24th International Conference on Renewable Energies and Power Quality (ICREPQ'26)
Santander (Spain), 10th to 12th June 2026
ISBN-13: 978-84-09-82044-3

Community Energy as a Distributed Flexibility and Social Innovation Mechanism in Central Europe: A V4 Comparative Study

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Abstract. The rapid expansion of decentralized renewable energy generation fundamentally transforms electricity systems by introducing variability, bidirectional flows and local balancing challenges. While technological flexibility solutions such as storage and grid reinforcement remain essential, they alone cannot ensure efficient operation without social acceptance and local coordination. Energy communities have therefore emerged as hybrid socio-technical arrangements integrating distributed generation, collective consumption and participatory governance. This paper investigates energy communities in the Visegrád countries (Hungary, Poland, Czechia and Slovakia) from a combined technical and institutional perspective. Using comparative policy analysis and the energy justice framework, we evaluate whether community energy can simultaneously enhance grid flexibility, energy independence and equitable participation in Central Europe. The results show that the primary barriers are institutional rather than technological. A five-factor operational pathway is identified including energy sharing, metering and data integration, financial sustainability, benefit-sharing mechanisms and governance partnerships. The study concludes that energy communities may become distributed flexibility providers only if regulatory design and social structures evolve together.

Keywords. Energy communities, energy sharing, energy independence, energy justice, Central Europe.

1. Introduction

European electricity systems are undergoing a structural transition from centralized generation toward distributed renewable production [4]. The rapid spread of photovoltaic installations, electrification of heating and mobility, and the appearance of active consumers introduce intermittency, bidirectional flows and local congestion at the distribution level [4],[8]. Traditional technical responses — grid expansion or large-scale storage — are capital-intensive and slow, highlighting the need for complementary organizational and institutional solutions operating closer to the point of consumption [8].

Energy communities represent such an organizational innovation [8]. By coordinating production, consumption and storage at local scale, they can reduce peak demand, increase self-consumption and improve acceptance of renewable technologies [8],[9],[11]. In Western Europe these initiatives evolved from long cooperative traditions and gradually integrated into electricity markets [5],[8]. In Central Europe, however, their emergence is mainly driven by regulation and pilot programmes, therefore their role is broader: they must address not only decarbonization but also energy security, affordability and public trust in the energy transition [6],[7],[8],[15].

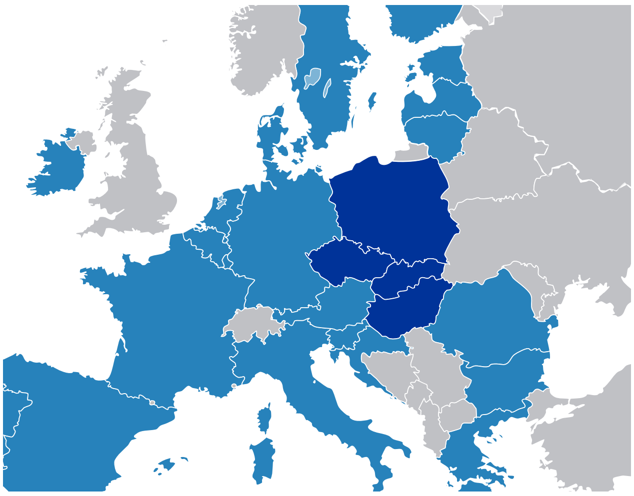

Fig. 1. Countries of the Visegrád Group (V4). Source: [2].

In this paper the regional focus is the V4 group (Visegrád Group), consisting of Hungary, Poland, Czechia and Slovakia [2]. These countries share similar historical and institutional trajectories and exhibit persistent reliance on imported energy in the EU context [15],[16],[17]. Consequently, decentralized renewable solutions in this region are evaluated not only by environmental performance but also by their contribution to energy independence and socially accepted transition outcomes [1],[8],[11]. The V4 region therefore provides a specific laboratory where community energy functions simultaneously as an energy policy, social policy and system operation instrument [12],[13].

The research therefore examines whether energy communities in the V4 region can function simultaneously as technical flexibility resources and socially legitimate institutions.

2. Conceptual Background

European legislation distinguishes renewable energy communities (REC) and citizen energy communities (CEC), yet in practice Central European implementations combine features of both models [6],[7]. Their effectiveness cannot be evaluated purely by technical indicators such as generation capacity or self-consumption rate [8],[10]. Long-term viability depends on fairness, participation and perceived legitimacy [1].

