

Slutrapport

Energimyndighetens titel på projektet – svenska
Byggnadsintegrerad energilagring och elektromobilitet för flexibla
energigemenskaper: Ett svenskt perspektiv

Energimyndighetens titel på projektet – engelska
Building-Integrated Energy Storage and Electro-Mobility for Flexible
Energy Communities: A Swedish Perspective

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Förord

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This report comes at a critical time when Sweden is accelerating its energy transition and energy communities are emerging as a key solution for democratizing and decentralizing our energy system. While the synthesis reveals significant knowledge gaps, particularly regarding integrated battery energy storage system and electric vehicle applications in Swedish contexts, it also identifies clear pathways forward. It is my hope that this work will catalyze further research and practical implementation of energy communities across Sweden.

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Sammanfattning

Denna syntesstudie kartlägger kunskapsläget kring batterienergilagringssystem (BESS) och elfordon (EV) i energigemenskaper, med särskilt fokus på svensk relevans. Studien har systematiskt granskat 218 vetenskapligt granskade publikationer (2016–2025) och kombinerat traditionell evidenssyntes med NLP-baserad textutvinning, ämnesmodellering och strukturerad taggning över tekniska, ekonomiska, sociala och styrningsrelaterade dimensioner. Syftet var att identifiera vad som fungerar, var kunskapsluckorna finns, och hur Sverige kan påskynda integreringen av energilagring och elektromobilitet i byggnader inom flexibla energigemenskaper.

Granskningen visar ett snabbt växande men ojämnt forskningsfält: publikationerna ökade kraftigt efter 2019; forskningen är huvudsakligen inriktad på kvartersnivå; och kombinationer av solceller (PV) och batterier dominerar, medan integrerade lösningar med EV, sektorkoppling och verklig prestanda fortfarande är begränsade. Sverige är underrepresenterat i litteraturen (~4 % av artiklarna), men utmärker sig genom starkare fokus på PV/EV-integration samt policy, reglering och social acceptans – styrkor som kan användas för att gå från modellering till verkligt genomförbara och rättvisa implementationer.

Centrala resultat

- **Snabbt växande forskningsfält:** Energiforskning inom energigemenskaper har ökat kraftigt sedan 2019, men fokuserar i stor utsträckning på PV–BESS på kvartersnivå. Integrerade el–värme–mobilitetslösningar och samverkan mellan flera aktörer är fortfarande sällsynta.
- **Metodologisk slagsida:** Scenarioanalys och optimeringsmodeller (särskilt MILP/LP) dominerar, medan empirisk validering, långtidsstudier och öppna datamängder är bristfälliga.
- **Begränsad användning av EV som flexibilitetsresurs:** EV modelleras ofta som belastningar snarare än som kontrollerbara tillgångar (smart laddning, V2B/V2G), vilket innebär att potentiella värdeskapande möjligheter förbises.
- **Obalans inom ESG-aspekter:** Miljödimensionen får ofta förtur, medan social rättvisa, demokratisk styrning och praktiska regleringsfrågor behandlas mer sporadiskt, vilket riskerar ojämlika utfall och genomförbarhetsproblem.
- **Sverige i fokus:** Endast nio artiklar (~4,1 %) behandlar Sverige explicit, men med relativt högre fokus på PV/EV, policy/reglering och social acceptans. Däremot är integration av värme och prosument-/transitionsstudier mindre framträdande.

Identifierade möjligheter

- **Samschemalägg BESS och EV:** Kombinera gemensamma batterier med smart laddning och V2B/V2G för att möjliggöra effekttoppskapning, tidsmässigt arbitrage och stödtjänster på byggnads- och kvartersnivå.

- **Utnyttja sektorkoppling:** Använd Sveriges fjärrvärmesystem och byggnadsbestånd för att integrera PV+BESS+värmepumpar/termisk lagring samt absorbera överskottsproduktion (t.ex. vid negativa elpriser).
- **Pilotprojekt med rik evidens:** Gå från simulationsdrivna studier till uppföljda demonstrationer med öppna data, standardiserade nyckeltal och flerårig rapportering om prestanda, användarbeteenden och degradering.
- **Rättvisa som designprincip:** Inför styrmodeller, kostnads-/nyttodelning och skydd för hyresgäster/låginkomsthushåll från början, för att bygga långsiktig social acceptans och legitimitet.

Rekommendationer

För beslutsfattare

- Skapa **regulatoriska sandlådor** för gemensamt ägda PV–BESS–EV-tillgångar, lokal P2P-handel och deltagande i flexibilitetsmarknader (DSO/TSO).
- Utforma **tariffsystem och mätning** (t.ex. dynamiska effektavgifter, sub-/virtuell mätning) som belönar nätavlastning, tidsskillnadslagring och lokal flexibilitet.
- Inför **standardiserade nyckeltal (KPI) och rapporteringskrav** som omfattar teknisk-ekonomisk prestanda, flexibilitetsintäkter, tillgångshälsa, sociala utfall och styrning.
- Utlys **målstyrda stödprogram** för sektorkopplade projekt med krav på el–värme–mobilitetsintegration och bedömning av staplad samhällsnytta (effekttoppar, robusthet, emissioner, användarvärde).

För industri och utvecklare av energigemenskaper

- **Designa för samschemaläggning:** Implementera styrsystem som koordinerar PV, BESS och EV-laddning/V2B/V2G utifrån verkliga priser och nätsignaler.
- **Investera i data:** Använd öppna gränssnitt, publicera anonymiserade datamängder och KPI-paneler för att snabba på lärande och finansiering.

För forskare

- Genomför **långtidsstudier i fält** för integrerade BESS–EV–värmesystem, inklusive prestanda, användarbeteenden, degradering och styrstabilitet.
- **Benchmarka styrstrategier** (regelbaserad, MILP/MPC, RL) med hjälp av gemensamma öppna datamängder och standardiserade osäkerhetsmått.
- **Utvärdera styrformer experimentellt**, jämför delningsregler och deras påverkan på acceptans, rättvisa och långsiktigt deltagande.
- **Stärk överförbarheten:** Analysera hur resultat skalar mellan olika byggnadstyper, nätmiljöer och tariffsystem för att möjliggöra nationell uppskalning.

Bidrag och nästa steg

Projektet levererar:

- (i) en kuraterad databas med 218 artiklar och omfattande tematiska etiketter,
- (ii) ett analytiskt ramverk som omfattar teknik, ekonomi, sociala och styrningsrelaterade aspekter, samt
- (iii) konkreta handlingsvägar för svensk implementering.

Summary

This synthesis study maps the state of knowledge on battery energy storage systems (BESS) and electric vehicles (EVs) in energy communities with a particular focus on Swedish relevance. It systematically reviewed 218 peer-reviewed publications (2016–2025) and combined conventional evidence synthesis with NLP-based text mining, topic modelling and structured tagging across technical, economic, social and governance dimensions. The goal was to identify what works, where the gaps are, and how Sweden can accelerate building-integrated storage and electro-mobility within flexible energy communities.

The review shows a rapidly expanding but uneven field: publications surged after 2019; research concentrates at neighbourhood scale; and PV–battery pairings dominate, while integrated treatment of EVs, sector coupling and real-world performance remains limited. Sweden is under-represented in the literature (~4% of papers) but stands out for stronger attention to PV/EV integration and to policy, regulation and social acceptance—assets that can be leveraged to move from modelling to bankable, equitable implementations.

Key Findings

- Research on energy communities has accelerated markedly since 2019, yet most studies prioritise PV–BESS at neighbourhood level; integrated electricity–heat–mobility solutions and multi-actor coordination remain comparatively scarce.
- Methods skewed to scenarios and optimization, as scenario analysis and MILP/LP dominate; empirical validation, long-term evidence and shared datasets are limited.
- EVs underused as flexibility resources. EVs are often modelled as loads rather than controllable assets (smart charging, V2B/V2G), leaving value-stacking opportunities underexplored.
- ESG imbalance. Environmental aspects are frequently primary, while social justice, democratic governance and practical regulatory details are less consistently integrated, leading to feasibility gaps and inequitable outcomes.
- Swedish perspective. Only nine papers explicitly involve Sweden (~4.1%), but with relatively higher emphasis on PV/EV,

policy/regulation and social acceptance; heat-integration and prosumer/transition studies are less prominent.

