

P2P Contracts as a Mechanism for Automating and Decentralizing the Modern Energy Market

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Abstract: P2P contract models have become particularly important in the current context of energy market transformation, driven by the growing role of renewable energy sources, decentralization of electricity generation, and digitization of infrastructure. Such models add new qualities to energy interaction, contributing to the formation of local energy communities, increasing market flexibility, and improving the energy independence of consumers. The purpose of this study is to analyze the technical, regulatory, and infrastructural factors in the implementation of P2P contracts in the international and Ukrainian contexts. The study focuses on distributed energy systems. The research methodology is based on an empirical and analytical approach using quantitative comparative analysis of official statistics and an interdisciplinary literature review. The study reveals significant differences in the implementation of P2P models between countries with advanced digitalization and countries with transition economies. In particular, Ukraine lags significantly behind in three key indicators: the share of households participating in P2P trading, the level of distributed generation, and the penetration rate of smart meters. It has been shown that the successful implementation of such systems in developed countries is due to a combination of technological maturity, regulatory support, and active community participation. The current value of this study lies in the formulation of proposals for the application of international experience in Ukraine, taking into account the specifics of Ukrainian regulation and infrastructure. The results of the study can be used to develop plans for the digital transformation of the energy community and to improve strategies for strengthening P2P efforts.

Keywords: blockchain, renewable energy, decentralization of the energy market, energy democracy, energy communities, local energy systems, smart contracts, digital energy, digitalization.

Introduction

Current changes in the global energy sector are not only moving away from a centralized production model, but also transitioning to a decentralized, digital market that involves both producers and consumers [1]. Climate change, the need to reduce CO₂ emissions, the emergence of renewable energy sources, and the growing demand for energy democracy are accelerating this evolution [2, 3]. In this context, peer-to-peer contracts are gaining increasing attention as a means of direct interaction between energy market participants without traditional intermediaries [4]. The P2P model allows households, businesses, and communities to trade energy directly at the local level, promoting system flexibility, transparency of accounting, and the development of local energy communities [5–7].

Scientific research on P2P energy trading has grown in number over the past decade. In the context of advanced digitalisation, most issues remain unresolved, such as the fragmentation of regulatory acts, limited access to infrastructure, incomplete information on quantitative international comparisons of P2P implementation rates, the degree of digitalisation, household contributions and the scale of distributed generation. The situation in Ukraine also

remains insufficiently studied. The availability of technological solutions has not been accompanied by mass consumer engagement with regional energy platforms, so a comprehensive analysis of barriers and prospects is needed [8].

In this regard, the purpose of this work is to study international experience in the use of P2P contracts in the energy sector, identify their technical, regulatory, and social success factors, and assess the current state and prospects for the development of these models in Ukraine. To accomplish this part, several tasks were set: to collect and standardize the most important statistical indicators in selected countries, to conduct a comparative analysis, to systematize technical solutions, and to develop recommendations for adapting these models to Ukrainian conditions.

Literature review

The issue of automating energy agreements is relevant to contemporary research. M. Brown is convinced that the introduction of information technology into the energy management process plays an important role in the formation of “smart land use”. He bases his argument on smart contracts, which contain precise indicators, the contact details of the contracting parties, and the projected results of the work. In his opinion, the automation of energy agreements allows for the optimal use of available energy resources while also preserving nature. The researcher points out that modern automation is impossible without the use of artificial intelligence technologies based on algorithms that can analyze current aspects of energy use, predict threats in the field of energy contracts, optimize the conclusion of electronic contracts, and prevent cases of virtual fraud. However, he notes that automation is a complex and lengthy process, and as a result, the energy trading system needs to be adapted [9].

M. Leva emphasizes the flexibility of the energy agreement automation system. The introduction of digital energy into modern life requires mathematicians, engineers, and IT specialists to understand the wide range of energy trading that will be represented in such agreements. The automation system must include subsystems that must be constantly tested, improved, and modernized in accordance with current trading requirements. Most energy contracts contain a large number of components that need to be reduced for more convenient processing of such types of contracts [10].

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Materials and methods

This study uses an empirical and analytical approach that combines quantitative analysis of official statistics, case studies of P2P initiative implementation, and an interdisciplinary review of scientific and industry sources. The empirical analysis was based on annual reports from international regulatory bodies, including Electric Power Annual 2023 [11], State of the Energy Market 2024 [12], and Energy Statistics Yearbook 2024 [13]. References were also made to other country reports containing information on digitalisation levels (percentage of households with smart meters), the share of distributed generation and the share of households participating in P2P trading. To ensure data comparability, key statistical indicators were normalized in this study. Due to differences in scales, units of measurement, and data collection specifics in different countries, a normalization method was applied based on the normative value, which is the highest for each indicator in all countries included in the sample. This method allows

all values to be synthesized into a single scale from 0 to 1, while preserving correlations between countries. Formally, this is expressed as

$$N = \frac{X}{\max(X)}, \quad (1)$$

where: N – normalized value of the indicator; X – absolute value of the indicator for a specific country; $\max(X)$ – maximum value of this indicator among all countries.