For this reason the analysis applies an energy justice perspective and introduces the 3EI framework (distributional justice, procedural justice and recognitional justice) developed in this study by extending the approach of Bielig et al. [1]. In this paper, distributional justice refers to how the benefits and burdens are allocated within and around energy communities, including affordability and access, value capture from local generation, and effects on vulnerability [1]. Procedural justice focuses on the fairness and inclusiveness of decision-making: who can enter the community, how rules are set, whether information is accessible, and whether governance enables meaningful participation beyond formal membership [1]. Recognitional justice addresses whose needs and lived experiences are acknowledged in the first place; in practice it examines whether groups that are often disadvantaged in energy transitions (such as tenants, low-income households, or otherwise underrepresented residents) are seen as legitimate stakeholders and whether barriers to their participation (financial, legal, informational, or social) are actively reduced [1].

The relevance of the framework is particularly strong in post-transition economies where energy affordability is politically sensitive and institutional trust is limited [15],[17]. Community energy initiatives must therefore produce measurable social value in addition to technical performance. The 3EI framework allows the simultaneous evaluation of operational efficiency and social inclusiveness.

2.1 SDG linkages of community energy in the V4 context

Beyond justice considerations, community energy initiatives can be interpreted as localized implementation mechanisms of the UN Sustainable Development Goals (SDGs) [3],[11]. Instead of evaluating SDGs as environmental indicators only, this study links each SDG contribution to one of the justice dimensions, thereby integrating technical performance and social value creation.

Table 1 reorganizes the typical SDG interpretation by reversing the logic: SDGs are treated as outcome categories, while justice dimensions act as explanatory conditions [3]. This structure allows the identification of whether sustainability goals are achieved because of technological performance or institutional inclusiveness.

Table 1. SDG–3EI interaction matrix in community energy systems (Source: authors' own elaboration based on [3] and extended from [1]).

SDG Outcome	Distributional dimension (who benefits)	Procedural dimension (who decides)	Recognition dimension (who is included)
SDG7 Affordable and clean energy	Reduction of household energy costs	Participation in tariff and sharing rules	Access for tenants and low-income households
SDG11 Sustainable communities	Local economic retention	Municipal and citizen co-governance	Inclusion of community institutions
SDG12 Responsible consumption	Load shifting and self-consumption	Collective consumption agreements	Behavioral change across user groups
SDG13 Climate action	CO2 reduction through local renewables	Community climate decision processes	Social acceptance of transition measures
SDG17 Partnerships	Shared investments and revenues	Multi-actor governance platforms	Cross-sector cooperation and inclusion

The matrix shows that technical sustainability outcomes cannot be separated from governance structure. In the V4 region SDG-related outcomes are therefore expected to be strongly shaped by institutional participation and legitimacy, not only by installed capacity [1],[8],[15].

3. Methodology

The research applies a qualitative comparative case study approach focusing on institutional and operational characteristics of energy communities in Hungary, Poland, Czechia and Slovakia. The objective is not statistical generalization but analytical comparison in order to identify systemic patterns determining operational viability. The cases were selected because the four countries share similar regulatory transposition timelines, grid structures and market regulation traditions, while differing in implementation intensity and policy instruments [6],[7].

The analysis combines three types of sources: (i) national regulatory documents and implementation rules related to energy sharing and aggregation, (ii) documented pilot projects and demonstrator programs, and (iii) academic and policy literature evaluating social and technical outcomes [5],[8],[11]. Each case was examined along a common evaluation protocol structured around the 3EI framework and key operational system characteristics identified in the community energy literature [8].

First, institutional coding identified energy sharing arrangements, metering requirements, eligibility conditions and participation rights [6],[7]. Second, operational coding assessed whether the community could coordinate production and consumption (self-consumption ratio, demand response potential, local balancing role) [8]. Third, social coding evaluated participation openness, decision-making transparency and accessibility for tenant and low-income households [1],[10],[11]. The results were then compared across countries to determine recurring enabling and limiting factors.

Rather than comparing installed capacities, the methodology evaluates functional capability: whether a community can operate as an energy management unit. This functional perspective allows identification of scalability conditions independent of project size. The approach therefore links governance structure with technical system performance and enables the formulation of a generalized operational pathway.

