

“Convergence and divergence patterns in Ukraine’s household solar energy development: Policy implications”

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CONVERGENCE AND DIVERGENCE PATTERNS IN UKRAINE'S HOUSEHOLD SOLAR ENERGY DEVELOPMENT: POLICY IMPLICATIONS

Abstract

The study examines regional convergence and divergence in the development of household solar energy in Ukraine during 2016–2022 and explores implications for adaptive energy management and policy coordination. Using β - and σ -convergence models, the analysis investigates whether regional household solar electricity generation demonstrates tendencies toward structural alignment or, conversely, follows autonomous trajectories that indicate the absence of a common attractor. The results reveal a lack of both beta- and sigma-convergence, implying that initial regional conditions exerted little influence on subsequent development and that disparities across regions have persisted or even deepened over time. These findings suggest a divergent and spatially fragmented pattern of solar energy expansion, where regional dynamics are determined not only by differences in economic and institutional capacity but also by disruptions linked to the onset of the full-scale Russian invasion in 2022. The study emphasizes the need for a more adaptive and integrated energy policy that recognizes regional heterogeneity, supports decentralized renewable energy deployment, and strengthens coordination between national and local authorities. Such an approach would enhance the effectiveness of planning and implementation of household renewable energy programs, contributing to a more balanced and resilient low-carbon transition in Ukraine.

Keywords solar energy, households, convergence, divergence, energy policy, Ukraine

JEL Classification Q42, Q48

INTRODUCTION

The idea of economic convergence (also known as the “catch-up effect”) assumes that regions or countries with lower levels of development have the potential to grow faster than those that have already achieved higher socio-economic indicators. This concept underlies the Solow–Swan economic growth model, which explains the mechanism by which economic systems approach a steady state through the accumulation of physical capital and the influence of technological progress. According to this model, once the optimal level of capital per worker is reached, the economy stabilizes, and further growth depends on exogenous factors, primarily technological advancement (Michaelides, 2024). Understanding these patterns helps to shape more balanced policies for the regulation and development of specific economic sectors. In particular, in the context of managing energy transformations, this knowledge enables more effective investment allocation, stimulates the adoption of innovative technologies, and supports sustainable economic growth in line with long-term decarbonization goals.

In the context of the ongoing transformation of the energy sector – particularly against the backdrop of prioritizing climate neutrality goals – renewable energy is playing an increasingly important role in socio-economic development (Halkos & Aslanidis, 2024; Zakirova et al., 2024; Ostapenko et al., 2023; Sotnyk et al., 2025). In Ukraine, the development of renewable energy in the residential sector is one of the key manifestations of this economic modernization. Households are becoming active participants in the energy market, particularly through the installation of small-scale renewable energy systems that generate electricity both for self-consumption and for sale to the grid. It is also worth noting that Ukrainian households tend to prefer installing solar power plants. This preference is driven by the accessibility of the technology, ease of installation, and the more attractive rates of the feed-in tariff (Trypolska et al., 2024; Trypolska et al., 2025). Thus, as of the end of 2022, Ukrainian households had installed 52,205 solar power systems with a total installed capacity of 1,411 MW. In contrast, wind energy has seen virtually no adoption in the residential sector: only five small wind power plants with a total installed capacity of 61 kW were in operation during the same period, which does not have a systemic impact on household energy production (Kurbatova et al., 2024).

The dynamic growth of solar energy in the household sector is shaping a new research direction – analyzing the regional dynamics of decentralized electricity production. This opens up the opportunity to assess how coordinated and synchronized the energy transition is across different regions of the country. At the same time, a key question arises: are we witnessing a process of convergence, that is, the narrowing of regional disparities in the development of residential solar energy, or vice versa, with divergence – when the gap between regions is only growing? In addition, it is important to determine whether a single attractor is forming in the energy sector of Ukraine – a common development trajectory to which all regions gravitate, or whether regional policies are showing signs of dissipative changes, when development is fragmented and uncoordinated. Answers to these questions are crucial for shaping an effective energy transition policy and achieving decarbonization goals, as they allow for the timely identification of disparities, adjustment of strategies, and promotion of more harmonized development across the country.

1. LITERATURE REVIEW

One of the modern approaches to improving management and economic policy is the theory of convergence, which provides insights into the characteristics of economic development processes. Economic convergence models suggest faster growth when the level of physical capital per capita is low, a phenomenon often referred to as “catch-up” growth. The beginning of the discussion around the concept of economic convergence lies in the hypothesis of absolute convergence, which assumes that countries converge with each other in the long term in absolute values of all indicators, regardless of initial conditions. Since the long-term equilibrium of an economy depends on its structural characteristics (such as technology, preferences, population growth, government policy, the structure of the factor market, etc.), absolute convergence requires the convergence of structural characteristics across different countries (Oded, 1996). The

hypothesis of absolute convergence has been refuted in empirical studies in international analysis (Barro et al., 1991). However, there are certain exceptions in economic processes, as noted by Powell and Rutten (2013). Using data from 85 countries, including 23 European ones, it was empirically demonstrated that countries with lower initial wheat yield levels tend to increase their yields faster than countries with higher initial levels. In this case, the reason for absolute convergence lies in the fact that countries with lower initial wheat yields can more easily adapt and introduce existing technologies, and the level of institutional development has no impact in this specific case. In other words, lower initial wheat yields correlate with higher growth rates during the period 1961–2010. The importance of these empirical findings lies in the fact that, on average, it can be expected that the new European countries with lower initial wheat yields will increase their yields at a faster rate than the “old” EU member states.