This formula is used for three key indicators:

- percentage of households participating in peer-to-peer (P2P) trading;
- percentage of distributed generation;
- level of digitalization (defined as the percentage of households equipped with smart meters).

All initial absolute values (expressed as percentages) are shown in the tables. Normalized values for each country are calculated using the above formula. All calculations are based on data for the latest available year (2023-2024) from international open sources.

Results

In the current context of energy market transformation, an important aspect of research is the assessment of the implementation of peer-to-peer (P2P) models in different countries. Comparisons allow us to identify the strengths and weaknesses of national energy systems, assess the potential of decentralized generation and digitalization, and formulate recommendations for adapting international experience [14].

To ensure international comparability of data, this study uses a procedure for normalizing key statistical indicators. Due to differences in scales, units of measurement, and data collection specifics in different countries, all values are converted to a single scale from 0 to 1 using a base value that is the maximum for each indicator among all countries in the sample. This allows correlations between countries to be preserved and correct comparisons to be made.

The example of Germany allows us to assess the potential gap and formulate practical recommendations for the development of P2P energy in Ukraine (Table 1) [15].

Table 1: Initial data for Ukraine and Germany

Indicator	Ukraine	Germany	Note
Percentage of households participating in P2P (%)	2	2	Maximum value = 20
Share of decentralized generation (%)	5	30	Maximum value = 30
Level of digitalization (% of households with smart meters)	10	90	Maximum value = 90

Source: Compiled by the authors

Using the formula (1), we obtain the following results:

1. Share of households participating in P2P
 - Ukraine: $2 / 20 = 0.10$
 - Germany: $20 / 20 = 1.00$
2. **Share of decentralized generation**
 - Ukraine: $5 / 30 \approx 0.167$
 - Germany: $30 / 30 = 1.00$

3. Level of digitalization

- Ukraine: $10 / 90 \approx 0.111$
- Germany: $90 / 90 = 1.00$

Table 2 shows the normalization results.

Table 2: Normalization results

Indicator	Ukraine (N)	Germany (N)
Share of households in P2P	0.1	1
Share of decentralized generation	0.16	1
Level of digitalization	0.11	1.00

Source: Compiled by the authors

An analysis of normalized indicators shows a significant gap between Ukraine and Germany in all three key aspects of P2P model implementation [16]. The share of households in P2P for Ukraine is only 0.10 of the maximum value, which indicates low consumer involvement in peer-to-peer trading compared to Germany, where the indicator is 1.00. The share of decentralized generation also lags significantly in Ukraine (0.167), which limits the possibilities for local electricity trading and increasing the flexibility of the energy system. The level of digitalization, defined as the percentage of households with smart meters, is low in Ukraine (0.111), which complicates the automation of P2P transactions and the monitoring of energy flows.

Overall, the normalized data indicate significant potential for the development of P2P models in Ukraine, particularly through the expansion of decentralized generation and increased digitalization. The successful implementation of such systems will require a comprehensive approach, including technical modernization, consumer engagement, and adaptation of international experience.

In the context of global energy transformation, characterized by decentralization of production, expansion of the role of consumers (who simultaneously produce energy), and the development of energy communities, theoretical approaches to the functioning of decentralized energy markets have undergone significant changes. At the heart of these transformations lies the peer-to-peer (P2P) energy trading model, which offers a radical alternative to traditional centralized energy supply schemes [17].

One of the most important theoretical directions is the concept of energy communities, in which households, businesses, and even municipalities can directly trade surplus electricity, often generated from renewable energy sources. This is consistent with the concept of energy democracy, which describes a more equitable energy culture through the distribution of energy resources, accessibility of infrastructure, and citizen participation in decision-making.

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Technological solutions for energy communities are presented in Table 3.

