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SMART CONTRACTS IN DECENTRALIZED ENERGY MARKETS: OPPORTUNITIES AND REGULATORY CHALLENGES

The accelerating digitalization of the energy sector is redefining how electricity is generated, traded, and consumed. Among emerging innovations, smart contracts being self-executing programs embedded on blockchains have become pivotal to the development of decentralized energy markets. This article reviews the state of knowledge and practical progress in applying smart contracts to energy systems, with particular attention to their potential in Ukraine's evolving energy and digital infrastructure. Through a systematic analysis of academic studies, pilot projects, and policy frameworks, the article identifies the main opportunities, challenges, and future trajectories of blockchain-based automation in energy markets. The starting sections introduce the conceptual foundations of smart contracts, highlighting their essential properties of transparency, immutability, and autonomy. These characteristics enable direct peer-to-peer transactions without intermediaries, potentially lowering transaction costs and improving market efficiency. The subsequent analysis focuses on how smart contracts can support decentralized energy trading, renewable integration, and dynamic pricing, using examples from Australia's Power Ledger, Brooklyn Microgrid in the United States, and Europe's Enerchain, WePower, and Sunchain initiatives. To complement international evidence, the article discusses Ukraine's readiness for pilot adoption in microgrid environments, given its digital transformation agenda and renewable energy policies. The study further examines technological, regulatory, and security challenges hindering large-scale deployment. Issues such as interoperability, scalability of consensus algorithms, and the legal enforceability of smart contracts remain critical barriers. Nevertheless, emerging frameworks like regulatory sandboxes and advances in IoT and AI integration offer pathways to overcome them. MATLAB-based simulation examples illustrate the potential for dynamic pricing and automated market balancing. The article concludes with strategic recommendations for policymakers, engineers, and researchers by emphasizing the need for hybrid architectures combining blockchain, artificial intelligence, and energy optimization models. Overall, the article underscores that while smart contracts promise to democratize and decarbonize energy systems, their success ultimately depends on coordinated technical innovation and adaptive governance.

Key words: *smart contracts, decentralized energy markets, blockchain, peer-to-peer energy trading, renewable energy, regulatory challenges, Ukrainian energy exchange, tokenization, microgrids.*

Романюк В. В. Смарт-контракти на децентралізованих енергетичних ринках: можливості та регуляторні виклики

Прискорена цифровізація енергетичного сектору докорінно змінює способи виробництва, торгівлі та споживання електроенергії. Серед новітніх інновацій особливе місце займають смарт-контракти, які є самовиконуваними програмами, вбудованими у блокчейн, що стали ключовим елементом розвитку децентралізованих енергетичних ринків. У статті здійснено огляд сучасного стану знань і практичних напрацювань у застосуванні смарт-контрактів до енергетичних систем, з особливою увагою до їхнього потенціалу в контексті трансформації енергетичної та цифрової інфраструктури України. На основі системного аналізу наукових досліджень, пілотних проєктів і політичних рамкових документів визначено основні можливості, виклики та перспективи впровадження блокчейн-автоматизації на енергетичних ринках. Початкові розділи розкривають концептуальні засади смарт-контрактів, підкреслюючи їхні ключові властивості прозорості, незмінності й автономності. Ці характеристики забезпечують можливість прямих операцій між учасниками (peer-to-peer) без посередників, що потенційно знижує транзакційні витрати й підвищує ефективність ринку. Подальший аналіз зосереджено на тому, як смарт-контракти можуть підтримувати децентралізовану торгівлю енергією, інтеграцію відновлюваних джерел та динамічне ціноутворення. Розглянуто приклади з міжнародного досвіду: Power Ledger (Австралія), Brooklyn Microgrid (США), а також європейські проєкти Enerchain, WePower і Sunchain. Для доповнення міжнародних прикладів у статті проаналізовано готовність України до пілотного впровадження смарт-контрактів у мікромережевих середовищах, враховуючи її курс на цифрову трансформацію та політику у сфері відновлюваної енергетики. Окремо розглянуто технологічні, регуляторні та безпекові перешкоди, які стримують масштабне розгортання технології, а також проблеми інтероперабельності, масштабованості алгоритмів консенсусу та юридичної чинності смарт-контрактів. Попри це, нові регуляторні підходи, зокрема регуляторні пісочниці, а також розвиток інтеграції IoT і штучного інтелекту, створюють шляхи для подолання зазначених бар'єрів. Для ілюстрації потенціалу технології наведено приклади MATLAB-моделювання *динамічного ціноутворення та автоматизованого балансування ринку. У підсумку стаття формулює стратегічні рекомендації для політиків, інженерів і науковців, наголошуючи на необхідності створення гібридних архітектур, що поєднують блокчейн, штучний інтелект і моделі енергетичної оптимізації. Загалом підкреслюється, що хоча смарт-контракти мають потенціал демократизувати та декарбонізувати енергетичні системи, їхній успіх зрештою залежить від скоординованих технологічних інновацій і адаптивного врядування.*