4. Limitations

The study relies on documented pilot projects and regulatory frameworks rather than large-scale operational datasets, as market-integrated community energy operation remains limited in the V4 region [8],[15]. Consequently, the findings indicate structural tendencies and enabling conditions rather than quantitative performance benchmarks. Differences in project maturity and data availability across countries may also influence comparability; however, the standardized evaluation protocol mitigates this limitation by focusing on functional capability instead of project scale [5],[8].

5. Results and Discussion

Table 2 summarizes the comparative V4 assessment. Across the four cases, the main differences do not lie in core technology choice, which is predominantly photovoltaic and increasingly linked to smart metering, but in regulatory maturity, settlement arrangements, financing structures and the inclusiveness of local governance [6],[7],[8]. Hungary and Slovakia remain more pilot-dependent, while Poland and Czechia show more diversified institutional pathways toward community-based energy operation [6],[7],[8],[15].

Table 2. Summary of V4 assessment (Source: authors' own elaboration)

Country	Regulatory maturity	Sharing / metering readiness	Financing pattern	Participation pattern	Functional maturity
Hungary	Legal basis exists, but operation remains pilot-oriented	Smart metering and sharing appear in projects, but settlement practice remains limited	Mostly grant- and programme-based	Municipal, civil and SME actors present	Emerging
Poland	Most differentiated framework, including cluster-type arrangements	Broader practical experimentation with cooperative/cluster forms	Strong mix of public, EU and member-based funding	Municipalities, associations and firms all present	Advancing
Czechia	Clearer recent framework for energy sharing	Metering and sharing rules are becoming more operational	EU and regional/project-based support	Municipality-led with household and institutional inclusion	Advancing
Slovakia	Partial transposition and weaker institutional maturity	Limited pilot-based readiness	Mainly EU/project-based support	Municipality-led, narrower participation base	Early-stage

A country-level reading of the cases suggests a clear gradient of functional maturity. In Hungary, community energy remains strongly programme- and pilot-driven, with promising examples but limited evidence of stable market-integrated operation. Slovakia shows a similar early-stage pattern, where pilot activity is present but institutional consolidation remains weaker. By contrast, Poland benefits from a more differentiated organizational landscape, including cluster and cooperative forms, while Czechia is moving toward a clearer operational framework through recent energy-sharing and metering arrangements [6],[7],[8],[15].

These cross-country differences support the central finding of this study: the main barriers in the V4 region are institutional rather than technological. In all four countries, the technological basis for community energy is relatively similar, as photovoltaic generation, smart metering and local coordination tools increasingly appear in projects and pilot schemes [8]. What varies more significantly is whether regulation, settlement logic and governance arrangements allow these technical elements to operate as an integrated energy management unit [6],[7],[8].

The comparative assessment also explains the five enabling conditions identified in this paper. First, a clear energy-sharing and settlement framework is essential, because distributed assets cannot function collectively without transparent accounting and allocation rules [6],[7],[8]. Second, smart metering and digital data integration are required to transform local generation into measurable balancing potential [8]. Third, financial sustainability beyond grants is necessary, since pilot-based initiatives rarely scale without stable revenue logic [5],[8],[11]. Fourth, benefit-sharing mechanisms are important for retention, legitimacy and perceived fairness [1],[10],[11]. Fifth, stable cooperation among municipalities, citizens and local businesses appears critical for implementation beyond isolated demonstration projects [1],[8],[11].

Where these conditions are present, energy communities can contribute to peak reduction, demand response and local balancing at the distribution level [8]. However, the examined cases indicate that participation in flexibility-oriented market arrangements remains limited, which constrains the monetization of technical benefits [8],[15]. As a result, community energy in the V4 region currently operates more as a transitional socio-technical experiment than as a fully integrated market actor [8],[12],[13].

6. Conclusions

Energy communities in Central Europe currently function as transitional socio-technical experiments rather than integrated market actors. Their future relevance lies in acting as intermediary flexibility providers linking consumers and distribution networks. Achieving this role requires regulatory frameworks that simultaneously support measurement, participation and fair value allocation. The study demonstrates that community energy should not be interpreted solely as a social initiative nor purely as a technical solution. Its effectiveness depends on the co-evolution of technical infrastructure and institutional design. Properly implemented, it can enhance renewable integration while strengthening local acceptance of the energy transition. This paper connects power system flexibility with social acceptance in a region where energy transition is strongly linked to energy security and affordability. The paper provides a combined institutional-technical assessment and identifies a five-factor operational pathway for scalable community energy operation in Central Europe.

This research was supported by the Sustainable Development and Technologies National Programme of the Hungarian Academy of Sciences (FFT NP FTA).

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