Specific factors are driving convergence among member states and the emergence of clearly defined convergence processes, one of which is economic integration (Jena, 2018). Economic cooperation is expected to enhance efficiency, allocate limited resources more effectively, and lead to homogenization and convergence (Jena, 2018; Toplu, 2022). Among other factors, technological progress helps less developed economies catch up with more developed ones (Luo et al., 2020).

Besides absolute convergence, which has little practical support in economic research, conditional convergence is also used. The hypothesis of conditional convergence assumes that among countries similar in terms of comparative advantages, technologies, population growth rates, or government policies, the lower the levels of per capita output, the higher the growth rates will be. Thus, it is expected that countries similar in all respects except for the initial level of per capita output will converge in the relevant economic indicators. In economic literature, the concept of conditional “convergence” has some specific methods of definition and interpretation. Primarily, when assessing convergence, the approach of “sigma-convergence” (σ -convergence) is used, which refers to a reduction in the variation (dispersion) of income levels (or other development indicators of economic systems) among economies. Sigma-convergence itself tests for convergence to the average by determining whether the standard deviation among a group of countries decreases over time. If the standard deviation decreases over time, the analyzed economic systems become more homogeneous and similar. The concept of convergence has been quite controversial over the past few decades. The debate has been mostly empirical, focusing primarily on the validity of competing hypotheses (Oded, 1996):

1. The hypothesis of conditional convergence states that countries similar in their structural characteristics (such as preferences, technologies, population growth rates, or government policies) converge with each other in the long term regardless of initial conditions.
2. The hypothesis of club convergence (polarization, persistent poverty, and clustering) suggests that countries similar in their structural

characteristics converge with each other in the long term only if their initial conditions are also similar.

The hypothesis of conditional convergence is assessed through “beta-convergence,” which occurs when poorer economies grow at faster rates than richer ones. “Conditional beta-convergence” is synonymous with “beta-convergence” if other variables (namely the investment rate and population growth rate) remain unchanged. At the same time, “unconditional beta-convergence” or “absolute beta-convergence” occurs when economic growth rates decline as the economy approaches a steady state (equilibrium level). The concept of beta-convergence helps determine whether a “catching-up” process is occurring. For example, the “catching-up” process implies that countries with initially lower per capita CO₂ emissions experience a greater increase in per capita CO₂ emissions. Eventually, both high- and low-emitting countries converge to the same level (Li & Lin, 2013).

The hypothesis of club convergence is considered by Pukin-Sowul and Włodarczyk (2024), through evaluating beta- and sigma-economic convergence of Central and Eastern European countries toward the EU-12. Thus, the study argues that Central and Eastern Europe constitutes one of the EU “clubs,” consisting of the new member states that joined the Union in 2004, 2007, and 2013. Central and Eastern European countries share a common history and are similar in terms of their economic, geographic, and political characteristics. The countries that formed the Eurozone represent the second EU convergence club (EU-12), which is also closely aligned in economic, geographic, and political terms. Other EU countries (Denmark, Sweden, Cyprus, and Malta) were excluded from the study, as Denmark and Sweden are not part of the Eurozone, and Cyprus and Malta are island nations with limited economic significance.

Among the aforementioned methods, only beta-convergence can provide comprehensive information on the future distribution of per capita indicators or regional estimates. Specifically, beta-convergence enables the estimation of the steady-state absolute level, the speed of convergence toward this equilibrium, and the relationship between

the desired dependent variable and other factors. According to Li and Lin (2013), for sigma-convergence to occur, beta-convergence is required.

The above highlights the diversity of approaches to analyzing economic convergence, with a focus on beta- and sigma-convergence, which are widely applied in the study of macroeconomic dynamics, particularly in indicators such as crop yields, gross domestic product, CO₂ emissions, and others.

Understanding convergence in this domain is crucial for assessing whether decentralized energy systems promote an equitable energy transition. Financial incentives, particularly feed-in tariffs and power purchase agreements, play a central role in enabling regional catch-up and reducing household electricity generation disparities (Lyeonov & Moroz, 2025). When effectively designed, these instruments support convergence processes by creating stable investment conditions across geographic areas (Moroz & Lyeonov, 2024).