Ключові слова: *смарт-контракти, децентралізовані енергетичні ринки, блокчейн, P2P-торгівля енергією, відновлювана енергетика, регуляторні виклики, Українська енергетична біржа, токенізація, мікромережі.*

Problem statement. The global energy sector is undergoing a profound transformation driven by decarbonization, decentralization, and digitalization [1, 2]. These "three D's" have reshaped the traditional paradigm of energy production and consumption, creating an ecosystem in which individuals and small entities are not only consumers but also producers of electricity – so-called prosumers [3, 4]. This shift toward distributed generation, particularly through renewable sources such as solar photovoltaics and wind power, challenges the legacy centralized market structure dominated by large utilities and transmission system operators. In this evolving landscape, mechanisms for secure, transparent, and automatic energy exchange have become crucial, stimulating the search for innovative technological solutions that can enable real-time settlement and trustworthy coordination among decentralized participants [1, 5].

One of the most promising technologies responding to this challenge is the smart contract, a self-executing digital agreement stored and run on a blockchain [6, 7]. Smart contracts allow parties to transact energy, validate data, and enforce agreements automatically without relying on a central intermediary [8, 9]. In decentralized energy markets, these capabilities can enable peer-to-peer (P2P) energy trading, automated billing, and dynamic pricing mechanisms, all based on verifiable generation and consumption data from smart meters and Internet-of-Things (IoT) devices. When properly implemented, smart contracts can thus ensure trust among participants who may not know each other personally, provide transparent and tamper-proof transaction records, and reduce the costs associated with traditional energy clearing and settlement procedures [4, 5, 7].

Recent research has shown that blockchain-based smart contracts can also facilitate tokenization of energy units. This impies the conversion of kilowatt-hours or renewable certificates into digital tokens that can be traded or used as collateral [10, 11]. The tokenization opens new economic opportunities, such as local microgrid markets, energy communities, and distributed renewable investment schemes. However, despite this promising outlook, a number of unresolved regulatory, technical, and market challenges limit widespread adoption [8, 12, 13]. These include questions of legal enforceability of smart contracts, data privacy compliance under existing frameworks (such as General Data Protection Regulation or, abbreviated, GDPR), grid stability and balancing obligations, interoperability with legacy energy management systems, and the environmental footprint of blockchain technologies themselves [14, 15].

The purpose of this article is to synthesize and critically analyze the current state of knowledge regarding the use of smart contracts in decentralized energy markets. In addition, the article aims to identify the main opportunities for improving market transparency, efficiency, and inclusivity, while also highlighting key obstacles related to legal, technical, and regulatory aspects. To achieve this goal, the article integrates findings from recent academic and industrial studies, complemented by brief illustrative simulations in MATLAB that demonstrate the operational logic of automated settlement and token-based trading. A particular emphasis is placed on the emerging developments in Ukraine, where the transition to renewable and distributed energy systems is a declared national priority [7, 16, 17]. Although large-scale blockchain-based energy markets are not yet implemented, several pilot initiatives, regulatory discussions, and digital infrastructure projects suggest growing readiness for experimentation with decentralized energy trading. By comparing global experiences from Australia, the United States, and the European Union (EU) with Ukraine's institutional and legislative context, this article seeks to draw conclusions about feasible directions for future integration of smart contracts into the country's evolving energy ecosystem.

Accordingly, the article is structured as follows. Section 1 provides the conceptual background of decentralized energy markets and explains the basic functions of smart contracts in this environment. Section 2 outlines the main opportunities and advantages that blockchain-based automation can bring to energy trading. Section 3 examines the regulatory and technical challenges that currently constrain adoption. Section 4 presents international and Ukrainian case studies, while Section 5 includes MATLAB-based illustrations of automated market mechanisms. Finally, Section 6 discuss future directions and summarize the key findings of the article.