Identified opportunities

- Co-optimize BESS and EVs. Combine community batteries with smart charging and V2B/V2G to deliver peak shaving, temporal arbitrage and ancillary services at building and neighbourhood levels.
- Exploit sector coupling. Leverage Sweden's building stock and district-heating context to integrate PV+BESS+heat pumps/thermal storage and to absorb surplus generation (incl. during negative price periods).
- Evidence-rich pilots. Shift from simulation-heavy studies to monitored demonstrators with open data, standard KPIs and multi-year reporting on performance, user behaviour and degradation.
- Fairness-by-design. Embed governance, cost/benefit sharing and protections for tenants/low-income users from the start to build durable social licence.

Recommendations

For policymakers:

- Create regulatory sandboxes for community-owned/shared PV–BESS–EV assets, peer-to-peer trading within the community, and participation in DSO/TSO flexibility markets.
- Provide tariffs and metering (dynamic capacity charges, sub/virtual metering) to reward congestion relief, temporal shifting and community-level flexibility.
- Set standard KPIs and disclosure rules covering techno-economics, flexibility revenues, asset health, social outcomes and governance, to reduce risk and improve comparability.
- Target sector-coupling calls that require electricity-heat-mobility integration and evaluate stacked value (peak reduction, resilience, emissions, user benefits).

For industry and community developers:

- Design for co-optimisation. Deploy control systems that jointly schedule PV, BESS and EV charging/V2B/V2G against real prices and grid signals.
- Invest in data. Use open interfaces and publish anonymised datasets and KPI dashboards to accelerate learning and financing.

For researchers

- Run long-term field studies on integrated BESS-EV-heat communities, tracking performance, control stability, user behaviour and degradation.
- Benchmark control strategies (rule-based, MILP/MPC, RL) on shared open datasets with common metrics and uncertainty.

- Evaluate governance experimentally, comparing sharing rules and their effects on acceptance, justice and sustained participation.
- Advance transferability. Study how results scale across building types, grid contexts and tariff regimes to inform national roll-out.

Contribution and next steps

The project delivers: (i) a curated database of 218 papers with rich categorical labels; (ii) an analytical framework spanning technology, economics, social and governance aspects; and (iii) a set of actionable pathways for Swedish implementation.

Inledning/bakgrund

In the face of escalating climate change and the pressing need for sustainable energy solutions, energy communities have emerged as a transformative approach to democratize and decentralize our energy systems [1]. These communities represent a paradigm shift from traditional centralized energy provision, enabling citizens, local authorities, and small businesses to actively participate in energy production, consumption, and management [2]. This transition is particularly crucial for Sweden, as Sweden aspires to achieve net-zero emissions by 2045 and a 100% renewable electricity system by 2040. These goals demand innovative approaches to energy system flexibility and citizen engagement.

The European Union has recognized the transformative potential of energy communities through the Clean Energy Package, with approximately 3,000 such initiatives now operating across 12 member states as of 2023 [3]. While countries like Germany and Denmark lead with 1,750 and 700 energy community initiatives respectively [4], Sweden reports approximately 200 such initiatives, indicating both growing momentum and significant untapped potential [5]. This difference between Sweden and its neighbors suggests that understanding and addressing the barriers to energy community development is critical for achieving national energy transition goals.

The central role of storage and electromobility

At the heart of successful energy communities lies the integration of **flexibility resources**, particularly Battery Energy Storage Systems (BESS) and Electric Vehicle (EV) charging infrastructure [6]. These technologies offer complementary benefits that are essential for managing the variability inherent in renewable energy systems [7]. BESS provide crucial balancing services for intermittent renewable sources, enhance grid resilience, and enable temporal shifting of energy consumption [8]. Meanwhile, EVs, which accounted for 55% of new car sales in Sweden in 2022, serve dual roles as both flexible loads and potential mobile energy storage units through vehicle-to-grid (V2G) capabilities [9].

The integration of BESS and EV charging infrastructure into buildings represents a critical frontier in the formation of successful energy communities in Sweden. When these flexibility resources are aggregated and optimized at the community level, they can provide system benefits that far exceed the sum of individual actions. This aggregation enables participation in flexibility markets, provides enhanced resilience during grid disturbances, and creates new revenue streams that improve the economic viability of renewable energy investments.

Multifaceted challenges requiring synthesis

Despite the clear potential, there remain substantial challenges in understanding and realizing the future role of BESS and EV charging in flexible energy communities in Sweden. These challenges span multiple dimensions:

Technical Complexity: Significant uncertainty persists regarding optimal sizing, placement, and control strategies for BESS and EV charging within different building types and community configurations. The technical challenges vary substantially between densely populated urban areas with mixed residential and commercial buildings, suburban communities dominated by detached houses with rooftop solar, and industrial areas with high energy demands and potential for large-scale flexibility provision. Each context requires tailored solutions that consider local grid constraints, renewable resource availability, and demand patterns [10].

Economic Paradigm Shifts: While high upfront costs of BESS and EV charging infrastructure have historically been barriers to adoption, Sweden's energy market is experiencing fundamental changes that could reshape the economic landscape. The increasing frequency of negative electricity prices presents a new paradigm that could transform the business case for energy storage. However, the economic viability also depends on factors such as capacity market participation, grid service provision, and the evolution of electricity tariff structures, all of which remain uncertain and require careful analysis [11].

Social Dynamics and Acceptance: There exists limited understanding of user acceptance and behavior regarding shared energy resources within community settings. Questions persist about how residents perceive and engage with community-owned storage systems, what motivates participation in demand response programs, and how to ensure equitable distribution of benefits and costs within diverse communities. The success of energy communities fundamentally depends on social cohesion and collective decision-making, yet these social dimensions are often overlooked in technical and economic analyses [12].

Regulatory Evolution and Uncertainty: Swedish regulatory frameworks are still evolving to accommodate new energy community models, creating uncertainty for potential adopters. While the transposition of EU directives has established the legal basis for energy communities, practical implementation faces challenges related to grid connection procedures, market access for small-scale flexibility providers, and the allocation of network costs and benefits. This regulatory uncertainty extends to tax treatment, subsidy mechanisms, and the long-term stability of support schemes [13].

Knowledge gap and research imperative

Despite growing research interest in energy communities, BESS, and EV integration, there remains a critical lack of comprehensive synthesis that brings together these multifaceted aspects in the Swedish context. Existing studies tend to focus on isolated technical solutions, economic optimization models, or policy analyses, failing to capture the complex interactions between technology, economics, social dynamics, and regulation that determine real-world success. This fragmentation of knowledge hinders the development of effective strategies and policies to leverage the full potential of building-integrated BESS and EV charging in creating flexible, resilient energy communities.

Moreover, the temporal dimension adds another layer of complexity that current research inadequately addresses. Energy community concepts are relatively recent, with few operational examples exceeding five years. This limited operational history makes it challenging to assess long-term performance, particularly considering factors such as battery degradation, evolving EV technology, changing user behaviors, and shifting policy landscapes. Time emerges as the biggest uncertainty, affecting everything from technology performance to social learning and regulatory stability.

Scope and approach of this synthesis study

This synthesis study aims to address these knowledge gaps by providing a comprehensive analysis of the technical, economic, social, and governmental aspects of energy communities, with a special focus on BESS and EV integration in Swedish context. Using a multidisciplinary approach, knowledge is synthesized from scientific publications to identify best practices, highlight critical uncertainties, and point toward future research needs.