Beyond financial measures, entrepreneurial engagement and regional start-up ecosystems also influence the pace and spatial distribution of solar adoption. Regional differences in access to capital and innovation infrastructure shape the speed of solar technology diffusion (Dobrovolska et al., 2024). However, regulatory burdens remain unevenly distributed, limiting adoption in less developed areas (Myroshnychenko et al., 2024). The need to safeguard minority investors and promote ethical business leadership has also been identified as a driver of more balanced renewable energy development (Halynskyy & Telizhenko, 2024; Alsayed, 2024).

Socioeconomic conditions, including household income and savings, directly impact the willingness to invest in solar systems. As shown in health-related sectors, broad acceptance and affordability are tied to public perceptions of energy and infrastructure investments (Badreddine & Larbi Cherif, 2024; Otieno et al., 2025). Social inclusion and gender-sensitive policy design may accelerate adoption among underrepresented groups (Shen & Mullens, 2024), contributing to convergence by engaging new population segments. The availability of domestic savings as a financial buffer can also stimu-

late solar adoption by reducing liquidity constraints, particularly in developing economies where private investment must offset limited public support (Alsubaie, 2025).

Organizational and institutional capacity are equally crucial. Effective leadership, adaptive learning, and robust knowledge management systems have been recognized as successful factors in promoting sustainability across sectors. These organizational pillars can drive energy transitions at the household level by fostering public trust and accelerating behavioral change (Tessema, 2025). Technological innovation and digitalization also shape the convergence landscape, as smart energy management and decentralized solutions become more accessible (Chygryn et al., 2023). Moreover, policy responsiveness to public preferences for green transition supports widespread adoption. Meanwhile, European energy security debates highlight the urgency of reducing territorial disparities in production and losses (Wołowiec et al., 2022).

From a management perspective, these convergence frameworks provide a valuable analytical basis for assessing how policy instruments and institutional coordination shape decentralized renewable energy development. In view of the above, the purpose of this study is to assess the processes of convergence and divergence in the development of solar energy in the residential sector at the regional level in Ukraine. Moreover, it seeks to identify structural patterns or their absence/presence in the form of attractors, and formulate recommendations for adjusting energy policy to increase the effectiveness of managing the development of renewable energy in households.

2. METHOD

According to Miller and Gench (2025), similarity in economic, environmental, and social policies within a specific country should promote convergence processes and the formation of certain equilibrium states in the respective areas. The initial research on economic convergence was initiated by Barro and Sala-i-Martin (2003), focusing on a single country and its specific territorial divisions under such a model (1):

$$Ipc_{it} = e^{-\alpha_0 \tau} Ipc_{it-1} + (1 - e^{-\alpha_1 \tau}) Ipc_{it}^* + v_{it}, \quad (1)$$

where Ipc_{it} , Ipc_{it-1} – per capita income in the i -th region in year t (the current year) and $(t-1)$ (the previous year), respectively; Ipc_{it}^* – the steady-state level of per capita income in the i -th region in year t ; e – Euler’s number; v_{it} – standard error; τ – the length of the study period, years; α_0 and α_1 – slope coefficients of the regression models to be estimated.

Empirically, beta-convergence occurs when less developed regions grow faster than more developed ones (Ram, 2021), assuming the existence of a certain steady-state long-run equilibrium for all regions. To assess the degree of beta-convergence in this study, the following approach is used (2):

$$\frac{1}{T} (LnGESP_{iT} - LnGESP_{i0}) = \beta_0 + \beta_1 LnGESP_{i0} + \varepsilon, \quad (2)$$

where $GESP_{iT}$ та $GESP_{i0}$ – electricity generation by solar power plants in the household sector in the i -th region, respectively, in the current (latest, T) and initial (starting, 0) years; T – the number of years between the final and initial years ($T = 7$ for the period 2016–2022); β_0 , β_1 – empirical coefficients of the regression model (slope and intercept); ε – the random error term (regression disturbance).

From a methodological point of view, beta-convergence is present when the estimate of the parameter β_1 is negative and statistically significant. Conversely, if β_1 has a positive value, it means that more developed regions are growing even faster. The empirical results based on the “log-log” model indicate that the coefficient β_1 is interpreted as an elasticity. A one percentage point excess in solar power generation in the household sector in the i -th region in the first year (compared to the average values) leads to a β_1 percent change in the average solar power generation in the household sector in the i -th region over the analyzed period (in our case, during 2016–2022).

An alternative way to test for convergence is to use a linear model with solar power generation in the household sector in the i -th region as the dependent variable. Model (2) can be extended using the following linear specification:

$$\ln \left(\frac{GESP_{iT}}{GESP_{i0}} \right) = \gamma_0 + \gamma_1 LnGESP_{i0} + \sigma, \quad (3)$$

where γ_0 , γ_1 – empirical coefficients of the new regression model (slope and intercept).

