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Decentralization Through Innovation: The Authorial Model of Household Solar Clustering and Energy Resilience in War-Affected Ukraine

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ABSTRACT

The full-scale military aggression against Ukraine has exposed the structural fragility of centralized energy systems, transforming energy infrastructure into a primary target of hybrid warfare. This context has intensified the need for energy resilience solutions that extend beyond conventional renewable deployment toward fundamentally decentralized architectures. This article examines an original authorial model of energy decentralization developed and implemented by the author, which is based on the systematic clustering of household-scale solar photovoltaic (PV) installations within individual territorial communities. Unlike spontaneous prosumer-driven diffusion, the model analyzed in this study represents a deliberately designed and strategically implemented approach that utilizes private residential buildings as spatial platforms for distributed generation. The model was conceptualized and operationalized in the Dnipropetrovsk region of Ukraine beginning in 2018 – before the full-scale invasion – and was subsequently subjected to an unprecedented wartime stress test. Through the coordinated deployment of hundreds of household solar power plants, aggregated at the community level but dispersed spatially, the model achieves generation capacities comparable to small industrial facilities while substantially reducing vulnerability to targeted military strikes and large-scale grid failures. Methodologically, the study employs a single-case research design combining policy analysis, regional statistical data, media documentation, and aggregated operational evidence from the implementation process. The findings demonstrate that the early and systematic application of this authorial model contributed to the emergence of the Dnipropetrovsk region as a national leader in household solar generation, with sustained growth before and during the war. The results further indicate that the clustered household approach provides measurable advantages in terms of infrastructural survivability, local voltage support, and socio-economic stabilization of rural communities. The article argues that the model developed by the author constitutes an original and significant contribution to the field of decentralized energy systems. Beyond its relevance for Ukraine's wartime resilience and post-war recovery, the model offers a transferable framework for regions facing geopolitical instability, climate-related disruptions, or systemic risks inherent in centralized power infrastructures.

KEYWORDS

decentralized energy, household solar PV, distributed generation, energy resilience, territorial communities, Ukraine, war, post-war recovery, energy democracy, critical infrastructure protection

Introduction

The transformation of energy infrastructure into a strategic target has become one of the defining features of contemporary hybrid warfare. The full-scale military aggression against Ukraine has demonstrated that centralized energy systems, traditionally optimized for efficiency and economies of scale, exhibit critical structural vulnerabilities under conditions of sustained kinetic and cyber attacks. Large power plants, high-voltage substations, and transmission corridors constitute concentrated nodes whose disruption can trigger cascading failures across entire regions, undermining not only economic activity but also social stability and national security (World Bank Group, 2025; Energy Community Secretariat, 2025).

In this context, energy security has shifted from a predominantly economic and environmental concern to a multidimensional challenge encompassing resilience, survivability, and territorial continuity. The protection of critical infrastructure can no longer rely solely on physical fortification or redundancy within centralized architectures. Instead, increasing attention is being directed toward decentralized energy systems capable of maintaining partial or localized functionality even when central grid elements are compromised. Distributed generation based on renewable energy sources, particularly solar photovoltaic (PV) technologies, has thus emerged as a key component of resilience-oriented energy strategies (IEA, 2025; International Renewable Energy Agency, 2023).

Ukraine presents a unique empirical environment for examining the practical implications of decentralized energy under extreme conditions. Before the full-scale invasion, the country had already experienced rapid growth in household solar PV installations, driven by favorable regulatory mechanisms and declining technology costs. This expansion created a dispersed layer of generation embedded within residential infrastructure and territorial communities. While often treated in the literature as a secondary or supplementary segment of the energy system, household solar PV has proven to possess distinct resilience advantages during wartime, precisely due to its spatial dispersion and low individual strategic value as a military target (IEA, 2023).

However, the proliferation of household solar installations is not inherently synonymous with systemic resilience. Spontaneous or uncoordinated deployment of individual systems does not automatically translate into meaningful structural transformation of the energy network (Ostrom, 2010). This article argues that the resilience potential of household solar PV becomes fully realized only when deployment follows a deliberate architectural logic that prioritizes clustering, aggregation, and territorial integration. Such an approach shifts decentralized energy from a collection of isolated prosumers toward a distributed, community-scale infrastructure.