Background of decentralized energy markets and smart contracts. Conventional energy systems have long been structured around centralized generation facilities that deliver electricity through hierarchical transmission and distribution networks [18]. Prices, scheduling, and balancing are typically administered by regulated utilities and wholesale market operators. Although this structure provides stability, it also produces inefficiencies and limits consumer participation. The rapid proliferation of small-scale renewable energy sources (like solar rooftops, wind micro-turbines, and storage units) has eroded the distinction between producers and consumers [4]. As households and local communities become prosumers, capable of generating surplus electricity, a need arises for new mechanisms of direct exchange and market participation beyond centralized control. Decentralized or P2P energy markets represent a natural response to this evolution [9, 19]. In such markets, individual participants may trade surplus electricity locally through microgrids or virtual power plants, negotiating prices dynamically based on supply and demand.

Blockchain technology offers a distributed ledger that records transactions across multiple nodes, ensuring transparency, immutability, and resistance to tampering. Each transaction, once validated through a consensus mechanism, becomes a permanent record in the chain [5, 7, 15]. In the context of energy markets, this allows participants to exchange data and value without relying on a central clearinghouse. Blockchains such as Ethereum, Hyperledger Fabric, and Energy Web Chain have been explored for implementing energy-related applications, from renewable certificate tracking to P2P trading and dynamic grid balancing [12, 20].

The blockchain architecture consists of several critical components [5]:

1. Consensus mechanism – determines how network nodes agree on transaction validity (e. g., Proof-of-Stake, Proof-of-Authority).

2. Distributed ledger – stores a chronological, tamper-resistant record of energy transactions.

3. Cryptographic tools – ensure authenticity and privacy of participant identities.

4. Smart contracts – self-executing pieces of code that automate transaction logic based on predefined conditions.

Together, these elements enable trust by design: once transaction conditions are coded and deployed, execution occurs automatically when data triggers are met.

A smart contract can be defined as a deterministic program that encodes the terms of an agreement, executes them autonomously, and records outcomes on the blockchain [6]. In decentralized energy markets, smart contracts govern the automatic transfer of energy tokens or digital currency in exchange for measured electricity. They receive input data from smart meters or IoT sensors (commonly through secure middleware called data oracles) and trigger payment once the predefined energy quantity is delivered [12, 21, 22].

Typical smart-contract-enabled use cases include [8, 9]:

1. P2P trading: automatic matching of sellers (prosumers with surplus generation) and buyers within microgrids.

2. Automated billing and settlement: instantaneous payments once consumption data are validated.

3. Dynamic pricing mechanisms: price adjustments in real time according to grid conditions or renewable availability.

4. Green certificate and carbon-credit trading: transparent issuance and verification of renewable generation credentials.

The integration of these functions promises substantial gains in transparency, cost reduction, and operational efficiency. Nonetheless, implementation challenges persist: energy consumption of certain consensus algorithms, data integrity risks from faulty sensors, and the absence of clear regulatory recognition of blockchain transactions [5, 7, 10, 12].

Consider a simplified microgrid with three participants, two households and one small enterprise, each possessing both consumption and production capabilities. Smart meters continuously measure net energy flows. A smart contract deployed on a blockchain platform can automatically execute the following logic:

1. Aggregate all surplus and deficit data at each time interval.

2. Match buyers and sellers according to available quantities.

3. Transfer payment tokens at the current price per kWh.

In practice, such operations can be illustrated through MATLAB simulations, where energy balances, price adjustments, and settlements are computed in real time according to predefined "contract" conditions. These illustrative models, provided later in Section 5, demonstrate the operational logic of decentralized automation without delving into blockchain coding details [23].

Opportunities and advantages of smart contracts in decentralized energy markets. The integration of smart contracts into decentralized energy markets creates new opportunities for efficiency, transparency, and sustainability. Their main benefits can be viewed through five dimensions: transaction automation, transparency, cost reduction, system resilience, and inclusion of small-scale participants.

Smart contracts automate processes that in traditional markets require multiple intermediaries such as system operators or clearinghouses. By encoding transaction logic on a blockchain, they execute payments and update ownership records automatically when predefined conditions are met. It is, for example, confirmation of energy delivery or a specific price threshold. A prosumer with rooftop solar panels can thus sell surplus energy directly to a neighbor under a contract that verifies smart-meter data and triggers payment instantly, reducing latency and disputes over consumption data [8, 9]. MATLAB simulations can model this with conditional payment functions that process time-stamped generation data once thresholds are reached [7].