The study employs innovative methodological approaches, including advanced text mining techniques with natural language processing and topic modeling, to analyze a selected group of literature and identify emerging trends and gaps. This data-driven approach provides a more objective and comprehensive view of the field than traditional literature reviews, enabling the identification of patterns and connections that might otherwise remain hidden.

Significance for Swedish energy transition

The significance of this synthesis extends to multiple stakeholder groups critical for Sweden's energy transition. Business owners will gain insights into viable models for integrating BESS and EV charging into their buildings and participating in energy communities. Governmental bodies at national, regional, and municipal levels will receive evidence-based insights to inform policy development, potentially accelerating the adoption of these technologies while ensuring equitable outcomes. Energy users will better understand the benefits and challenges of participating in energy communities, enabling more informed decision-making. Researchers will identify critical areas for future investigation, potentially spawning new research projects and collaborations that advance the field.

This synthesis also opens several avenues for future research and development. It may highlight needs for pilot projects testing specific BESS and EV integration strategies under Swedish conditions, inspire studies on new business models adapted to Nordic energy markets, or prompt investigations into the long-term impacts of widespread energy community adoption on grid stability and market dynamics. By identifying both successful practices and persistent challenges, the study will help prioritize research funding and policy attention where it can have the greatest impact.

Structure of this report

Following this introduction, the implementation section presents the methodology for conducting this comprehensive synthesis, including systematic literature review process and analytical framework. The result section follows the implementation section to present data analysis outcomes of the collected literatures in the database. The discussion section integrates these findings to identify critical success factors, persistent barriers, and emerging opportunities, with extra focus on Swedish context. Finally, we present concrete recommendations for different stakeholder groups and outline a research agenda to address the most pressing knowledge gaps.

Genomförande

This synthesis study employed a mixed literature review methodology to map the current state of knowledge within energy communities. The review process was designed to capture the interdisciplinary nature of energy communities, encompassing technical, economic, environmental-social-governmental (ESG), methodological as well as several different dimensions.

Literature assembly strategy

The literature assembly followed a structured dual-phase approach:

Phase 1: Keyword Development and Search Strategy

A comprehensive keyword strategy was developed to ensure broad coverage of the research domain. Primary keywords included "battery energy storage systems", "BESS", "EV-charging", "electric vehicles", "energy communities/community", "community energy", "flexibility", and "Sweden". These were supplemented with secondary keywords and synonyms such as "renewable energy cooperatives", "smart grids", "demand response", "peer-to-peer energy trading", and "virtual power plants".

Complex search queries were constructed using Boolean operators to capture the intersection of technologies and community applications. For example: ("BESS" OR "battery storage") AND ("energy community" OR "community energy") AND ("flexibility" OR "grid services"). This approach ensured that retrieved papers addressed the integration of storage technologies within community contexts rather than isolated technical studies.

Phase 2: Research Database Selection and Search Execution

While the initial plan included comprehensive searches across Scopus and Web of Science, preliminary keyword analysis revealed that specialized energy databases provided more targeted and relevant results for this interdisciplinary field. ScienceDirect and IEEE Xplore emerged as the best databases for this topic due to their strong coverage of both energy engineering research and the socio-technical aspects of energy transitions. These databases offered superior indexing of energy community research compared to general scientific databases, with more nuanced categorization of interdisciplinary energy studies.

The systematic search covered publications from 2016 to present (2025), corresponding to the post-Paris Agreement period when interest in decentralized energy solutions accelerated significantly. The search was restricted to peer-reviewed journal articles in English within the domains of engineering, energy, and social sciences.

Screening of the papers

The initial search yielded over 500 potential sources, which were subjected to a multi-stage screening process:

1. **Title and abstract screening** to assess relevance to energy communities
2. **Full-text review** applying inclusion/exclusion criteria
3. **Quality assessment** based on methodological rigor, citation impact, and relevance to the synthesis objectives

Inclusion criteria focused on studies that explicitly addressed community-scale energy systems with distributed resources, storage, or flexibility services. Exclusion criteria eliminated studies focusing solely on individual technologies without system integration perspectives or community considerations.

This screening process resulted in 218 peer-reviewed academic papers. Supplementary grey literatures, however, were excluded due to the following 2 reasons:

1. The number of academic papers has exceeded 200, which fulfils the requirement on a minimum of 200 publications
2. Grey literatures are often not well indexed by bibliometrics, making them not standard documents to process in reference management tools such as Zotero or Mendeley. This brought much hinders on data processing and thus becomes quite time consuming if included in the database.

Analytical framework

Multi-dimensional categorization system

To structure the analysis of collected literature, a comprehensive categorization framework was developed addressing four key dimensions:

Table xx. Multi-dimensional categorization system	
Category	Keywords
Technology	PV; Battery; EV; Heat pumps; Other
Geographical level	<5 Buildings; Neighbourhood; District; City
Building types	Resid villa; Resid multi-family; Commercial; Public; Industry
Theme	Prosumer; Transition; Microgrid; Control; VPP; Trading; Sharing; Optimisation, Flexibility
Economic objectives	Sys cost minimization; Oper cost minimization; Self-consumption rate; NPV/DPP/etc.
Method	(Mixed Integer) LP; Non-LP; Agent Based Modelling; LCA; Machine Learning; Scenario Analysis
Environmental aspects	Emission; Circularity
Social aspects	Energy justice; Social acceptance; Community engagement; User behavior

Category	Keywords
Governmental aspects	Policy; Democracy; Regulations; Market issue; Business model
Data availability	Open data unrestricted; Open data on request; Open data not available
Paper type	Technical research paper; Non-technical research paper; Review paper

Machine learning-assisted analysis

Given the volume of literature (218 peer-reviewed academic papers), a hybrid human-machine approach was employed for efficient categorization:

1. **Manual annotation phase:** A stratified sample of 40 papers (approximately 20%) was manually categorized by expert reviewers to establish ground truth across all dimensions.
2. **NLP-powered classification:** Natural language processing techniques were applied to automate categorization of the remaining papers:
 - Text preprocessing and feature extraction from titles and abstracts
 - TF-IDF vectorization to identify key terms and concepts
 - Supervised classification algorithms to assign papers to categories
 - Topic modeling to identify emerging themes and research clusters

Synthesis methodology

The synthesis process followed a three-stage analytical approach:

Stage 1 - Bibliometric analysis: Mapping the evolution of the field through publication trends, citation networks, author collaborations, and geographic distribution of research. This revealed research hotspots and knowledge flows in the energy community domain.

Stage 2 - Thematic synthesis: Systematic extraction and integration of findings across the four dimensions. Key themes were identified through iterative coding, with particular attention to:

- Technological integration challenges and solutions
- Economic viability factors and business model innovations
- Social acceptance determinants and engagement strategies
- Regulatory enablers and barriers

Stage 3 - Critical analysis: Integration of findings to identify:

- Knowledge gaps critical for Swedish energy transition
- Conflicting findings requiring further investigation
- Best practices with high transferability to Swedish contexts

- Emerging trends and future research directions

Special attention was paid to studies from Nordic countries or similar contexts to ensure relevance for Swedish policy and implementation.

Limitations

This synthesis study acknowledges several limitations:

- **Language bias:** Restriction to English-language publications may have excluded relevant Nordic research published in Swedish or other Scandinavian languages
- **Publication bias:** Focus on peer-reviewed literature may underrepresent innovative industry practices not yet documented academically
- **Temporal constraints:** The rapid evolution of the field means very recent developments (post-2024) may not be fully captured
- **Geographic transferability:** While efforts were made to identify Swedish-relevant studies, some findings from different regulatory and cultural contexts may have limited applicability

Resultat

Overview of the database

The synthesis study generated a compiled database which contains a total of 218 scientific research papers focusing on the topic of **Energy Communities**. In the database, each entry (or row) represents a unique paper, accompanied by a range of bibliographic information and detailed thematic labels. The dataset includes 64 columns in total. The first set of columns records bibliometric and descriptive information such as:

Paper Number (paper index in the dataset), **Citations** (number of times the paper has been cited, until 2025-05-23), **Abstract**, **DOI**, **ISSN**, **Pages**, **Volume**, **Journal title**, **Publication date**, **Authors**, **Paper title**.