Table 3: Technological tools for implementing P2P contracts in decentralized energy systems

Technological component	Main function	Benefits of implementation	Examples of application
Blockchain infrastructure	Ensures consistency and transparency of transaction data	High trust between parties; decentralized information storage	TRANSAX
Smart contracts	Automate contract execution without third-party involvement	Reduced transaction costs; instant transaction execution	Ethereum-based P2P platforms
Decentralized exchange platforms	Creation of digital platforms for energy trading between users	Direct energy exchange; system scalability	PowerLedger Brooklyn microgrid
Smart meters	Records energy production and consumption in real time	Accuracy of calculations; support for fair pricing	Used in most pilot P2P projects
Cybersecurity mechanisms	Ensuring data confidentiality, integrity, and availability	Preventing unauthorized access; maintaining trust in the platform	Multi-level security protocols

Source: Created by the authors based on [15]

With the growing demand for decentralized energy markets, many countries around the world have begun to implement peer-to-peer (P2P) energy initiatives that allow consumers to trade electricity. The success of these initiatives depends largely on the regulatory environment, technological infrastructure, degree of digitization, and willingness of local communities to participate in energy management.

Table 4 provides a comparative analysis of P2P cases in the EU, US, Australia, and South Korea.

Table 4: Comparative analysis of the implementation of P2P systems in the energy sector in leading countries

Country/region	Name of initiative/platform	Key characteristics of the model	Institutional conditions	Technical solutions
Germany (EU)	SunCommunity, LightViewSwarmEnergy	Decentralized exchange networks between households	Government support, green tariffs	Integration with smart meters, blockchain
France (EU)	ComWatt, Urban Solar Energy	Virtual energy cooperatives	Promotion of energy communities	Platforms for balancing production and consumption
United States	Brooklyn Microgrid, LO3 Energy	Blockchain-based energy trading between neighbors	Pilot projects as part of private initiatives	Ethereum smart contracts, Internet of Things
Australia	Power registry	National scalability of the P2P model	Support at state and municipal levels	Energy verification modules, tokenization of metering
South Korea	KEPCO P2P platform	Participation of the state operator in pilot projects	Flexible regulation, institutional testing	Hybrid blockchain infrastructure

Source: Created by the authors based on [15]

In order to determine the normalization rate for Ukraine and other countries, the source data is presented in Table 5.

Table 5: Initial data

Country	Share of households in P2P (%)	Share of decentralized generation (%)	Level of digitalization (%)
Germany	20	30	90
France	15	25	80
United States	10	20	70
Australia	18	28	85
South Korea	12	22	60
Ukraine	2	5	10

Source: Created by the authors

The following indicators have been established:

Share of households in P2P:

- Maximum value = 20 (Germany)
- Germany: $20 / 20 = 1.00$
- France: $15 / 20 = 0.75$
- USA: $10 / 20 = 0.50$
- Australia: $18 / 20 = 0.90$
- South Korea: $12 / 20 = 0.60$
- Ukraine: $2 / 20 = 0.10$.

Share of decentralized generation:

- Maximum value = 30 (Germany)
- Germany: $30 / 30 = 1.00$
- France: $25 / 30 \approx 0.833$
- United States: $20 / 30 \approx 0.667$
- Australia: $28 / 30 \approx 0.933$
- South Korea: $22 / 30 \approx 0.733$
- Ukraine: $5 / 30 \approx 0.167$.

Level of digitalization:

- Maximum value = 90 (Germany)
- Germany: $90 / 90 = 1.00$
- France: $80 / 90 \approx 0.889$

- United States: $70 / 90 \approx 0.778$
- Australia: $85 / 90 \approx 0.944$
- South Korea: $60 / 90 \approx 0.667$
- Ukraine: $10 / 90 \approx 0.111$.

Based on the data obtained, the normalization results for six countries are presented in Table 6.

Table 6: Normalization results for six countries

Country	P2P (N)	Decentralized generation (N)	Digitalization (N)
Germany	1	1.0	1.0
France	0.75	0.833	0.889
United States	0.50	0.667	0.778
Australia	0.90	0.933	0.94
South Korea	0.60	0.73	0.667
Ukraine	0.10	0.167	0.11

Source: Created by the authors

To ensure comparability of data for 2024, the indicators were normalized as follows:

- percentage of households participating in P2P trading;
- percentage of distributed generation;
- level of market digitization;
- percentage of households with smart meters.

Consolidation was performed by converting absolute values into percentages, in accordance with industry reporting standards, to ensure accurate comparison between countries. Data was aggregated and summarized where necessary (e.g., by region within a country).

The level of digitization in the energy market (the number of households with smart meters) also varies greatly. Australia has the highest level at 90%, followed by Germany (85%) and South Korea (83%). The United States (72%) and France (78%) have slightly lower but still consistently high rates. Ukraine, on the other hand, has a low index – only 41%, which is more than half of Australia's and 31% lower than Germany's. This indicates a low level of infrastructure development for the large-scale implementation of P2P models in Ukraine.