Blockchain ensures that all transactions are immutable, traceable, and verifiable (within privacy limits). This transparency builds trust among participants without prior relationships and prevents manipulation or double counting of renewable certificates. In some pilots, blockchain verification has replaced traditional registries for guarantees of origin, simplifying compliance [24]. Furthermore, combining blockchain transparency with privacy-preserving methods such as zero-knowledge proofs can secure confidentiality while maintaining accountability [7].

By removing intermediaries and automating settlements, smart contracts significantly cut transaction costs. They also support dynamic pricing that reflects real-time supply and demand, helping distributed resources optimize their participation. Prosumers can automatically adjust production or consumption according to encoded bidding rules. MATLAB agent-based simulations can illustrate this, showing how households and storage units autonomously trade energy by minimizing costs or maximizing self-consumption [25].

Decentralized blockchain systems enhance grid resilience by allowing microgrids to operate autonomously during disruptions. Smart contracts balance local generation and demand while transparently recording renewable production, facilitating monitoring of carbon footprints [26]. When connected with IoT sensors, contracts can also enforce environmental standards automatically (for example, rewarding low-emission behavior or penalizing excessive use).

Smart contracts lower entry barriers for small producers, enabling them to join energy trading on equal terms with larger actors. This democratization of access fosters community participation and wider public acceptance of renewable energy [27]. For Ukraine, such inclusivity is particularly promising given its growth in small renewable installations and plans for energy communities. Smart-contract-based platforms could offer transparent and automated frameworks for local power exchange, encouraging investment in small-scale solar and biomass projects.

Regulatory and technical challenges in implementing smart contracts for energy markets. Despite their promise, smart contracts face intertwined legal, regulatory, and technical obstacles that complicate large-scale use in decentralized energy markets. The technology automates contractual relations, yet must comply with national laws, market rules, and grid standards. Addressing these constraints is vital for policymakers and developers alike.

The foremost challenge concerns legal validity. Smart contracts execute code autonomously, but their recognition as binding agreements remains ambiguous. In most jurisdictions, including the EU and Ukraine, contract law requires human-readable interpretation and enforceability. Code-based agreements may obscure intent and accountability, creating risks of liability in case of error or malfunction [28]. Current legislation, such as the EU Electricity Directive (2019/944) and Ukraine's Law On the Electricity Market, does not yet define decentralized, P2P blockchain operators. Projects therefore rely on regulatory sandboxes or temporary exemptions, limiting investment confidence and scalability [29]. Cross-border transactions add complexity: determining applicable jurisdiction and dispute resolution mechanisms across digital platforms remains unresolved. A promising solution involves hybrid contracts, where on-chain code automates execution while off-chain legal terms ensure compliance [30].

Smart contracts depend on continuous data from smart meters and IoT devices. They are the sources often containing personal consumption information governed by the GDPR. Because blockchain data are immutable, this conflicts with the "right to be forgotten" [31]. Mitigation strategies include off-chain data storage, pseudonymization, or zero-knowledge proofs, though these increase system complexity and can reduce transparency. Cybersecurity vulnerabilities also persist: coding flaws or oracle attacks can trigger erroneous transactions. In energy systems, such risks may disrupt payment flows or grid operations. Hence, code auditing, formal verification, and multi-signature control are crucial safeguards [19].

Integrating blockchain with traditional energy management systems is technically demanding. Legacy protocols (e. g., IEC 61850, DNP3) rely on centralized databases, while decentralized ledgers require standardized data formats and interfaces [23]. Smart contracts must also respect operational constraints of grid stability, reserve balancing, and frequency control. These constraints can be modeled in MATLAB to simulate grid-aware contracts ensuring that autonomous trades do not disturb system equilibrium.

Current blockchain protocols struggle to process the high transaction volumes typical of energy markets. Layer-2 solutions and permissioned systems (e. g., Hyperledger Fabric, Energy Web Chain) partially improve throughput but sacrifice some decentralization [22, 32]. Environmental sustainability remains another concern: Proof-of-Work consensus consumes substantial energy. Transitioning to Proof-of-Stake and similar algorithms mitigates these effects but does not eliminate blockchain's total energy footprint [33].