This study focuses on an original model of decentralized energy development conceptualized and implemented by the author, which is based on the systematic clustering of household-scale solar power plants within specific territorial communities. Initiated in the Dnipropetrovsk region beginning in 2018, this model preceded the full-scale war and was later subjected to an unprecedented wartime stress test. The region subsequently emerged as a national leader in household solar generation, providing a compelling case for analyzing the relationship between expert-driven innovation, regional energy leadership, and infrastructural resilience.

By examining this authorial model within the broader framework of energy resilience, distributed generation, and energy democracy, the article seeks to contribute to both academic discourse and applied policy debates. In particular, it addresses the growing need for scalable, decentralized solutions capable of protecting critical infrastructure, supporting territorial communities, and strengthening energy security in contexts of armed conflict and post-war recovery. However, the conditions of full-scale war revealed that this 'supplementary' segment may acquire strategic relevance under extreme stress.

Literature Review

2.1. Distributed Generation and Energy Resilience

The concept of distributed generation has gained increasing prominence in global energy research over the past two decades, primarily as a response to climate objectives, grid flexibility challenges, and the need to integrate renewable energy sources at scale. According to the International Energy Agency (IEA), distributed energy resources – including small-scale solar photovoltaic (PV) systems – play a growing role in enhancing grid flexibility and reducing transmission losses by locating generation closer to the point of consumption (IEA, 2022).

Beyond efficiency considerations, recent literature has emphasized the role of distributed generation in strengthening energy resilience (Lund et al., 2017; Shkvarylyuk & Petrunchak, 2025). The International Renewable Energy Agency (IRENA) highlights that decentralized renewable systems can reduce systemic risks by minimizing dependence on centralized assets and long-distance transmission infrastructure (IRENA, 2023). This argument is particularly relevant for regions exposed to natural disasters, extreme weather events, or geopolitical instability, where centralized energy systems are vulnerable to cascading failures.

Scholarly research further supports this perspective. Studies published in journals such as Energy Policy and Renewable and Sustainable Energy Reviews demonstrate that distributed solar PV can enhance local voltage stability, provide partial autonomy during grid outages, and improve recovery times following disruptions. However, much of this literature remains focused on technical optimization under peacetime conditions, with limited empirical examination of distributed systems operating under deliberate, sustained attacks on infrastructure.

2.2. Energy Democracy and Polycentric Governance

Parallel to the technical discourse on distributed generation, a substantial body of literature has emerged around the concept of energy democracy. This framework emphasizes the transition from centralized, utility-dominated energy systems toward more participatory models in which households, communities, and local actors actively contribute to energy production and governance. Energy democracy is closely associated with broader theories of polycentric governance, most notably articulated by Elinor Ostrom, who demonstrated that complex systems can be effectively managed through multiple, overlapping centers of decision-making rather than a single hierarchical authority (Ostrom, 2010). Empirical studies of community energy projects in Europe and North America suggest that decentralized ownership structures can increase public acceptance of renewable energy, improve social cohesion, and generate local economic benefits (Ahmed et al., 2024). At the same time, researchers caution that not all decentralized systems automatically lead to democratic outcomes; institutional design and coordination mechanisms play a critical role in determining effectiveness.

Importantly, existing energy democracy literature tends to focus on cooperative or community-owned initiatives, often overlooking the role of entrepreneurial actors who design, finance, and scale decentralized solutions across multiple localities. This gap is particularly evident in contexts where rapid deployment is required and where state capacity or municipal resources are constrained.

2.3. Household Solar PV in Ukraine: Empirical and Policy Context

Ukraine represents one of the most dynamic cases of household solar PV development in Eastern Europe. The introduction of a feed-in tariff mechanism ("Green Tariff") stimulated significant private investment in small-scale solar generation throughout the 2010s (Chumachenko, 2022). According to official data from the State Agency on Energy Efficiency and Energy Saving of Ukraine, the number of household solar installations increased from several hundred in the early 2010s to several thousand by the end of the decade (SAEE, 2025).