Starting from the column "PV", the remaining columns serve as keyword-based binary indicators describing the research scope, methodology, and other characteristics of the papers. For these keyword columns:

- A value of 1 indicates that the paper explicitly covers the topic or method described by the keyword.
- A value of 0 indicates that the topic is not addressed in the paper.

Examples of such keyword columns include:

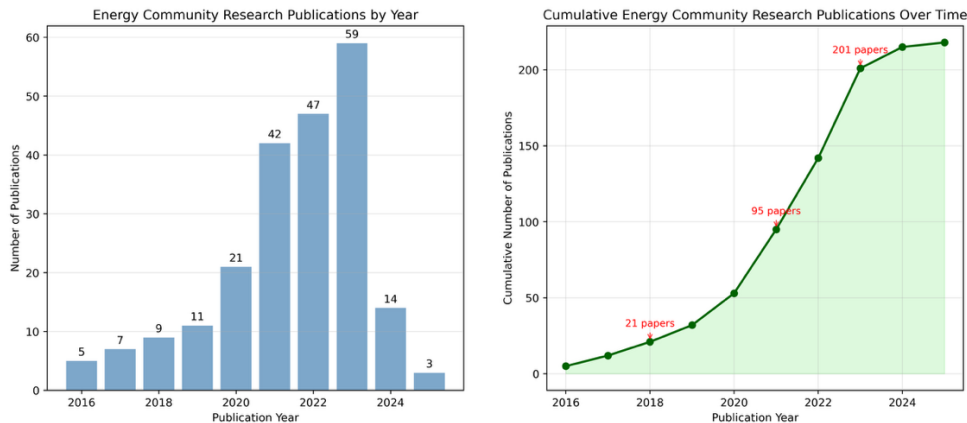
- **Technology focus:** PV, Battery, EV, Heat pumps, Other technology.
- **Geographical scale:** e.g., Geographical level: <5 buildings, Neighbourhood, City, National.
- **Building types:** Resid single-family, Resid multi-family, Commercial, Industrial.
- **Research themes:** Theme: Sharing, Theme: Optimisation, Theme: Flexibility, etc.
- **Methodologies:** Method: ML, Method: simulation, Method: scenario analysis, and others.
- **Data availability** and **Paper type:** specifying openness of datasets and classification of research paper type.

This structured keyword tagging system allows for both quantitative and qualitative analysis of the literature, enabling an in-depth synthesis of technological focus areas, methodological approaches, and thematic trends in the study of energy communities.

Publications temporal trends

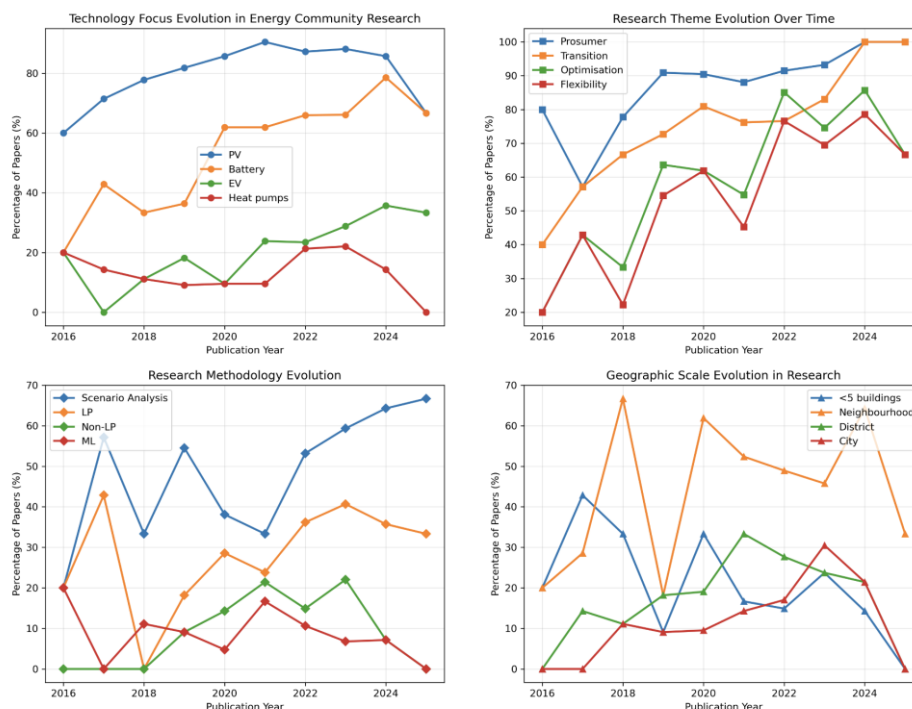
Based on the database's collection of 218 scientific papers, the left-hand side subplot of figure xx presents the annual distribution of publications related to energy community research from 2016 to 2025. The trend reveals a growth in research activity over the past decade, with particularly notable increases after

2019. A sharp acceleration of publications started in 2020 and peaked at 59 publications in 2023. Although the number dropped in 2024 and 2025 (partial year, until May 2025), this decline is likely due to the incomplete data coverage for 2025 rather than a genuine reduction in research interest.



The right-hand side subplot of figure xx complements this view by illustrating the cumulative growth in publications over time. The cumulative curve shows a gradual increase between 2016 and 2019, followed by a steep upward trajectory beginning in 2020. This rapid accumulation indicates a strong surge of academic and practical interest in energy communities, reflecting the rising relevance of the topic in energy transition policies, technological innovations, and sustainable development strategies.

Together, these figures highlight two critical observations. First, the research field of energy communities is still relatively young but expanding rapidly, especially in the post-2020 period. Second, the surge in publications aligns with global policy shifts and increased funding for decentralised, renewable-based energy systems. This suggests that the growth is likely driven by both technological advancements—such as PV, battery storage, and smart control systems—and broader socio-political emphasis on decarbonisation and community-driven energy initiatives.



The composite figure xx presents the temporal evolution of four key dimensions in energy community research: technology focus, research themes, methodologies, and geographic scales.

Technology Focus Evolution: Photovoltaics (PV) dominate the technological landscape across the entire period. Battery storage technologies have shown a strong upward trajectory, increasing from around 20–40% in early years to above 70% in 2024, indicating growing interest in storage as a complement to renewable generation. Electric vehicles (EVs) started with modest coverage but have steadily gained ground, reaching nearly 40% by 2024. Heat pumps have maintained a low and fluctuating presence, rarely exceeding 20%, suggesting they remain a niche focus in the energy community literature compared to PV and batteries.

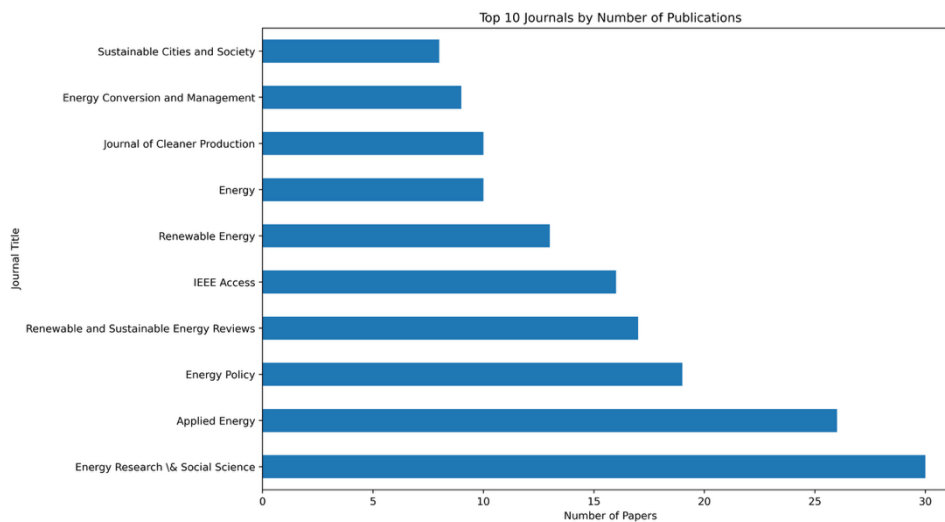
Research Theme Evolution: Themes related to **Prosumers** and **Transition** dominate, with Prosumer-focused studies reaching near-universal coverage (>95%) in the last few years. Transition-oriented research also shows sustained growth, rising from about 50% in 2016 to full coverage (100%) by 2024–2025. Optimisation and Flexibility varies over time, possibly linked to the increasing sophistication of community energy management strategies.