Economic sigma-convergence refers to a situation in which the standard deviations of solar power generation levels in households across the regions of a given state decrease over time (Maulana et al., 2020):

$$s.d.(LnGESP_t) = \mu_0 + \mu_1 t + \varphi, \quad (4)$$

where $s.d.(LnGESP_t)$ – the standard deviation of the natural logarithms of solar power generation levels in the household sector in year t ; μ_0 , μ_1 – empirical coefficients of regression model (slope and intercept); φ – the standard error of the regression.

The variable t on the right-hand side of the regression model (4) is a time variable – an empirical linear negative relationship. Moreover, interregional convergence of economic indicators can be assessed using a modified Cobb-Douglas production function:

$$\ln(y_{it}) = \alpha_0 + b_1 \ln(y_{i,t-1}) + c_k Z_{ki,t-1} + d_i D_i + e_i T_i + \varepsilon_i, \quad (5)$$

where $\ln(y_{it})$ – logarithmic value of per capita income in the i -th region in year t ; $\ln(y_{i,t-1})$ – logarithmic value of per capita income in the i -th region for the year prior to year t ; $Z_{ki,t-1}$ – vector k of additional regional characteristics (investment policy, intellectual capital, health capital, etc.) for the year prior to year t ; D_i – vector of binary variables for the i -th region; T_i – vector of time binary variables for the i -th region; a_0 , b_1 , c_k , d_i , e_i – estimated coefficients of the impact of the respective indicators; ε_i – standard error of the regression.

A specific research interest lies in the coefficient b_1 , which indicates the “difficulty” of overcoming higher initial levels of the calculated indicators (for example, per capita income in a region) and ensuring subsequent growth. Practically, convergence is confirmed when the coefficient b_1 is nega-

tive. Within the logarithmic model framework, b_i is interpreted as an elasticity, where a one percent change in the base year leads to a b_i percent change in the calculated indicator (e.g., per capita income in the region) in the following year.

By adapting model (5) to the energy sector, where the dependent variable represents solar power generation in the household sector at the regional level, the model can be reformulated as follows (6):

$$\begin{aligned} (\ln GESP_{it}) = & \beta_0 + \beta_1 \ln(GESP_{i,t-1}) \\ & + c_1 E_{it} + c_2 S_{it} + c_3 W_{it} + c_4 TR_{it} + c_5 AGE_{it} \\ & + c_6 TEMP_{it} + c_7 E_{it} + \varepsilon, \end{aligned} \quad (6)$$

where $\ln GESP_{it}$, $\ln GESP_{i,t-1}$ – logarithmic values of solar power generation in the household sector in the i -th region in year t and $(t-1)$; E_{it} – educational level of an individual household in the i -th region in year t (measured by the education level of the household head); S_{it} – savings level of an individual household in the i -th region year t (thousands of US dollars); W_{it} – wage (income) level of an individual household in the i -th region in year t (thousands of US dollars); TR_{it} – electricity tariff for an individual household in the i -th region in year t (average value across tariff zones 1, 2, and 3), USD/kWh; AGE_{it} – average age of the head of an individual household in the i -th region in year t , years (it is expected that younger household heads are more likely to invest in solar power generation); $TEMP_{it}$ – average annual ambient temperature at the location of an individual household in the i -th region in year t , °C (it is expected that higher temperatures drive increased investment in solar power generation); β_0 , β_1 , c_1, \dots, c_7 – estimated coefficients of the impact of the respective indicators.

In the proposed model (6), the selection of the aforementioned variables is based on the results of current scientific research, which emphasize that household decisions to invest in solar power plants are largely determined by a number of socio-economic, demographic, and climatic factors (Günther et al., 2021; Wall et al., 2021; Zeru & Guta, 2021; Ahmar et al., 2022; García-López et al., 2023; Trypolska & Rosner, 2022). In particular, the previous level of electricity generation is included in the model to reflect the inertia of the

process. Households that have already invested in solar power plants are highly likely to continue operating, upgrading, or expanding them. This variable also captures the impact of existing infrastructure, technical capacity, and accumulated experience, all of which contribute to the further development of household electricity generation. The educational level of the household head is a significant factor influencing decisions regarding the adoption of new energy technologies. Educated individuals are better able to assess the long-term benefits of installing solar power plants, understand the technical aspects of their operation, and more effectively utilize national and regional support programs. A high level of accumulated savings is also an important prerequisite for making capital investments in solar power plants installation. Despite the gradual reduction in the cost of solar energy technologies, the initial expenses for implementing such investment projects remain significant, making household financial capacity a key determinant in decision-making. A household's current income, in turn, defines its solvency and financial stability, directly affecting its ability to invest in new energy solutions (Li et al., 2022; Prokopenko et al., 2024). The electricity tariff also serves as an important economic incentive. The rising cost of electricity increases interest in reducing dependence on centralized power supply, particularly through the installation of solar power stations. Demographic factors, especially the age of the household head, also play a role. Younger household heads tend to be more open to innovation, more active in decision-making, and have a longer planning horizon, which increases the likelihood of investing in solar energy systems. In contrast, older household members may be less inclined to change or lack the motivation to see a return on investment in the long term. Climatic conditions, in particular the average annual temperature, impact the efficiency of solar power plants. Higher temperatures can be an indicator of the favorable solar potential of the region, which, together with the number of sunny days, determines the economic feasibility of investing in solar generation. Thus, the selected factors cover both socio-demographic, economic, and climatic aspects (Trypolska et al., 2022), which comprehensively determine the opportunities and motivations of households to invest in solar energy.