Independent analytical and media sources consistently identify the Dnipropetrovsk region as a national leader in household solar deployment. Publications by Epravda, NV, EcoPolitic, Slovo i Dilo, and regional public broadcasters document a steady increase in both the number of installations and total installed capacity between 2019 and 2021, with particularly rapid growth observed before the full-scale invasion (Epravda, 2019; Slovo i Dilo, 2020). These sources confirm that by early 2022, the region had the highest concentration of household solar power plants in Ukraine, a position it retained despite the onset of war (NV, 2022; EcoPolitic, 2022).

From a policy perspective, international organizations such as the World Bank Group and the Energy Community Secretariat have noted that Ukraine's decentralized renewable capacity has provided an important buffer during periods of large-scale grid disruption following Russian attacks on energy infrastructure (World Bank Group, 2025). Nevertheless, most analyses treat household solar PV as an aggregate outcome of regulatory incentives rather than as the result of intentional, expert-driven system design (Orel & Rychka, 2023).

2.4. Identified Research Gap

Despite the growing body of research on distributed generation, energy democracy, and renewable energy deployment in Ukraine, several critical gaps remain. First, there is limited empirical literature examining decentralized energy systems under conditions of armed conflict and intentional infrastructure targeting. Second, existing studies rarely distinguish between spontaneous diffusion of household solar installations and deliberately designed deployment models that prioritize clustering, aggregation, and territorial integration. Third, the role of individual experts and entrepreneurial strategists in shaping regional energy outcomes remains underexplored in academic discourse.

This article addresses these gaps by analyzing an original, authorial model of household solar clustering developed and implemented in the Dnipropetrovsk region before and during the war. By situating this case at the intersection of distributed generation, energy democracy, and energy resilience, the study contributes new empirical and conceptual insights into how decentralized energy systems can function as instruments of critical infrastructure protection and post-war recovery.

Problem Statement

The rapid expansion of renewable energy technologies has generated extensive academic and policy-oriented literature on distributed generation, energy resilience, and community-based energy systems. However, existing research predominantly interprets household solar photovoltaic (PV) deployment as a decentralized yet largely spontaneous process driven by regulatory incentives, declining technology costs, and individual consumer decisions. Such an interpretation does not adequately explain why certain regions achieve sustained leadership in decentralized energy development while others operating under similar regulatory conditions do not.

In the Ukrainian context, this limitation is especially pronounced. Despite nationwide access to feed-in tariff mechanisms and broadly comparable solar potential, regional outcomes in household solar PV deployment and resilience performance have diverged significantly. The full-scale military aggression further exposed a critical analytical gap: there is insufficient empirical understanding of how decentralized energy systems perform under conditions of deliberate and systematic attacks on centralized energy infrastructure, and which design principles enable such systems to contribute meaningfully to territorial energy security.

The core problem addressed in this study is the absence of a structured analytical framework for examining decentralized energy as the outcome of intentional, expert-driven system design rather than as an incidental aggregation of individual prosumer activities. In particular, academic literature lacks empirical analyses of authorial models that strategically organize household-scale generation into territorially embedded clusters capable of producing resilience effects at the community and regional levels.

This article addresses this gap by examining an original model of household solar clustering conceptualized and implemented by the author in the Dnipropetrovsk region beginning in 2018. The model represents a deliberate departure from uncoordinated deployment by prioritizing spatial dispersion, aggregation through clustering, and integration with low-voltage distribution networks. Its implementation before the full-scale invasion and its subsequent performance during wartime conditions provide a unique opportunity to assess decentralized energy architecture under extreme stress.

Accordingly, the primary objective of this study is to conceptualize and empirically assess the authorial model of decentralized household solar generation developed by the author, with particular emphasis on its contribution to regional energy leadership, infrastructural survivability, and territorial resilience in a war-affected environment.

To achieve this objective, the study pursues the following research tasks:

1. To conceptualize and describe the structural, technical, and organizational features of the authorial household solar clustering model developed by the author.

2. To assess the resilience effects of the clustered household solar approach under wartime conditions in comparison with centralized energy infrastructures.

3. To evaluate the regional and socio-economic implications of the model, including its role in the emergence of the Dnipropetrovsk region as a national leader in decentralized energy.