Research Methodology Evolution: According to the analysis, scenario analysis emerges as the dominant methodology over time, reflecting it as a widely adopted analysis method. Linear programming (LP) methods appear in a moderate but consistent proportion of papers, while non-linear programming (Non-LP) methods and machine learning (ML) approaches remain less frequent, generally below 20% per year.

Geographic Scale Evolution: Neighbourhood-level studies are by far the most prevalent, indicating a strong research interest in community-scale applications rather than individual buildings or city-wide systems. The category “<5 buildings” shows a declining trend after early prominence, reflecting perhaps a shift from micro-scale case studies to larger, more representative scales. District- and city-level studies maintain low, suggesting these scales are less frequently explored, possibly due to complexity in data and system modelling.

Publications categorical analysis

The publications often cluster around certain journals, as shown in figure xx below:



Technical research papers distribute between different technical-focus scientific journals such as *Applied Energy*, *Energy*, *Energy Conversion and Management*. Review articles almost center around *Renewable and Sustainable Energy Reviews*. Non-technical articles, for example social and governmental studies, business studies or policy studies, are often published in *Energy Research and Social Science* and *Energy Policy*.

Diving into the subjects of the papers, we can also notice some interesting patterns, as shown in figure xx below.

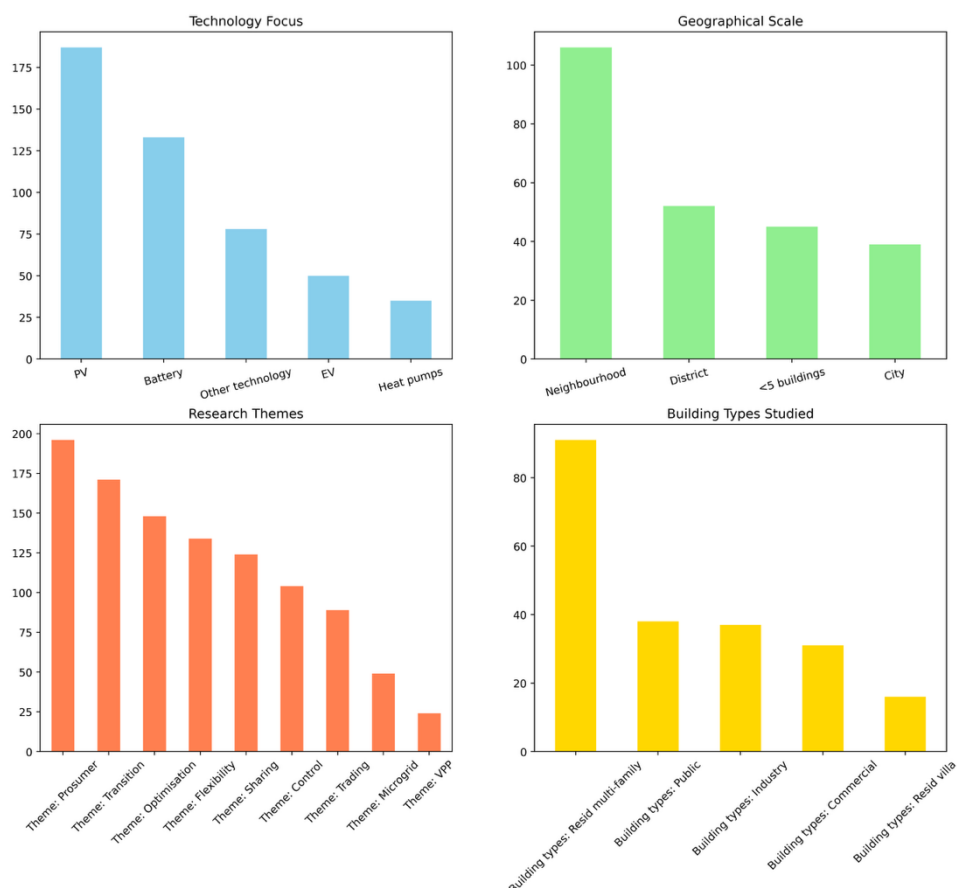
Technology Focus: PV technology is by far the most studied, appearing in over 180 papers—more than 80% of the dataset—reflecting its central role in energy community systems. Battery storage follows as the second most prevalent technology, with over 130 studies, highlighting its importance for energy balancing and self-consumption optimisation. EVs (≈ 50 papers) and heat pumps (< 40 papers) remain relatively less explored, suggesting potential areas for future research expansion. “Other technologies” (e.g., fuel cells, CHP systems) show a moderate presence.

Geographical Scale: Neighbourhood-scale studies dominate the dataset, with more than 100 papers, indicating that this scale is the most relevant for energy

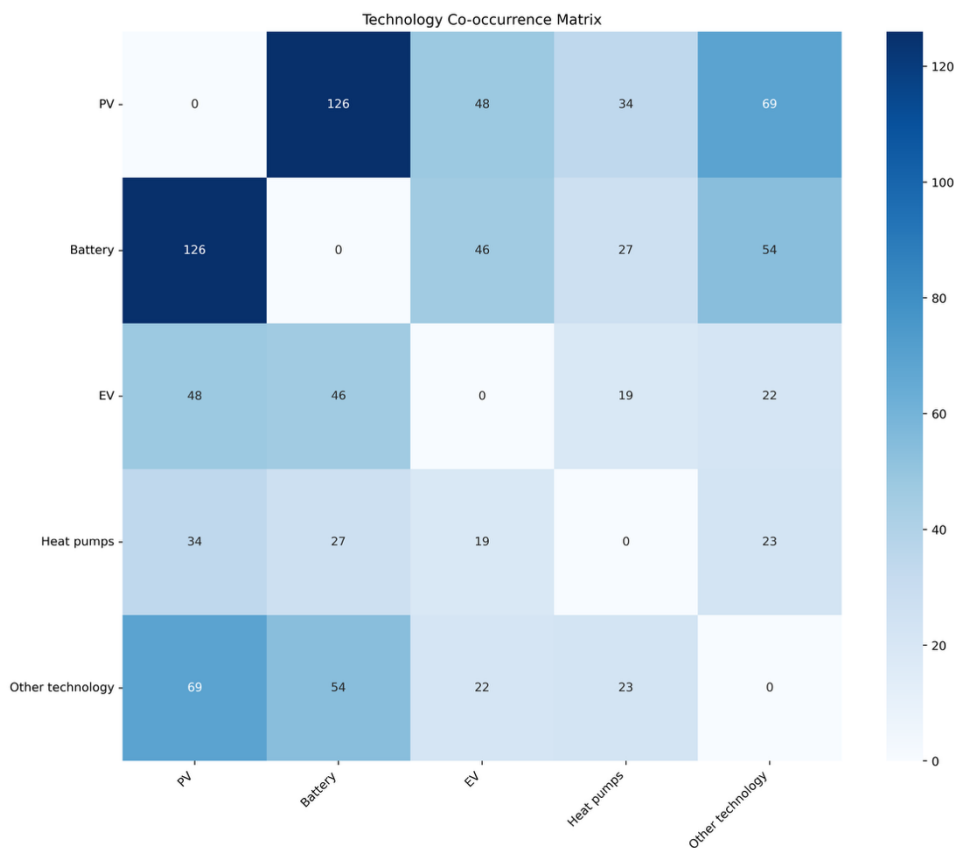
community modelling and implementation. District-scale studies (≈ 50 papers) are less common, and micro-scale cases (< 5 buildings) and city-wide analyses are even less frequent.