Ukraine's regulatory and infrastructural conditions still constrain blockchain-based market adoption. Although the Diia platform and Energy Strategy to 2035 support digital transformation, the national electricity market remains centralized, and NEURC has not yet formalized blockchain trading or energy communities. Nevertheless, Ukraine's growing digital capacity and pilot projects with USAID and UNDP demonstrate potential. Regulatory reforms introducing sandbox environments, similar to EU models, could allow municipal or community-level trials of smart-contract-based energy markets.

Case studies and pilot projects in decentralized energy markets. Pilot projects worldwide already demonstrate how blockchain and smart contracts can decentralize energy trading. Although they differ in design and regulation, all aim to enhance trust, transparency, and efficiency without central intermediaries. This section reviews key examples from Australia, the United States, Europe, and emerging developments in Ukraine.

Australia's advanced solar adoption and supportive innovation policy made it a testing ground for blockchain-based P2P trading. The Power Ledger platform, founded in Perth, Australia, enables prosumers and consumers within microgrids to trade electricity directly via smart contracts [34]. These contracts automatically record generation and consumption, settling payments in real time according to predefined formulas. Trials in Fremantle, Australia, and

Bangkok, Thailand, confirmed the model's scalability, later extended to renewable certificate trading. This can be simulated by a simplified price-adjustment rule

$$p_{t+1} = p_t + \alpha \cdot (D_t - S_t), \quad (1)$$

where price p_t at time t changes with supply-demand imbalance, and trades execute automatically when $p_t \geq p_{\min}$ by demand D_t, supply S_t, and a sensitivity coefficient α. Such modeling helps illustrate how blockchain logic stabilizes supply-demand balance through algorithmic local market clearing (equilibrium).

The Brooklyn Microgrid (BMG) by LO3 Energy showcases localized energy exchange using Ethereum-based smart contracts [19]. Smart meters act as oracles, verifying solar generation and triggering automated energy-credit transfers between neighbors. Although US regulations restrict direct P2P trading, BMG demonstrated both technical feasibility and strong community engagement under an experimental framework.

Across the EU, several initiatives link blockchain to market transparency and renewable certification. The Enerchain project tested blockchain-based bilateral trading among large utilities, removing central clearinghouses [35]. WePower in Lithuania and Spain tokenized renewable output, enabling investors to pre-purchase and trade energy digitally. Sunchain in France used blockchain smart metering to automate settlements within eco-districts [36]. Together, these projects advance blockchain's integration into EU Guarantees of Origin systems, reinforcing traceability and compliance with sustainability directives.

Ukraine's energy system, now digitalizing and liberalizing, faces challenges of inefficiency and limited consumer trust. Though still nascent, several initiatives and institutional signals indicate readiness for decentralized models. The Energy Strategy of Ukraine to 2035 and the Diia e-governance ecosystem promote smart grids and digital integration. Joint efforts by the Ministry of Energy, UNDP, and USAID explore blockchain for renewable certificate tracking and transparent auctions. Universities and research centers (such as Kyiv Polytechnic Institute and the Energy Research Centre of NASU) are conducting feasibility studies on distributed ledgers for balancing and origin tracking [37]. Local cooperatives in western regions are also considering token-based settlements, while the Ministry of Digital Transformation promotes blockchain within the WINWIN strategy, regulatory sandboxing, and the planned e-hryvnia project [38]. A near-term pilot could involve a university or industrial microgrid, integrating smart meters, IoT gateways, and a permissioned blockchain (e. g., Hyperledger Fabric) with MATLAB simulations for pricing and settlement testing under NEURC supervision. Such frameworks would allow Ukraine to explore decentralized trading safely while aligning with Europe's emerging green digital infrastructure.

Comparative reflections on global and Ukrainian insights are presented in Table 1. The comparison reveals that technical feasibility is no longer the key barrier – regulatory adaptability and institutional support are. While developed economies proceed with regulatory sandboxes and industry consortia, Ukraine's progress will depend on coupling innovation with legal modernization and capacity building. The introduction of smart contract-based micro-trading systems in controlled environments (universities, business parks, industrial zones) could yield significant insights into cost savings and renewable integration, paving the way for national-scale deployment.