Building on these conceptual insights, this study employs β - and σ -convergence models to examine regional patterns in Ukraine's household solar energy sector from 2016 to 2022. This approach allows for the evaluation of spatial homogeneity in renewable energy development and helps determine whether Ukraine is forming a unified energy "attractor" or, conversely, experiencing asynchronous and fragmented regional dynamics in its solar transition.

Table 1 presents the input data for the research, namely, the average annual volumes and coefficients of variation of electricity generation by solar power plants in the Ukrainian household sector by regions for the years 2016–2022.

Thus, the combination of β - and σ -convergence models within this study provides a comprehensive analytical view of the spatial patterns in the development of the household solar energy sector in Ukraine. Considering socio-economic, demographic, and climatic factors enables a deeper understanding of regional differences and identification of the driving forces behind both convergence and divergence. The applied methodology not only allows for a quantitative assessment of the degree of regional alignment but also forms the basis for developing recommendations to improve national and regional energy policies, taking into account the actual level of spatial homogeneity in renewable energy development.

Table 1. Electricity volumes generated by household solar power plants in Ukraine's regions in 2016–2022, million kWh

Source: State Agency on Energy Efficiency and Energy Saving of Ukraine (2025).

Region	Amount of electricity generation, million kWh							Dynamics of changes 2022/2016, times
	2016	2017	2018	2019	2020	2021	2022	
Vinnitsia	0.140438	0.660098	2.853343	12.03145	28.19575	39.88806	57.005916	405.9151797
Volyn	0.053926	0.220881	1.395169	6.179457	18.6436	27.39115	40.694009	754.6268776
Dnipropetrovsk	0.29381	2.596585	11.44878	43.84816	118.7897	176.3164	242.05842	823.860386
Donetsk	0.037694	0.227702	1.257415	4.742631	15.6334	30.05464	15.755992	417.9973471
Zhytomyr	0.028979	0.263974	1.587166	7.135307	17.97736	25.24917	32.37764	1117.279409
Zakarpattia	0.224658	1.348849	6.013384	18.41842	52.43867	102.9183	159.26051	708.9020333
Zaporizhzhia	0.038605	0.209293	0.659722	2.460932	8.025931	14.07771	18.526257	479.8926823
Ivano-Frankivsk	0.2615	1.295983	5.680981	22.44766	55.79324	79.87523	122.86918	469.8630057
Kyiv (region)	0.814721	3.460319	8.84756	21.24913	45.92622	64.36339	76.614645	94.0378915
Kirovohrad	0.238025	1.794518	9.191525	24.05798	48.95901	67.86817	92.597297	389.0234093
Luhansk	0.008482	0.015387	0.057819	0.435364	1.790064	2.794229	0.268439	31.64807828
Lviv	0.266054	1.072617	3.459704	10.51746	22.73142	36.28954	59.754385	224.5949506
Mykolaiv	0.098727	0.920807	3.038761	8.778251	2.591855	28.2698	33.266418	336.9535993
Odesa	0.159033	1.049109	3.904876	12.02674	31.50524	48.12447	77.052017	484.5033232
Poltava	0.04192	0.431516	1.818556	5.881451	13.34369	18.54546	27.030463	644.8106632
Rivne	0.089233	0.328386	1.106712	5.023964	11.95777	19.66777	32.68451	366.2827653
Sumy	0.159892	0.629854	1.961557	5.926207	16.82567	26.23454	35.473535	221.8593488
Ternopil	0.599032	2.142342	9.631421	35.50036	74.36122	100.1381	133.95136	223.6130223
Kharkiv	0.096484	0.483883	1.981084	5.785682	15.93966	20.00855	18.31002	189.7726048
Kherson	0.13865	0.904554	4.538309	17.56802	48.85701	58.88547	24.278227	175.1044064
Khmelnyskyi	0.13265	0.891742	4.034078	10.15456	44.53326	69.9272	90.241576	680.298349
Cherkasy	0.083962	0.509995	1.766189	6.922586	20.38041	25.33891	29.64681	353.0979491
Chernivtsi	0.216021	0.997819	4.51743	14.42399	36.18069	62.23184	101.48704	469.8017184
Chernihiv	0.023588	0.256585	0.76924	2.303608	4.755135	6.72295	9.155648	388.1485501
Average	0.17692	0.946367	3.813366	12.65914	31.50566	47.96588	63.765013	360.4168697
Standard deviation, sd	0.186639	0.837681	3.165064	10.6458	26.74857	38.94008	56.876793	