Research Themes: The most common research themes are Prosumer (nearly 200 papers) and Transition (≈ 170 papers) studies, reflecting the social and systemic transformation focus of the field. Optimisation and Flexibility are also highly prevalent, each appearing in more than 120 papers, pointing to a strong emphasis on improving technical and economic performance. Other themes such as Sharing, Control, and Trading appear in smaller numbers, while Microgrid and Virtual Power Plant (VPP) are niche themes with limited coverage, indicating more specialised or emerging research directions.

Building Types Studied: Multi-family residential buildings dominate the building-type analysis, appearing in nearly 90 papers. Public buildings, industrial facilities, and commercial buildings appear less frequently, while villa-type residential buildings are the least studied category.



If we take a deeper look into technology focus, the following co-occurrence matrix shows interesting pattern.



The figure presents a co-occurrence matrix of technologies studied in the context of Energy Communities, highlighting how frequently different technologies are researched together. The darker colors in the heatmap indicate higher levels of co-occurrence.

Photovoltaics (PV) and Batteries show the strongest relationship, co-occurring in 126 papers, confirming their dominant role as a coupled system in energy community studies. PV also co-occurs frequently with Other technologies (69 papers) and with Electric Vehicles (EVs, 48 papers), showing its centrality as a foundational technology. Batteries appear often alongside other technologies too, co-occurring 54 times with Other technologies and 46 times with EVs. Heat pumps are less frequently combined with other technologies but still show moderate links, such as 34 co-occurrences with PV.

Beyond pairwise relations, multi-technology system configurations reveal interesting patterns:

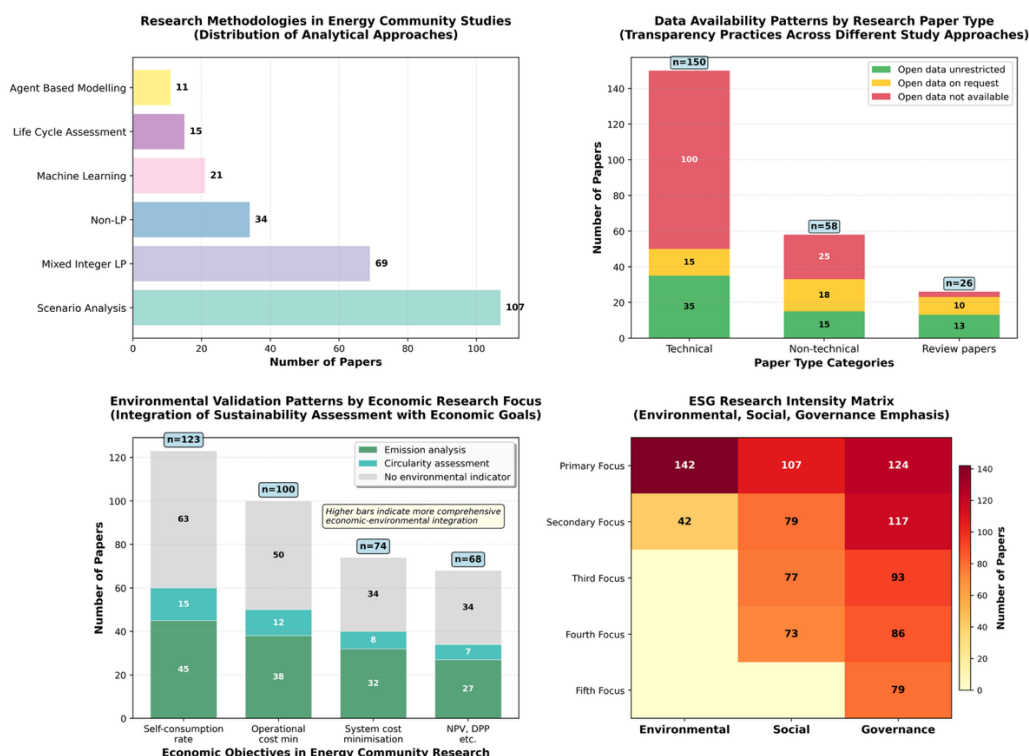
- The most common multi-technology combination is Battery + PV (47 papers).
- Expanded systems such as Battery + Other technology + PV (25 papers) and Battery + EV + PV (20 papers) are also widely studied, indicating strong interest in hybrid setups.
- Broader integrations appear less frequently but are still notable, for example:

- Battery + EV + Heat pumps + Other technology + PV (11 papers)
- Battery + EV + Other technology + PV (8 papers)
- Battery + Heat pumps + Other technology + PV (6 papers)
- Battery + EV + Heat pumps + PV (5 papers)
- Heat pumps + Other technology + PV (5 papers)
- Battery + Heat pumps + PV (4 papers).

Overall, the results show that while PV and Battery systems dominate research, there is a growing interest in integrating EVs, heat pumps, and other technologies into more complex multi-technology energy community configurations. This reflects a trend towards more holistic system designs that aim to capture synergies across diverse energy vectors.

Other research landscapes

Figure xx provides a comprehensive overview of current trends, methodologies, and thematic emphases in scientific research on Energy Communities:



Research Methodologies in Energy Community Studies: The top-left bar chart illustrates the distribution of analytical approaches employed in Energy Community research. The analysis shows that Scenario Analysis is the most commonly used methodology, appearing in 107 papers, indicating a strong focus on exploratory modeling and future-oriented planning. Mixed Integer Linear Programming (MILP) follows, used in 69 papers, reflecting its popularity for optimization in energy system design. Non-linear and linear programming (Non-LP) methods are used in 34 papers, while Machine Learning is applied in 21

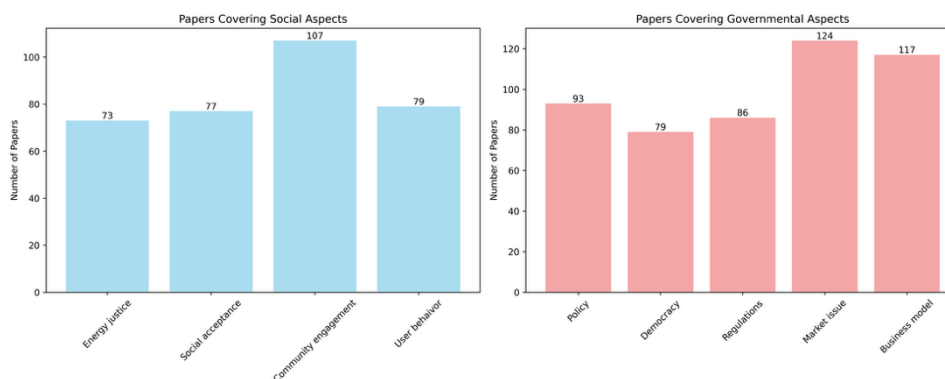
papers, showing growing but still limited use of data-driven techniques. Life Cycle Assessment (LCA) and Agent-Based Modelling (ABM) are less common, with 15 and 11 papers respectively, suggesting underexplored potential in these areas for deeper sustainability and behavior modeling.