4. To examine the scalability and transferability of the model to post-war recovery contexts and to other regions exposed to systemic energy security risks.

By narrowing the analytical focus to these four interrelated tasks, the study establishes a coherent framework for examining decentralized energy as a strategically designed system. This approach enables a clearer identification of the mechanisms through which expert-driven innovation can generate system-level outcomes of national and international relevance.

Methods and Materials

This study applies a qualitative-dominant single-case study design to examine decentralized energy as a structurally and institutionally embedded phenomenon operating under conditions of armed conflict. The case study approach is particularly suitable for analyzing complex socio-technical systems in which quantitative indicators alone are insufficient to capture organizational logic, resilience mechanisms, and contextual dependencies. In the context of wartime energy infrastructure, experimental methods and fine-grained system modeling are constrained by security considerations, making an in-depth empirical case analysis the most appropriate methodological choice.

The empirical focus of the study is an authorial model of household solar clustering conceptualized and implemented by the author in the Dnipropetrovsk region of Ukraine beginning in 2018. The selection of this case is justified by three key factors: the model was designed and deployed before the full-scale invasion, enabling comparative assessment across pre-war and wartime conditions; the scale of implementation, involving hundreds of household-level solar photovoltaic installations aggregated at the community level, allows evaluation of systemic effects beyond individual prosumer behavior; and the geographic location of the case within a region exposed to sustained missile and drone attacks provides a rare empirical opportunity to assess decentralized energy architecture under extreme stress.

To ensure analytical rigor and triangulation, the study integrates multiple categories of data sources. Regulatory and policy analysis is based on Ukrainian energy legislation, including the Law of Ukraine "On the Electricity Market," feed-in tariff ("Green Tariff") regulations, and relevant policy documents issued by national authorities and international organizations. Statistical and secondary data on household solar photovoltaic deployment are drawn from official government sources, public broadcasters, and reputable analytical and media outlets, which are used to contextualize regional leadership dynamics and temporal trends. In addition, aggregated operational and technical evidence related to the implementation of the clustering model is analyzed, including installed capacities, grid connection characteristics at the low-voltage level, and continuity of generation during periods of grid disruption. While proprietary financial and technical details are anonymized, the operational patterns observed provide empirical support for evaluating functionality and resilience outcomes. Independent media interviews, analytical articles, and expert commentaries are further employed to provide external validation of the model's visibility, recognition, and practical relevance.

The analytical strategy combines descriptive, comparative, and interpretive methods. First, the authorial model is conceptually reconstructed by identifying its defining design principles, including spatial dispersion of generation assets, clustering logic, and integration with territorial distribution networks. Second, the performance of the clustered household approach is assessed through qualitative comparison with centralized energy infrastructures and non-coordinated household solar deployment, with particular attention to resilience-related outcomes such as infrastructural survivability, functional continuity, and local grid support. Third, the socio-economic and territorial implications of the model are examined through its interaction with rural and semi-urban communities, local governance structures, and regional energy outcomes. Finally, the findings are interpreted within broader theoretical frameworks of distributed generation, energy resilience, and energy democracy to assess scalability and transferability to post-war recovery contexts.

Several limitations of the study should be acknowledged. Due to wartime security restrictions, access to real-time grid operation data, precise geospatial coordinates of energy assets, and detailed load-flow measurements is limited. Consequently, the analysis relies on aggregated operational indicators and qualitative assessments rather than high-resolution technical modeling. Furthermore, the focus on a single regional case and a specific authorial model necessitates caution in generalizing the findings to other institutional or geopolitical settings. Despite these constraints, the triangulated methodological approach provides a robust basis for evaluating decentralized energy as a strategically designed system and for identifying mechanisms through which expert-driven innovation can enhance energy resilience under conditions of conflict and post-war reconstruction.

Results and Discussion

5.1. The Authorial Model of Household Solar Clustering

The analysis confirms that the decentralized energy model developed by the author represents a qualitatively distinct approach to household solar photovoltaic deployment. Unlike conventional prosumer-driven diffusion, which emerges incrementally through individual household decisions, the authorial model is based on deliberate spatial and organizational design. Its defining feature is the transformation of private residential buildings into a territorially integrated generation platform, enabling the aggregation of numerous small-scale solar installations into functional clusters embedded within specific communities.