3. RESULTS AND DISCUSSION

The empirical results reveal both positive trends in the development of households' solar energy and existing regional disparities. As shown in Table 1, from 2016 to 2022, all regions of Ukraine experienced a rapid increase in electricity generation by residential solar power plants. On average across the country, electricity generation grew 360-fold during this period, indicating that households have become a significant component of Ukraine's energy transition. The highest growth rates were recorded in the Zhytomyr region, where the increase over seven years reached 1117%, followed by the Dnipropetrovsk region with 824% and the Volyn region with 755%. This reflects the effective synergy between national and regional programs supporting the development of small-scale energy generation (Kurbatova et al., 2021; Zhytomyr Regional State Administration, 2018; Dnipropetrovsk Regional Council, 2025). The Kyiv region is characterized by moderate growth rates, largely due to its structural features - high population density, predominance of urban development, and uneven development of the household sector, which hinder the widespread adoption of solar power plants in the residential sector. The Kherson and Kharkiv regions, after significant growth until 2021, experienced a sharp decline in 2022 as a result of Russian war intervention and the occupation of part of their territories. The lowest growth rates of solar generation in households were recorded in the Luhansk region, which is due to the almost complete occupation of the territory and prolonged military operations (Kyiv School of Economics et al., 2024).

Overall, during 2016–2022, a stable trend toward energy decentralization and active expansion of local electricity production by households through solar power plants emerged in Ukraine.

Alongside the positive dynamics, there is an increase in regional disparities in the implementation of such projects due to political, economic, and security factors. Thus, as the coefficient of variation in electricity generation by household solar power plants increases at the regional level, regional differences also grow - a trend opposite to convergence (Figure 1).

Thus, there is no sigma-convergence among Ukraine's regions in terms of electricity generation by household solar power plants, based on graphical analysis. Following the assessment of beta-convergence, we conducted a modelling of sigma-convergence in electricity generation by residential solar power plants in Ukraine to confirm or refute the conclusions drawn from the graphical analysis.

Therefore, we evaluated the beta-convergence models (2) for electricity generation by household solar power plants across Ukraine's regions for the period 2016–2022 (Figure 2).

According to Figure 2, it is evident that $GESP_{i2016}$ - electricity generation by household solar power plants in the i -th region in 2016 (the initial year) is a statistically insignificant indicator. This means that the initial higher or lower levels of electricity generation by residential solar power plants in the regions of Ukraine have no impact on the further develop-

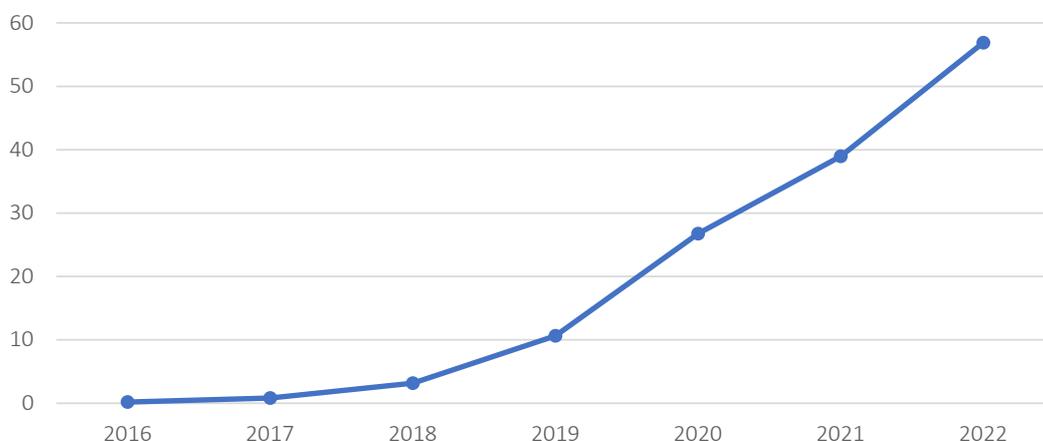


Figure 1. Standard deviations of electricity generation by household solar power plants in Ukraine in 2016–2022

reg 1/T(ln(GESP_{i2022})-ln(GESP_{i2016})) ln(GESP_{i2016})

Source	SS	df	MS	Number of obs	=	
Model	.000655922	1	.000655922	F(1, 22)	=	0.05
Residual	.272864137	22	.012402915	Prob > F	=	0.8202
				R-squared	=	0.0024
				Adj R-squared	=	-0.0429
Total	.27352006	23	.011892177	Root MSE	=	.11137

1/T(ln(GESP _{i2022})-ln(GESP _{i2016}))	Coefficient	Std. err.	t	P> t	[95% conf. interval]
ln(GESP _{i2016})	.0050317	.0218803	0.23	0.820	-.0403453 .050408

Figure 2. Beta-convergence modelling of Ukraine’s regions in electricity generation by household solar power plants (Model 2)

reg (ln(GESP_{i2022}) / (GESP_{i2016})) ln(GESP_{i2016})