Data Availability Patterns by Research Paper Type: The top-right stacked bar chart shows transparency practices in terms of data availability across different types of research papers. Among Technical papers (n=150), only 23% (35 papers) provide open access to data, 10% (15 papers) provide data upon request, while 67% (100 papers) do not provide data access. Non-technical papers (n=58) and Review papers (n=26) show slightly better transparency, with around 43% and 50% of papers respectively offering open data or data on request. Despite growing awareness of reproducibility, a significant number of studies still do not make their data available, highlighting a major area for improvement in research transparency.

Environmental Validation by Economic Research Focus: The bottom-left stacked-bar chart evaluates how environmental indicators are integrated into economically-focused energy community studies. Papers with a Self-consumption rate objective show the highest level of environmental validation (n=123), with 15 papers including emission analysis and 45 papers incorporating circularity assessments. Studies focused on Operational cost minimization (n=100) and System cost minimization (n=74) also include notable but lower levels of environmental validation. Net Present Value (NPV) and Discounted Payback Period (DPP)-oriented studies (n=68) show the least comprehensive integration, with over 50% of the papers (34 papers) excluding any environmental indicators. These results indicate a trade-off between economic modeling detail and environmental assessment, suggesting a need for more holistic research approaches.

ESG Research Intensity Matrix: The last subplot on bottom-right is a heatmap representing the thematic emphasis on Environmental, Social, and Governance (ESG) dimensions across varying levels of research priority. Environmental focus is the most common as a primary research priority (142 papers), followed by Governance (124 papers) and Social aspects (107 papers). As the research priority shifts from primary to lower ranks, the number of papers decreases, though Governance and Social aspects still receive considerable attention as secondary and tertiary priorities. The Environmental dimension shows a sharp drop-off beyond the primary and secondary focus, indicating it is often treated as either a central topic or not at all. This matrix reveals that while ESG themes are well-represented overall, they are rarely addressed with equal depth across studies, pointing to a fragmentation in ESG integration.

A more detailed social-government aspect analysis is shown in figure xx.



For social aspects, community engagement (107 papers) emerges as the most frequently studied social aspect, showing that scholars recognize the critical role of citizen involvement and participatory practices in successful energy community projects. User behavior (79 papers) and social acceptance (77 papers) are moderately represented, indicating growing but not yet dominant interest in how individuals and groups interact with, adopt, or resist energy community initiatives. Energy justice (73 papers) receives the least attention, despite its importance for ensuring equitable access and fair distribution of benefits in energy transitions.

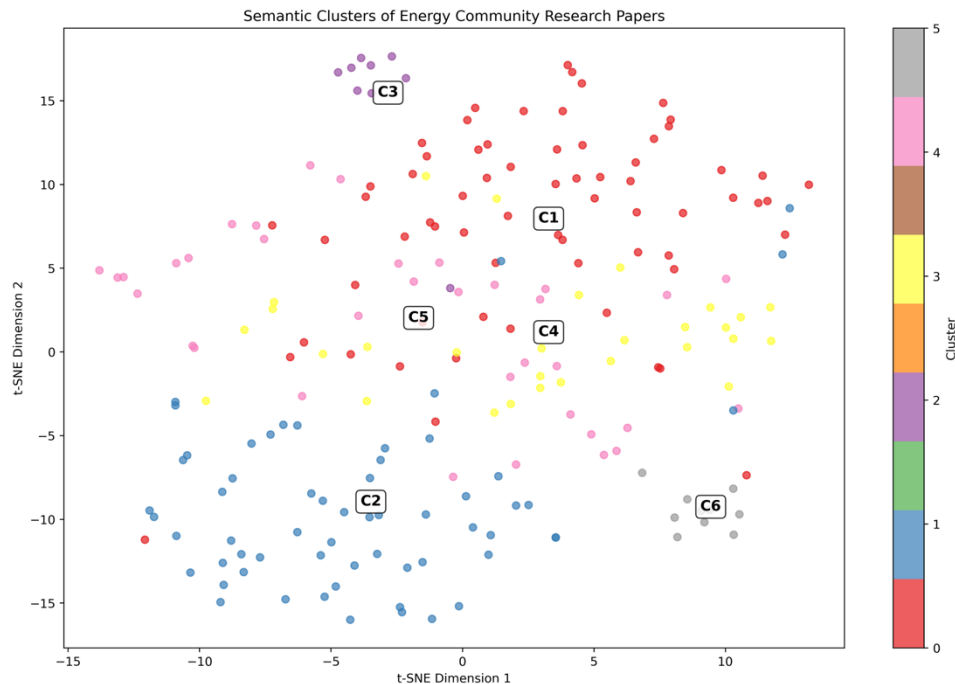
It can be seen that while social participation is well-covered, research tends to emphasize **engagement and acceptance** rather than **equity, fairness, and justice**, suggesting a need for stronger integration of social science perspectives into technical and economic studies.

For governmental aspects (right panel), market issues (124 papers) and business models (117 papers) dominate governmental discussions, reflecting the strong focus on the economic regulation and commercialization of energy communities. Policy (93 papers) and regulations (86 papers) are moderately covered, showing considerable interest in institutional frameworks but less than market-centered topics. Democracy (79 papers) is the least covered, suggesting limited attention to participatory governance, decision-making structures, and democratic control within energy communities.

We can see from the data that research heavily prioritizes **market mechanisms and business viability** over **governance and democracy**, indicating that while financial and structural models are being developed, questions of inclusiveness, fairness, and collective decision-making remain underexplored.

Text mining analysis for paper abstracts

Text mining (clustering) analysis has been carried out for paper abstracts. Figure xx illustrates the results of the semantic clustering analysis using t-SNE dimensionality reduction, which groups Energy Community research papers based on thematic similarity of keywords. Six distinct clusters were identified, each representing a different research orientation within the field.



Cluster 1 (C1 – 67 papers):

- **Keywords:** battery, community, consumption, cost, demand, grid, local, power, renewable, storage
- **Focus:** This is the largest cluster, emphasizing **technical and operational aspects** of energy communities, particularly around renewable integration, storage solutions, and demand–supply balancing.
- **Implication:** It highlights a strong research concentration on energy optimization and system design, reflecting the dominance of technical approaches in the literature.

Cluster 2 (C2 – 60 papers):

- **Keywords:** business, community, initiative, local, new, policy, project, renewable, social, transition
- **Focus:** Papers in this cluster emphasize **policy, business models, and social transitions**, focusing on how communities organize, initiate, and manage renewable energy projects.
- **Implication:** This cluster captures the **social innovation and governance** side of energy communities, pointing to an increasing interest in **policy frameworks and collective action**.

Cluster 3 (C3 – 9 papers):

- **Keywords:** benefit, community, cost, demand, generation, load, market, power, storage
- **Focus:** This smaller cluster is centered on **cost-benefit and market aspects**, linking generation and storage with economic trade-offs.

- **Implication:** While limited in size, this cluster underlines the **importance of techno-economic evaluations** for energy community viability.

Cluster 4 (C4 – 29 papers):

- **Keywords:** battery, building, community, consumption, different, economic, electricity, renewable, sharing, storage
- **Focus:** This cluster explores **building-level energy sharing and storage systems**, with a particular focus on economic outcomes and local consumption.
- **Implication:** It suggests growing attention to **decentralized building-level communities and peer-to-peer energy sharing models**.

Cluster 5 (C5 – 35 papers):

- **Keywords:** benefit, community, consumer, cost, electricity, local, market, solar, storage, value
- **Focus:** Research here emphasizes the **value distribution and consumer benefits** of energy communities, analyzing electricity markets, solar integration, and fairness of cost-sharing.
- **Implication:** This reflects concerns about **equity, value creation, and consumer roles**, pointing toward broader social acceptance challenges.

Cluster 6 (C6 – 10 papers):

- **Keywords:** case, community, demand, factor, local, member, operation, policy, renewable
- **Focus:** This cluster contains **case-study-based research**, addressing local factors, member participation, and operational aspects of energy communities under specific policy conditions.
- **Implication:** These case studies provide **practical validation of theoretical models**, but their small number suggests limited empirical grounding in the field overall.