Table 1

Comparison of global and Ukrainian insights

Region	Project Type	Blockchain Role	Regulatory Readiness	Key Lessons
Australia	P2P solar trading (Power Ledger)	Settlement automation	High (sandbox available)	Consumer empowerment, flexible tariffs
USA	Microgrid & transactive markets (Brooklyn)	Local trading, smart metering	Moderate	Community-driven models feasible
Europe (Germany, Nordics)	Renewable certificate and wholesale integration	Transparency, certification	Advanced (EU-level frameworks)	Need for interoperability
Ukraine (proposed)	Pilot microgrid, tokenized settlement	Transparency, simulation testing	Emerging (no sandbox yet)	Start from institutional testbeds

A simplified prototype for Ukraine could simulate a community-based token exchange system, where each kilowatt-hour generated by a prosumer is represented as a digital token E_i. Smart contracts would automatically allocate tokens among participants according to a local optimization rule, for instance:

$$\min_{\left\{\{x_{ij}\}_{j=1}^{N}\right\}_{i=1}^{M}} \sum_{i=1}^{M}\sum_{j=1}^{N}(c_i - p_j)x_{ij} \text{ by } \sum_{j=1}^{N} x_{ij} \leq G_i, \ i = \overline{1, M}, \text{ and } \sum_{i=1}^{M} x_{ij} \geq D_j, \ j = \overline{1, N}, \quad (2)$$

where x_{ij} is the energy flow from generator i with generation G_i to consumer j with demand D_j, c_i is the generation cost of generator i, and p_j is the local price at consumer j set by a community vote or automated algorithm. This model provides a computational framework for future Ukrainian blockchain pilots in decentralized trading with M generators (prosumers) and N consumers.

Meahwwhile, comparing international and Ukrainian cases (Table 1) reveals shared goals and local specifics. For Ukraine, the main challenges lie in ensuring institutional stability, advancing market liberalization, and updating regulations to support decentralized models. Yet, Ukraine's strong digital governance and still-developing electricity market offer a chance to design flexible frameworks from the ground up. With targeted pilot testing and adaptive legislation, Ukraine could position itself as a regional pioneer in community-level decentralized energy trading.

MATLAB illustrations of automated market mechanisms. Although smart contracts run on decentralized ledgers, their economic logic can be modeled and tested in MATLAB. The platform enables simulation of P2P trading, dynamic pricing, energy allocation, and automated settlement, which are the main components of decentralized markets. This section provides conceptual MATLAB examples showing how trading rules can be executed automatically, replicating the logic of on-chain transactions without focusing on blockchain syntax.

An M-code example of automatic energy-matching process, showing how trades and payments would be triggered, is shown in Fig. 1. Another simple example (Fig. 2) involves a smart contract that verifies whether a prosumer has generated sufficient renewable energy to fulfill a trade and then triggers payment automatically. This script emulates a 24-hour operation where a MATLAB "smart contract" executes payments automatically when generation exceeds demand. In a blockchain system, such logic would be implemented in Solidity or another smart contract language, but the control flow is conceptually identical.

```
Prosumers_num = 36;  prosumers = ["1"];
for pr = 2:Prosumers_num
    prosumers(pr) = num2str(pr);
end
energy_produced = round(10*rand(1, Prosumers_num),2);  % kWh
energy_needed = round(7.5*rand(1, Prosumers_num),2);   % kWh
net_energy = energy_produced - energy_needed;          % Determine transferable energy
price_per_kWh = 0.18;  % USD/kWh;                   ---> Smart-contract-like logic: auto-match sellers/buyers
buyers = find(net_energy < 0);   sellers = find(net_energy > 0);   deal_num = 0;   deal = [];
for i = sellers
    for j = buyers
        traded = min(net_energy(i), abs(net_energy(j)));
        if traded > 0
            payment = traded * price_per_kWh;
            fprintf("Prosumer %s sells %.2f kWh to %s for $%.6f\n", prosumers(i), traded, prosumers(j), payment);
            deal_num = deal_num + 1;
            deal(deal_num,:) = [prosumers(i), traded, prosumers(j), payment];
            net_energy(i) = net_energy(i) - traded;   net_energy(j) = net_energy(j) + traded;
        end
    end
end
```