Source	SS	df	MS	Number of obs	=	
Model	.032140194	1	.032140194	F(1, 22)	=	0.05
Residual	13.3703433	22	.607742879	Prob > F	=	0.8202
				R-squared	=	0.0024
				Adj R-squared	=	-0.0429
Total	13.4024835	23	.582716675	Root MSE	=	.77958

ln(GESP _{i2022}) / (GESP _{i2016})	Coefficient	Std. err.	t	P> t	[95% conf. interval]
ln(GESP _{i2016})	.0352222	.1531623	0.23	0.820	-.282417 .3528614
_cons	5.943017	.3733912	15.92	0.000	5.168651 6.717383

Figure 3. Beta-convergence modelling of Ukraine’s regions in electricity generation by household solar power plants (Model 3)

Source	SS	df	MS	Number of obs	=	
Model	25.9797851	1	25.9797851	F(1, 5)	=	88.56
Residual	1.46676122	5	.293352244	Prob > F	=	0.0002
				R-squared	=	0.9466
				Adj R-squared	=	0.9359
Total	27.4465463	6	4.57442439	Root MSE	=	.54162

lnsd	Coefficient	Std. err.	t	P> t	[95% conf. interval]
year	.9632494	.1023566	9.41	0.000	.7001335 1.226365
_cons	-1942.993	206.658	-9.40	0.000	-2474.225 -1411.762

Figure 4. Sigma-convergence modelling of Ukrainian regions in electricity generation by household solar power plants (Model 4)

ment of solar energy in the respective region over the next seven years (2016–2022).

We evaluated three models of beta-convergence in solar power generation in the private household sector across Ukrainian regions from 2016 to 2022 (Figure 3).

According to Figure 3, $GESP_{i2016}$, electricity generation by household solar power plants in the i -th region in 2016 (the initial year), is a statistically insignificant indicator. This means that the initial higher or lower levels of solar power generation in the private household sector across Ukraine’s regions had no impact on the subsequent develop-

ment of solar energy in the respective region over the following seven years (2016–2022).

We evaluated model (4) of sigma-convergence in solar power generation in the household sector across Ukrainian regions from 2016 to 2022 (Figure 4).

The results in Figure 4 indicate the absence of sigma-convergence, as the standard deviations of electricity generation levels by solar power plants in the household sector across regions increase over time. Moreover, this result is statistically significant at the 99% confidence level.

Overall, the results of the β - and σ -convergence model estimations indicate the absence of statistically significant coefficients in the β -models (Figures 2 and 3), as well as a consistent increase in the coefficients of variation in the σ -models (Figure 4), suggesting the predominance of divergence processes. Thus, the Ukrainian regions do not exhibit convergence in the pace of development of solar energy in the household sector; on the contrary, divergence is observed. The results of the study indicate the absence of a single attractor – a common reference point or coordinated goal – toward which all regions would gravitate in their movement toward renewable energy transformation. Consequently, the development trajectories of the regions are asynchronous and uneven, driven by both external factors (such as military actions and the geopolitical situation) and internal factors (such as building density, the activity of local communities, and the presence of regional support programs).

The analysis also revealed that the initial starting conditions, specifically, the level of electricity generation by households in 2016, do not have a statistically significant impact on the subsequent dynamics of the sector's development. One possible explanation is that the solar energy sector in Ukraine is relatively new, and at the initial stage, all regions were in approximately equal starting positions. This supports the thesis regarding the innovative nature of the sector, where modern incentive policies and institutional support play a greater role than historical baseline data. In other words, regions with a low starting point in 2016 (such as Zhytomyr, Dnipropetrovsk, and Volyn oblasts) were able to achieve significant breakthroughs thanks to targeted regional initiatives, support from united territorial communities,

and a high level of public awareness and motivation to install solar panels in households.

At the same time, our results are consistent with those of researchers who have analyzed convergence processes in the energy systems of the EU countries. They have demonstrated that joint policy and coordinated support mechanisms are the primary factors that facilitate a balanced development of renewable energy across regions (Marques & Fuinhas, 2011; Berk et al., 2020). In the EU countries, common financial programs and environmental standards have gradually reduced disparities in the generation of energy from renewable sources. In Ukraine, by contrast, these differences persist due to the lack of policy coherence and weak interregional cooperation.

Similar conclusions are confirmed by studies (IEA, 2021), which demonstrate that 'catch-up development' is possible only when the state ensures stable support policies and access to long-term financing. The intensification of divergence processes in Ukraine may persist in the coming years, influenced by the full-scale military invasion. The destruction of critical infrastructure limits the country's ability to modernize its energy system and expand distributed renewable energy solutions, while significant regional differences in investment opportunities are likely to hinder the development of solar energy in households.