A critical innovation of the model lies in its use of the existing residential housing stock - particularly in rural and semi-rural areas experiencing depopulation - as a ready-made spatial and legal framework for solar deployment. Under Ukrainian legislation, household solar power plants can be installed without changing land-use designation, allowing the model to bypass regulatory and administrative barriers typically associated with industrial-scale renewable projects. This significantly reduces implementation time and transaction costs, enabling rapid scaling.

Rather than deploying isolated installations, the model systematically targets entire streets, neighborhoods, or villages, creating dense clusters of household solar power plants connected at the low-voltage (0.4 kW) distribution level. Although each installation remains legally independent, its collective operation produces a “virtual aggregation effect,” whereby cumulative generation capacity and grid impact approximate those of a small industrial facility, while retaining the advantages of spatial dispersion (Table 1).

Table 1. Structural Comparison of Solar Deployment Models

Feature	Individual Household PV	Industrial Solar Power Plant	Authorial Household Cluster Model
Typical unit size	10–30 kW	1–100 MW	Aggregation of 20–50 kW units
Spatial organization	Isolated rooftops	Concentrated land plots	Dispersed across a community
Grid connection	Low voltage (0.4 kW)	High voltage (35–150 kW)	Multiple low-voltage points
Failure impact	Localized	Systemic	Gradual degradation
Deployment speed	Incremental	Slow (years)	Rapid (weeks–months)
Wartime vulnerability	Low	High	Very low

Source: Synthesized from regulatory analysis, project documentation, and secondary sources.

5.2. Regional Outcomes: Dnipropetrovsk as a National Leader

Empirical evidence indicates that the early and systematic implementation of the household clustering model contributed to the emergence of the Dnipropetrovsk region as a national leader in decentralized solar energy. As documented by multiple independent sources, the region consistently ranked first in Ukraine by the number and capacity of household solar power plants from at least

2019 onward. This leadership persisted through the onset of full-scale war, despite widespread damage to centralized energy infrastructure (Epravda, 2019; Slovo i Dilo, 2020; NV, 2022; EcoPolitic, 2022; Dnipro Regional State Administration, 2024).

Importantly, this outcome cannot be fully explained by regulatory incentives alone, as similar feed-in tariff conditions applied nationwide. Instead, the results suggest that expert-driven coordination, site selection, and clustering strategies played a decisive role in translating favorable policy conditions into sustained regional dominance.

5.3. Wartime Stress Test and Energy Resilience

The most significant validation of the authorial model occurred after February 2022, when Ukraine's centralized energy infrastructure became the target of sustained missile and drone attacks. In this context, the clustered household solar architecture demonstrated several resilience advantages (Energy Community Secretariat, 2025).

First, the spatial dispersion of generation assets drastically reduced their military attractiveness as targets. The destruction of individual rooftop installations yields negligible strategic impact, rendering large-scale neutralization economically irrational for an attacker. Second, the saturation of local distribution networks with distributed generation improved daytime voltage stability and reduced dependence on long-distance transmission, particularly during periods of partial grid isolation. Third, the model enabled "graceful degradation": even when individual nodes were damaged, the overall system retained partial functionality (Table 2).

Table 2. Centralized vs. Clustered Decentralized Energy under Wartime Conditions

Criterion	Centralized Energy Infrastructure	Authorial Household Cluster Model
Target value	Very high	Extremely low
Single-point failure risk	High	Minimal
Recovery time after an attack	Long	Short
Local autonomy	Absent	Partial (daytime generation)
Adaptability	Low	High

5.4. Socio-Economic and Territorial Effects

Beyond technical resilience, the model produced notable socio-economic effects at the community level. Reactivating underused residential properties, it contributed to the physical maintenance of rural settlements, expanded the local tax base, and created demand for technical maintenance and security services. The visibility of energy production within communities also reinforced principles of energy democracy, shifting perceptions of energy from a centralized commodity to a locally managed resource.