Fig. 1. Simple energy trading settlement simulation

```
G = 5 + randn(1,24);     % hourly generation profile
D = 4 + randn(1,24);     % hourly demand profile
G(G<0) = 0; D(D<0) = 0; % physical non-negativity
% Contract parameters
price_per_kWh = 0.12;
threshold = 0.5;  % minimum energy surplus for trade (kWh)
% Smart-contract-like logic
payment = zeros(1,24);
for t = 1:24
    if G(t) - D(t) >= threshold
        energy_sold = G(t) - D(t);
        payment(t) = energy_sold * price_per_kWh;
    end
end
```

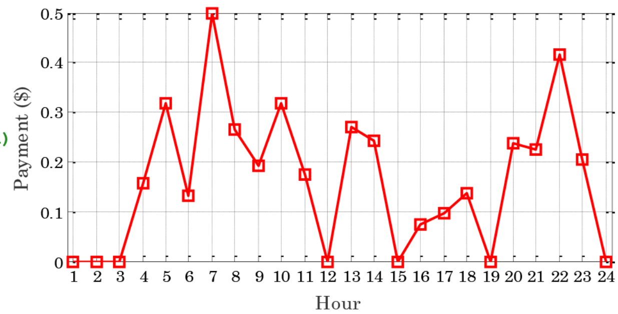

Fig. 2. Automated energy settlement between prosumer and consumer

Another key mechanism in decentralized markets is real-time price adjustment according to the difference between supply and demand. The example in Fig. 3 uses a simple proportional controller to adjust energy prices dynamically. Here, the smart contract autonomously adjusts price to balance the market by (1). A positive imbalance (where demand exceeds supply) increases the price, while an oversupply reduces it. This mechanism corresponds to algorithmic clearing implemented in projects such as Power Ledger or Sunchain.

Smart contracts in decentralized energy communities can manage internal allocation of energy tokens. MATLAB's optimization tools can simulate this through constrained minimization problem (2) whose example is shown in Fig. 4. The optimization simulates a smart contract allocating energy among participants to minimize the total cost while fulfilling local demands. The result matrix $[x_{ij}]_{M \times N}$ corresponds to automated token flows between producers and consumers.

A decentralized market may also employ bidding auctions, where each participant submits a bid automatically. Smart contracts then select winning bids transparently. The M-code algorithm in Fig. 5 replicates a smart-contract auction that transparently allocates energy based on bids. The process is deterministic and verifiable, having key features of on-chain energy auctions.

```
time = 1:48;
supply = 50 + 10*sin(0.2*time);
demand = 55 + 15*cos(0.2*time);

% price adjustment rate
alpha = 0.0002;

p = zeros(1,48);
% initial price ($/kWh)
p(1) = 0.10;

for t = 1:length(time)-1
    p(t+1) = p(t) + alpha*(demand(t) - supply(t));
end
```

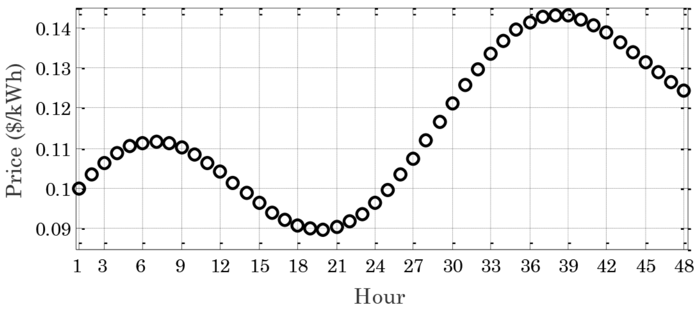

Fig. 3. Dynamic pricing based on supply-demand imbalance

```
nGen = 13;   nCons = 16;
G = randi(15, 1, nGen)+4;           % generation capacities (kWh)
D = randi(15, 1, nCons)+4;          % demands (kWh)
cost = rand(1, nGen)/10+0.05;       % generation costs ($/kWh)
price = rand(1, nCons)/10+0.05;     % local willingness to pay ($/kWh)
options = optimoptions(@fmincon, 'MaxIter', 4325, 'TolFun', 1e-10, 'MaxFunEvals', 5000, 'Display', 'none');
A = zeros(nGen+nCons, nGen*nCons);
for nn = 1:nGen
    for mm = 1:nCons
        A(nn, nGen*(mm-1)+1:nGen*mm) = [zeros(1,nn-1), 1, zeros(1,nGen-nn)];
        A(nGen+mm, nGen*(mm-1)+1:nGen*mm) = -ones(1,nGen);
    end
end
B = [G -D];
lb=zeros(nGen,nCons);   ub = 1000*ones(nGen,nCons);
f = @(X) ( sum(sum((cost'*ones(1,nCons) - ones(nGen,1)*price).*X)) );
[X_star, fval, exitflag, output, lambda, grad, hessian] = fmincon(f, ones(nGen,nCons), ...
A, B, [], [], lb, ub,  [], options);
disp('Optimal Energy Flow Matrix (kWh):'); disp(X_star);
```

