, but there is no concrete plan for repurposing second-life batteries (SLBs). Nevertheless, Freiburg with particular stakeholder constellation, legal frameworks and land development policy is in an outstanding position to support the use of SLBs in CSES projects. The recent record-breaking heatwaves in Germany especially in Freiburg, justify the need for community-driven mitigation and adaptation actions from the citizens who are immediately affected by climate change impacts. However, there are some challenges to promoting CSES in Dietenbach: institutional deficit and social exclusion of citizen in the CSES projects.

Institutional deficit

The construction of the Dietenbach city-district has just started and will be completed by 2040. The plan for Dietenbach city-district is characterised by a variety of infrastructures where a fragmented organisational, institutional and governance structure could hinder the use of SLBs in CSES systems for a low-carbon Dietenbach. Thus, CSES requires particular institutional and organisational coordination between many actors, which might be a challenging task to bring their interests together. The existing institutional framework can play a coordinating role between actors in shaping the co-evolution of technological and social elements of CSES system, as an important part of the future energy system in Dietenbach.

However, the City of Freiburg as the main actor, has so far focused on the techno-economic aspects of CSES systems and has not yet developed a plan for incorporating the soft elements, e.g., governance, institutional and organisational into the CSES systems. Facilitating organisational coordination and practices between the charging (storing) and discharging (releasing) in the community energy storage, would contribute to efficient supply-side management and demand response. In addition, urban planning and development is enacted and implemented by diverse actors and thus coordination and management across sectors might be hindered by institutional silos. It is therefore necessary to find community-driven coordination strategies and innovative solutions at the neighbourhood scale during the planning and construction of the new city-district of Dietenbach. The introduction of complex energy systems and cross-sectoral synergies must lead to aligned expectations between different actors.

Social exclusion

Most future residents of Dietenbach of practical reason are not able to participate in shaping the energy concept for their own neighbourhood except for those already engaged with collaborative housing groups that have been awarded a land plot, which as a platform can be used for establishing CSES systems. The main obstacle to incorporate the views and values of residents into the future energy system for the new city-district is that the residents are not yet in place to have a say in forming the energy infrastructure planning for their own neighbourhood. Therefore, the City of Freiburg, in the absence of future residents, might be ethically and politically committed to include “collectively held social beliefs and values” in the planning process for an integrated, just and sustainable energy system in Dietenbach (Levenda et al. 2019:181).

Furthermore, as part of the City of Freiburg policy to ensure affordable housing, the City Council created a resolution that 50 percent of the rental housing in Dietenbach need to be subsidised social housing. However, it is not sure if the affordable housing policy will be successfully implemented in Dietenbach. In the first construction phase ‘Am Frohnholz’, in which about 1,600 apartments are to be built, the average price per square meter of building land will be around €1,700, which is incredibly high, and it is estimated that tenants in Dietenbach will pay 25 euros per square meter, which is well above the rent index ‘Mietspiegel’ in Freiburg, €14.13/m² published in the second quarter of 2026. Economically disadvantaged people will simply not be able to afford housing in Dietenbach. They would not be awarded bank loan to take part in collaborative housing groups and local energy projects because of

their low equity capital or limited financial sources to pay back the loan (SWR 2026), and thus they might not be able to participate in the community projects such as CSES.

6. Concluding remarks

This study offers an important insight into the role of second-life batteries (SLBs) in enhancing community shared energy storage (CSES) systems for sustainable urban energy transitions. The current energy transition towards more renewable sources for electricity generation enables the repurposing pathway, in which the batteries are used in a stationary energy storage system (ESS). This study provides policymakers and practitioners updated and synthesised information by drawing on the opportunities and challenges of current energy planning practices in Dietenbach, which can be modified and implemented in other urban energy projects with similar conditions.