The results show a clear split between **technical/optimization-oriented clusters (C1, C4) and social, policy, and governance-oriented clusters (C2, C6)**. Clusters focusing on economic and consumer benefits (C3, C5) act as a bridge between technical system studies and socio-political discussions. The relative dominance of C1 and C2 indicates that research is most concentrated on technical optimization and social/policy frameworks, but integration across these domains remains limited. Smaller clusters (C3, C6) point to underexplored areas such as case-based validation and comprehensive cost-benefit studies, highlighting opportunities for future research.

Based on the semantic analysis, word clouds are generated.

Table xx. Sweden vs Global: Research focus comparison			
Technologies	Sweden	Global	Difference
Social acceptance	55.6%	34.4%	+21.1%
Community engagement	44.4%	49.3%	-4.8%
User behavior	44.4%	35.9%	+8.6%
Governmental Aspects	Sweden	Global	Difference
Policy	66.7%	41.6%	+25.0%
Democracy	44.4%	35.9%	+8.6%
Regulations	55.6%	38.8%	+16.8%
Market issue	55.6%	56.9%	-1.4%
Business model	55.6%	53.6%	+2.0%
Research Themes	Sweden	Global	Difference
Prosumer	77.8%	90.4%	-12.7%
Transition	66.7%	78.9%	-12.3%
Microgrid	33.3%	22.0%	+11.3%
Control	44.4%	47.8%	-3.4%
VPP	22.2%	10.5%	+11.7%
Trading	33.3%	41.1%	-7.8%
Sharing	55.6%	56.9%	-1.4%
Optimisation	66.7%	67.9%	-1.3%
Flexibility	55.6%	61.7%	-6.2%

Overall, Sweden contributes only a small fraction of the global Energy Community literature (4.1%), yet its research is thematically diverse and methodologically varied. Compared to global patterns, Swedish studies stand out in their emphasis on PV, EVs, social acceptance, energy justice, and policy/regulatory aspects, while being less active in exploring prosumer dominance, transition narratives, and thermal technologies such as heat pumps. This suggests that Sweden’s contribution is particularly relevant for understanding the social and governance dimensions of energy communities, complementing the more technology- and market-driven global research trends.

Diskussion

Global perspective from the database analysis

The database shows a rapidly growing but still fragmented field. Publications accelerate sharply after 2019 and peak in 2023, reflecting how energy communities have moved from concept to mainstream research agenda, yet with uneven coverage across technologies, methods and scales [14], [15]. Most work

concentrates at neighbourhood level and around PV–battery pairings; EVs and heat pumps appear in some papers, but integrated multi-technology solutions remain scarce [16], [17]. In practice this means global research has mapped PV + BESS for local balancing far better sector coupling, transport–power integration, and city/district coordination [18].

Technology co-occurrence confirms that PV and batteries dominate both individually and together [16]. However, the comparatively small share of studies combining BESS and EVs signals missed insights on charging strategies, V2X readiness, and shared-asset operation, despite their clear complementarities for flexibility and value stacking [19], [20]. EVs are often treated as isolated loads rather than as controllable, market-facing resources [19], [20]. This narrows the design space for community optimisations and underestimates revenue/risk profiles that depend on temporal arbitrage, ancillary services, and capacity products [19], [20].

Methodologically, scenario analysis and mathematical programming (especially MILP) dominate, while real-world validation is relatively scarce and data transparency uneven [15], [16]. Only a minority of technical papers provide open datasets; few studies publish long-run operational evidence on degradation, user behaviour, or control performance [21], [22].

Thematic balance is also uneven. Prosumer/transition studies are pervasive, but equity-centred concepts such as energy justice and democratic governance appear less often or as secondary concerns [23], [24]. On the policy/market side, “business model” and “market issues” receive more attention than democratic control and regulatory detail, suggesting that many designs optimise under special designed tariffs or market assumptions rather than the realities of interconnection rules, network charges, and market access for small actors [25]. This skews feasibility assessments and can overstate transferrability [24], [25].

In short, the global literature provides a solid base on PV–BESS communities, an expanding but under-integrated view on EVs. Future works should consider three directions: (1) studies that co-optimize multiple vectors (electricity, heat, mobility) and revenue streams, (2) standardised economic and performance reporting from real assets, and (3) governance models that embed fairness and participation without sacrificing operational excellence [14]–[18].

Swedish perspective: what Sweden can learn and do differently

Only 4.1% of papers in the database explicitly involve Sweden, even though Swedish studies show distinctive emphases: stronger focus on PV, EVs, and policy/regulation; relatively higher attention to social acceptance and energy justice; and more microgrid/VPP thinking than the global average. Conversely, Sweden appears less represented in prosumer/transition work and thermal integration (e.g., heat pumps). This mix suggests that Swedish research is well placed to shape rules and social licence—but could deepen practical integration of mobility and heat with electricity at community scale [24], [26].

Several correct insights are drawn from the literatures:

1. **Integrate EVs as flexibility assets, not just loads.** Combining smart charging, V2B/V2G pilots, and community-level BESS produces complementary time-shifting, peak-shaving, and reserve services; co-optimisation models point to material gains when EV/BESS are scheduled together, and Swedish pilots can lead on the empirical validation [19], [20], [27].
2. **Exploit sector coupling that others underuse.** Sweden's district-heating footprint and building stock make it well suited to demonstrate electricity-heat-mobility coupling (e.g., PV+BESS+HP with thermal storage; using heat networks as "sinks" for excess PV/negative prices) [17], [28].
3. **Shift from simulation-heavy to evidence-rich.** Sweden's comparative advantage could be rigorous field data: open datasets, standardised KPIs, and multi-year monitoring of real communities. This directly addresses global gaps in reproducibility and bankability [14], [15], [30].
4. **Design for fairness from early stage.** Hard-wire democratic governance, cost/benefit-sharing rules, and protections for tenants and low-income households are some of the measures for Sweden to leverage social strengths to build durable community models [23], [26].
5. **Broaden the building mix.** International case work skews toward multi-family housing; bringing industrial/commercial actors into communities (anchor loads, roofs, and flexibility) can unlock outsized system value in Sweden [29].

Implications for Swedish policy, market design and implementation

- **Regulatory sandboxes for integrated assets.** Simplified, time-bound pilots where communities can co-own/share PV/BESS/EV infrastructure, trade within the community and bid services to DSO/TSO, and test V2G/V2B—paired with standard reporting templates for public learning [21], [25], [30].
- **Tariff and metering that reward flexibility.** Pilot stronger temporal/locational signals (dynamic capacity charges, credits for congestion relief) and enable sub-/virtual metering for shared assets—aligning private incentives with grid needs [19], [20].
- **Standardised KPIs and disclosure.** Require techno-economic KPIs, flexibility revenues, asset health, social outcomes, and governance reporting to close the transparency gap [14], [15], [21].
- **Make sector coupling investable.** Targeted calls that require electricity-heat-mobility coupling and evaluate projects on stacked value (peak reduction, resiliency, emissions, user benefits) [17], [28].

Research priorities suggestion

- Longitudinal field studies on integrated BESS-EV-heat communities, including winter performance, degradation, user behaviour, and control stability under real prices [14], [15].
- Comparative trials of control strategies (rule-based, MILP, MPC/RL) using shared, open datasets to benchmark performance and robustness [16], [19].

- Governance experiments testing different sharing rules and measuring impacts on acceptance and justice [23], [24].

Implementation priorities

- Launch 3–5 flagship demonstrators in contrasting contexts: (1) urban multi-family with shared EV charging and BESS; (2) mixed-use neighbourhood with PV+BESS+HP and thermal storage; (3) industrial/commercial park aggregating flexibility to the DSO/TSO—each publishing open data and a replication guide [25], [26], [30].

Publikationslista

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Bilagor

Energy community publications database:

http://github.com/GoldenPotatis/Synthesis_study