Fig. 4. Community-level token exchange optimization

```
bidders = 10;
offers = 0.08 + 0.04*rand(1,bidders); % offers in $/kWh
energy_available = 100;               % total energy (kWh)
bid_qty = 10 + 20*rand(1,bidders);

% Sort bids (ascending price)
[sorted_offers, idx] = sort(offers);
sorted_qty = bid_qty(idx);

allocated = zeros(1,bidders);
remaining = energy_available;
for i = 1:bidders
    if remaining >= sorted_qty(i)
        allocated(i) = sorted_qty(i);
        remaining = remaining - sorted_qty(i);
    else
        allocated(i) = remaining;   break;
    end
end
```

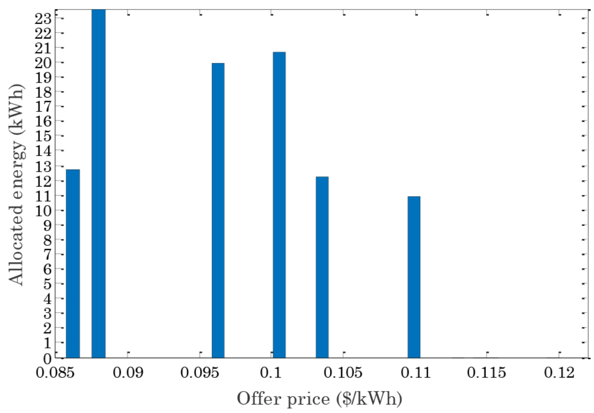

Fig. 5. Blockchain-inspired auction mechanism

In fact, MATLAB does not replace blockchain functionality but serves as a pre-blockchain testbed simulation environment where algorithms for pricing, settlement, and allocation can be verified before implementation in actual smart contract code. Researchers and engineers can use MATLAB to:

1. Validate economic consistency of automated market mechanisms.
2. Optimize parameter tuning (e. g., price sensitivity α).
3. Simulate grid balance and peer interactions before deployment.

Such pre-testing is particularly valuable for contexts like Ukraine, where pilot blockchain projects can first be evaluated in simulation mode to ensure regulatory compliance and technical feasibility before live rollout.

Conclusions. Smart contracts are becoming a key tool in building decentralized energy markets. They automate transactions, ensure transparency, and cut costs, reshaping how electricity is traded and managed. However, their adoption depends on solving technical and regulatory challenges, addressing which must take into account the following findings:

1. Automation and transparency are major strengths, enabling instant P2P trading and verified renewable tracking.

2. Feasibility is proven by pilot projects in Australia, the USA, and Europe, which show local energy autonomy in action.

3. Scalability and data security remain weak points; better consensus, APIs, and oracles are needed.
4. Regulatory gaps limit progress, though sandbox trials offer a workable bridge.
5. Ukraine can benefit from its digital governance systems to run pilot projects in microgrids and universities.

The strategic recommendations to these findings are:

1. Regulate – legally recognize blockchain contracts and protect consumers.
2. Standardize – align with international norms for interoperability.
3. Experiment – use sandboxes for academic and cooperative tokenized trading.
4. Train – build skills among engineers, lawyers, and regulators.
5. Integrate AI and IoT – link smart contracts with predictive and automated energy tools.

Future research should combine blockchain, AI, and edge computing for real-time energy optimization, where key priorities are:

1. Modeling game-theoretic market behavior under smart contract rules.
2. Creating formal verification tools for contract safety, possibly in MATLAB.
3. Measuring environmental impact to ensure that blockchain supports decarbonization.

In summary, the evolution of decentralized energy markets through smart contracts is not merely a technological innovation but a systemic transformation of energy governance. If guided by transparent regulation, robust engineering, and social responsibility, smart contracts are going to become the backbone of a resilient, democratic, and sustainable energy economy – for Ukraine and globally.

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