6.1 Policy recommendations

Second-Life Batteries (SLBs) are a key component for the sustainable energy transition. National governments can support a battery circularity strategy by supporting an appropriate end-of-life (EoL) battery pathway in priority order: reuse, repurposing and recycling. Then, there is a need for policy incentives to support safe collection, transportation and use of SLBs. Facilitating access to accurate information about the battery's state of health (SoH), already in the chain of custody is necessary to target only batteries with a high SoH for reuse or repurposing and therefore avoiding unnecessary shipments and reducing CO2 emissions caused by transportation. This would also lower the cost and environmental impacts by reducing the number of modules that must be evaluated onsite. Also, battery industry is required to reduce the reliance on the extraction of new materials when manufacturing new batteries. National governments should be able to help industry to find a right EoL management pathway by prioritising reuse and repurposing before recycling. Furthermore, the policymakers should push for appropriate strategy to enable a new market for SLBs by supporting a common set of standards for the SLB industry and by providing necessary incentives (e.g., tax exemption) to both industry and household prosumers aimed at encouraging the use of SLBs in CSES systems. So, the preconditions for sustainable CSES systems in Dietenbach, besides the existing social cohesion, is a framework for scaling up niche innovations of second-life batteries to mainstream market

6.2 Future research

Research about the benefits and challenges of second-life batteries (SLBs) is growing. Community shared energy storage (CSES) is highly characterised by territorially based factors including infrastructural artifact, institutional arrangements, actor constellation and energy community practices. Therefore, to provide new insights into the debate on socio-technical CSES systems, the following questions can be further investigated:

- What new institutional arrangements and organisational structures are required for increasing coordination among actors aimed at scaling up niche innovations of second-life batteries to

mainstream market?

- What is the primary goal of the community members to establish CSES projects (e.g., lowering energy bills, balancing local solar generation, or grid independence)? How to bring together interests and preferences of the members of CSES?

Further research can also provide insights into the key practices, policies and pathways of the EoL management of EV batteries in countries with a rapid uptake of EV market, e.g., Norway or China.

Declarations

Author Contribution

For this single-authored paper, A.M is solely responsible for all aspects of the work including conceptualisation, data collection, analysis, and manuscript preparation & submission.

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Footnotes

1. In this work, 'retired EV batteries' and 'second-life batteries' are interchangeably used, which both refer to the second service life of EV batteries.

Figures

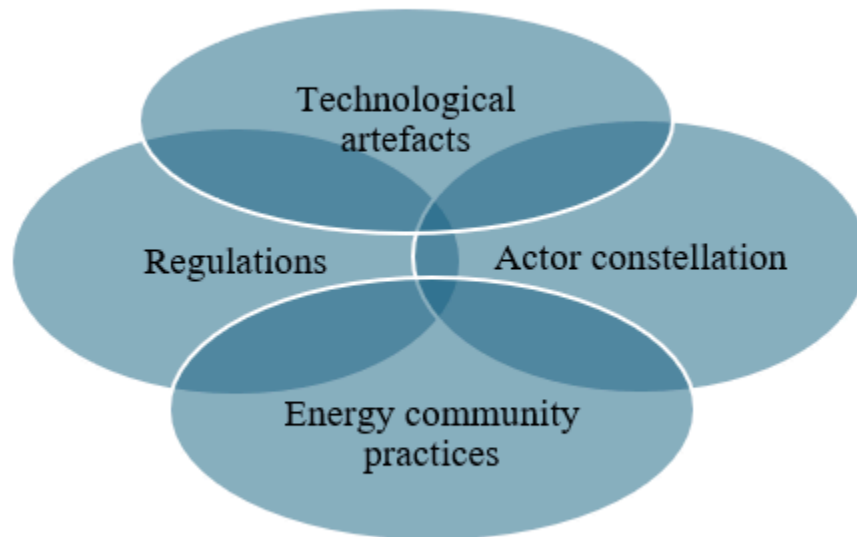


Figure 1

An integrated socio-technical approach to community shared energy storage system