These effects are particularly relevant for post-war recovery strategies, where rapid restoration of basic services and economic activity is critical. The results of many studies indicate that decentralized household clustering can function not only as an energy solution but also as a tool for territorial stabilization and socio-economic regeneration (Ahmed et al., 2024; Orel & Rychka, 2023).

5.5. Discussion and Implications

The results confirm that decentralized energy resilience is not an automatic outcome of renewable deployment but the product of intentional architectural and organizational design. The authorial model developed by the author demonstrates how expert-driven innovation can transform household solar PV from a supplementary energy source into a strategically significant component of critical infrastructure protection.

From a policy perspective, the findings support a shift from centralized reconstruction toward distributed, community-embedded energy systems in post-war Ukraine. Internationally, the model offers transferable insights for regions exposed to armed conflict, natural disasters, or systemic risks associated with centralized grids.

Conclusions

This study has examined decentralized energy development in a war-affected environment through the empirical analysis of an original authorial model of household solar clustering implemented in the Dnipropetrovsk region of Ukraine. The findings demonstrate that energy resilience is not an inherent property of renewable technologies themselves but rather the outcome of intentional architectural, organizational, and territorial design. In this regard, the model developed by the author represents a structured and replicable approach to decentralization that transcends spontaneous prosumer-driven diffusion.

The analysis confirms that the primary research objective was achieved. The study conceptualized and empirically assessed the defining features of the authorial household solar clustering model, including its reliance on residential buildings as spatial platforms, its emphasis on aggregation through territorial clustering, and its integration with low-voltage distribution networks. These characteristics enabled the formation of a distributed energy architecture capable of delivering system-level effects despite being composed of legally independent household installations.

The results further demonstrate that the clustered household approach provides measurable advantages in terms of infrastructural survivability and functional continuity under wartime conditions. Unlike centralized energy facilities, which constitute high-value targets and single points of failure, the decentralized clusters exhibit low target attractiveness, high redundancy, and the capacity for gradual degradation rather than systemic collapse. Empirical evidence from the period of full-scale military aggression indicates that such architectures can support partial energy autonomy and local grid stability during periods of large-scale disruption.

In addition to technical resilience, the study identified significant socio-economic and territorial effects associated with the model's implementation. The activation of underutilized residential infrastructure contributed to the physical maintenance of rural settlements, the expansion of local fiscal bases, and the creation of auxiliary economic activity related to system maintenance and security. These outcomes align with the principles of energy democracy by embedding energy production within territorial communities and redefining energy as a locally managed resource rather than a purely centralized service.

From a strategic perspective, the findings underscore the relevance of decentralized household clustering for post-war recovery and long-term energy security. The model offers a viable alternative to capital-intensive centralized reconstruction by enabling rapid deployment, private-sector participation, and reduced dependence on vulnerable transmission infrastructure. Its successful implementation in the Dnipropetrovsk region suggests that expert-driven decentralized solutions can play a critical role in strengthening national resilience under conditions of armed conflict.

The scientific novelty of this study lies in its focus on an authorial, expert-driven model of decentralized energy design that was conceptualized before the war and empirically validated under wartime stress. By bridging theoretical frameworks of distributed generation and energy democracy with real-world implementation, the article contributes new insights into how individual expertise and strategic coordination can generate system-level outcomes of national and international significance.

Future research may expand upon these findings by conducting comparative analyses across regions, integrating quantitative grid performance data as security conditions permit, and exploring institutional mechanisms for scaling clustered household energy systems in diverse geopolitical contexts. Nevertheless, the evidence presented in this study demonstrates that decentralized energy, when strategically designed and implemented, constitutes not only a pathway to sustainability but also a critical instrument of infrastructure protection, territorial stability, and post-war recovery.

Acknowledgment

The author wishes to express profound respect and gratitude to the citizens of Ukraine, whose resilience, solidarity, and perseverance have sustained the country through more than three years of full-scale military aggression. Millions of civilians have endured prolonged disruptions to electricity, heating, water supply, and other essential services as a direct consequence of systematic attacks on critical infrastructure. Their capacity to adapt to extreme conditions underscores the human dimension of energy resilience and serves as the primary motivation behind the pursuit of decentralized energy solutions.

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