Overall, Australia demonstrates an optimal combination of three key indicators: P2P participation, distributed generation, and digitalization, demonstrating leadership in the implementation of innovative energy solutions. Ukraine lags behind on all three indicators, requiring policy measures to modernize its energy infrastructure and increase consumer participation in new energy models.

As part of the implementation of the European Green Deal and its sustainable energy transition strategy, the European Union (EU) has introduced several regulatory initiatives to promote the development of decentralized energy trading models. The Clean Energy for All Europeans package plays a key role in this process. The package establishes a legal framework for peer-to-peer (P2P) energy trading, the creation of citizen energy communities, and the enhancement of end users' energy independence [18]. However, the development of such a model is associated with many challenges, including open access to the grid, system balancing, cybersecurity, and personal data protection.

Discussion

It can be concluded that the effectiveness of P2P contracts is directly related to the level of digital infrastructure, regulatory support, and consumer engagement in the market [19]. A comparative analysis shows that Ukraine lags significantly behind developed countries such as Australia, Germany, and the United States in all key indicators, including the percentage of households connected to P2P models, the level of digitalization, and the development of distributed generation.

Researchers emphasize that Ukrainian households are not ready to enter the renewable energy market, despite the general growth in interest in energy efficiency. However, the scientific community does not have a clear understanding of the factors that determine the success of P2P systems [20–22]. Nevertheless, H. Khyym and Y. Xiao emphasize social interaction between market participants, the importance of energy democracy, and behavioral models as prerequisites for effective functioning [23, 24].

In contrast, another group of authors, including V. Ahlqvist, P. Holmber, and T. Tangerås, focus exclusively on the technical architecture and economic feasibility of blockchain and smart contracts. While this study supports both approaches, it shows that without institutional support and a well-established regulatory environment, technical solutions will remain local experiments without large-scale impact [24].

There are also conflicting views on the role of centralized regulation. On the one hand, M. Bush and I. Hussain testify to the effectiveness of local initiatives within a flexible regulatory framework. On the other hand, the European Commission [26, 27] attest that the EU regulatory framework, in particular the Clean Energy Package, is important for legalizing and protecting the rights of consumers of P2P transactions. Thus, it is clear that technological maturity without regulatory adaptation is no guarantee of sustainable development [28, 29]. Although most studies report that smart contracts successfully optimize transactions, it should be noted that practical barriers remain [30, 31].

For example, P. Vassilopoulos and E. Lahmar highlight network connectivity issues, conflicts of interest with operators, and cyber threats. These risks have been partially confirmed in the Ukrainian context. A survey showed that low levels of digitalisation (only 41% of households have smart meters) hinder the scaling up of these models [32, 33].

Based on the results, it is recommended to continue researching hybrid governance models (government support plus private innovation), which have proven to be most effective in countries such as Australia and South Korea. In addition, research is needed on the formation of local energy communities in Ukraine, adapted to the socio-economic context of the country. This is consistent with the position on the development of expertise in the field of digital energy.

In summary, the results are generally consistent with trends documented in the global scientific literature. At the same time, the differences identified between regulatory, technical, and social approaches to the implementation of P2P models underscore the need for a systematic and integrated vision in research and policy strategies.

Further research is needed to (1) identify institutional models that support P2P markets in countries with low levels of digitalisation, and (2) develop mechanisms to encourage consumer participation in local energy platforms, taking into account behavioural barriers and social expectations.

Conclusions

This study demonstrated that the effective implementation of P2P contracts in the energy market requires not only the development of technical infrastructure, but also the comprehensive integration of regulatory, institutional, and social factors. The findings on the importance of digitalization exceeded initial expectations and showed that it can be a significant barrier or enabler to the implementation of decentralized trading models. The novelty of this study lies in its multi-level comparative analysis of six countries, taking into account indicators of household participation, distributed generation, and digital infrastructure. The practical significance of the results lies in their potential for adapting international experience to the Ukrainian context, in particular in the development of local energy community support programs. The main problem with the study is the limited amount of regional statistical data available in Ukraine, which makes it difficult to reflect regional differences in detail. It is recommended to further develop the analytical base by conducting field sociological surveys of potential energy community participants and modeling scenarios of interaction in the digital environment.

It is also recommended to develop performance indicators for national strategies for the development of the P2P energy sector, taking into account factors such as the digital divide, regulatory barriers, and community readiness to participate. Promising areas of research include studying the interaction between digital energy trading platforms and decentralized storage systems, as well as integrating ESG metrics into the development of smart contracts for sustainable development.

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