At the same time, some regions demonstrate examples of local convergence, the so-called 'energy clubs.' This phenomenon is consistent with the club convergence hypothesis and the results of Saba and Ngepah (2022) and Shakeel et al. (2023), who showed that regions with similar institutional capacity, access to financing, and supportive policy frameworks tend to form clusters of accelerated renewable energy development. In such clusters, local governance mechanisms and community-driven initiatives play a decisive role in facilitating adoption of renewable technologies.

Overall, the results of the study show that convergence among regions in the development of household renewable energy is possible only under macroeconomic stability, stable state support policy and effective financial cooperation. In Ukraine, the implementation of such conditions remains limited due to an unstable economic environment, military

risks, and uneven access to financial support instruments, which slows down the convergence processes between regions.

Summarizing the above, it is appropriate to outline the main directions for improving state policy in the field of households' solar energy development. At present, the development of this sector is characterized by features of a dissipative system, within which regions evolve along their own trajectories with minimal influence from centralized coordination. At the same time, regional differences in the development of solar energy in the household sector are determined not only by economic or institutional factors but also by external threats caused by the full-scale war. Therefore, the directions for improving energy policy should focus on:

- 1) harmonizing national and regional policies by agreeing on strategic goals, implementation tools and criteria for assessing the effectiveness of supporting the development of solar energy in the regions. Particular attention should be paid to the development of adaptive support programs for temporarily occupied territories to be implemented after their liberation and zones close to hostilities;
- 2) strengthening the institutional capacity of regions, particularly through the development of local energy agencies, the introduction of preferential financing, the establishment of information and advisory centers, as well as the implementation of mechanisms for managing crisis energy funds in frontline regions;
- 3) stimulating local initiatives through the introduction of flexible support instruments, taking into account the specifics of each region: tariff policy, tax breaks, targeted subsidies, access to technical assistance, etc. Particular attention should be focused on supporting households of internally displaced persons, military personnel, and veterans;
- 4) forming interregional synergy aimed at the transfer of knowledge, technologies, and best practices from more developed regions to those exhibiting slower rates of renewable energy adoption. Such interaction should be based on the development of horizontal part-

nerships between territorial communities, the creation of joint demonstration projects, the organization of training programs, and the exchange of experience within interregional cooperation platforms.

Despite the insights provided by this study, several limitations should be acknowledged. First, as noted, the empirical data primarily cover the pre-war period and the early stage of the full-scale Russian invasion in Ukraine. Consequently, the findings should be interpreted with caution as they may not fully reflect the current economic and infrastructural conditions, nor the ongoing impacts of military actions on energy systems, mass population displacement, and policy responses. Second, the study relies on formal modelling approaches that, while capturing key trends and convergence patterns, cannot fully incorporate behavioral, socio-economic, and motivational factors that influence household adoption of solar technologies. Third, regional analyses are constrained by the availability and granularity of data, which may limit the precision of conclusions regarding local disparities and support mechanisms.

Building on these limitations, future research could focus on several directions. Empirical validation of models (5) and (6) using detailed survey data from households that have installed or plan to install solar energy systems would allow for a more nuanced understanding of behavioral and motivational drivers behind adoption. Moreover, exploring the demonstration effect – whether successes in certain regions stimulate growth in others – could provide insights into the mechanisms of knowledge transfer, institutional learning, and interregional competition in renewable energy development. Finally, examining post-2022 developments under conditions of war and recovery could shed light on the resilience and adaptability of decentralized energy systems, as well as the effectiveness of targeted policies in mitigating regional disparities.

These directions for further study would not only enrich understanding of household solar energy dynamics but also inform the design of more effective, coordinated policies to support renewable energy development in Ukraine under evolving economic, social, and security conditions.

CONCLUSION

The aim of this study was to identify the presence of beta- and sigma-convergence processes in the development of solar energy in households across Ukraine's regions in 2016–2022. The analysis revealed no overall tendency toward convergence. The coefficients in the β -models proved to be statistically insignificant, and the differences between the regions continued to widen. This indicated a strengthening of regional disparities in the development of solar energy in the residential sector. The growing divergence was caused by differences in initial economic conditions and access to financial resources, as well as by external factors, in particular, the impact of war actions (in 2022) and uneven implementation of national and local renewable energy support programs.

The obtained results allow several important conclusions to be drawn. First, the absence of convergence processes suggests that the current market and policy mechanisms do not ensure a balanced development of the solar energy sector in households across Ukrainian regions. Second, since the initial level of development did not determine further dynamics, key factors are local initiatives, the availability of financial incentives, and support from local authorities. Third, to reduce regional asymmetry, it is advisable to strengthen the role of energy policy in developing adaptive support instruments, in particular, through the introduction of targeted grants and loan programs for solar energy project implementation. An important direction for further research is the study of behavioral and financial determinants influencing households' decision-making in installing small solar power plants, as well as the evaluation of the effectiveness of regional support programs in the post-war period. The implementation of these approaches will contribute to the reduction of territorial disparities and shape a more coherent national strategy for solar energy development in the residential sector.

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