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Blockchain-Enabled Pricing Mechanism in Energy Markets: Survey and Vision

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***Abstract*—The growth of distributed energy resources and local energy markets heightens the need for price formation that is transparent, privacy preserving, and compatible with network constraints. Blockchain provides a trust-minimized substrate for auditable clearing and settlement through consensus, tamper-evident ledgers, and smart contracts. This survey organizes blockchain-enabled pricing into three families, namely auction-based, game-theoretic, and optimization-based, and links them to enabling techniques such as metering oracles, secure multiparty computation, zero-knowledge proofs, and verifiable optimality certificates. Applications span wholesale electricity, carbon and green certificates, distributed energy trading, ancillary services, and electric vehicles. Evidence indicates gains in auditability, privacy, network awareness, and automated settlement, alongside challenges in scalability, data protection, grid integration, and regulation. The survey distills design patterns and research directions toward verifiable, interoperable, and governable pricing modules that complement system-operator markets.**

***Index Terms*—Energy Markets, Blockchain, Pricing Mechanism, Distributed Energy Resources, Mechanism Design**

I. INTRODUCTION

The global energy market anchors economic growth and climate security. Tight cross-border linkages transmit shocks across fuels, equipment, and finance, thereby magnifying volatility and policy risk [1]. Electrification and decarbonization targets raise electricity's share of final demand; flexibility and resource adequacy therefore become system imperatives [2]. In this setting, distributed energy markets with price-responsive DERs (batteries, EVs, flexible loads) offer strategic benefits, including diversified supply, shorter balancing loops, and granular prices that reveal congestion and scarcity while mobilizing retail capital for clean deployment. These gains depend on credible price formation, interoperable data and device standards, cybersecure automation, and governance that links distribution-level transactions to wholesale operations.

Realizing these benefits requires overcoming persistent pricing frictions driven by spatial granularity, uncertainty, and network constraints. Heterogeneous, location-dependent DERs and peer-to-peer transactions induce stochastic, correlated injections and information asymmetries, making price discovery sensitive to noise and strategic behavior. At the distribution level, nonconvex and discrete operating limits impede marginal-cost pricing and necessitate uplift or side payments. Limited observability and privacy or security requirements complicate distribution locational marginal prices, weakening auditability and stakeholder acceptance. In addition, thin local competition and layered policies distort incentives across energy, capacity, flexibility, and carbon products, misaligning short-run dispatch signals with long-run investment decisions.

Blockchain is a distributed, tamper-evident ledger with programmable smart contracts that strengthens execution integrity, auditability, and privacy-preserving verification in low-trust markets [3]. It has already been applied to trading and pricing in IoT [4], [5], generative and creative ecosystems [6], and supply chains [7], [8], illustrating credible settlement and composable automation. Motivated by these properties, we consider blockchain for energy price formation. Smart contracts encode bidding, matching, and payments and settle atomically under Byzantine-fault-tolerant consensus, which improves auditability and limits off-ledger discretion. Cryptographic tools, including commit–reveal and zero-knowledge proofs, protect private bids while enabling public checks of rule compliance. Authenticated metering oracles and device identities ground prices in trustworthy telemetry. Hybrid designs keep optimal power flow (OPF) computation off-chain and publish succinct proofs on-chain. Tokenized incentives and programmable escrows coordinate flexibility, capacity, and carbon products and strengthen investment signals.

Blockchain has already been applied across multiple layers of the energy market, including peer-to-peer trading, renewable-certificate tracking, electric-vehicle charging coordination, and decentralized microgrid management. These efforts emphasize transparency, tamper resistance, and automated settlement, and they show how distributed ledgers can build trust in data sharing and asset provenance. Nevertheless, most implementations focus on system architecture, platform design, and high-level business models rather than the pricing rules that determine market outcomes [9]–[11]. Studies of local energy markets identify gaps in handling network constraints, scalability, and privacy, yet they do not examine in detail how bidding and pricing are executed on-chain.

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This survey adopts a mechanism-centric perspective in which we classify blockchain-enabled pricing into auction-based, game-theoretic, and optimization-based families and distill their assumptions, clearing and payment pipelines, and verifiability features. We further abstract a blockchain layer that enables price formation along four pillars. Building on this foundation, we map mechanisms to five application domains, namely wholesale electricity, carbon and green certificates, distributed energy trading, ancillary services, and electric vehicles (EVs), and we summarize the pricing tasks and requirements in each domain. For each mechanism–blockchain pairing, we enumerate implementable methods and realization paths and highlight deployments and differentiated advantages across scenarios, as illustrated in Fig. 1.

II. RELATED WORK

A number of surveys and review articles have examined blockchain applications in energy systems, but none to date have centered specifically on the pricing mechanism design aspect. General energy-blockchain surveys: Andoni et al. [9] provided one of the first comprehensive reviews of blockchain in the energy sector, cataloguing 140 projects and initiatives. They classified use cases such as P2P trading, renewable certificate tracking, electric vehicle charging, and IoT-based grid management, and discussed how blockchain's transparency and security can enable these novel marketplaces. However, their focus was broad: the study covered system architectures and business use cases, with less emphasis on the detailed market-clearing or price-formation rules within those projects. Di Silvestre et al. [10] presented another extensive review, mapping blockchain components to power system operations. They highlighted features like audit trails and smart-contract automation as key enablers for transactive energy and flexibility services, but again the discussion remained at the architectural level (platform modules and functionalities) rather than evaluating specific pricing rules. More recently, Choobineh et al. [11] offered a state-of-the-art overview of blockchain in energy systems, noting that properties such as immutability and decentralized consensus build trust in energy data sharing and asset provenance, while smart contracts can automate trading, billing, and settlement processes. Their survey, like the others, primarily enumerates applications (e.g., energy trading platforms, microgrid pilots) and technical challenges (scalability, privacy), without a dedicated analysis of market price formation strategies under blockchain.

In parallel, several literature reviews examine the design of distributed or local electricity markets more broadly. Capper et al. [12] conduct a systematic review of peer-to-peer and community self-consumption market models and identify six archetypes of LEM design. Notably, they pinpoint evidence gaps that impede real-world LEM adoption, including the absence of mechanisms to incorporate physical network constraints, unclear scalability, and unresolved privacy and security issues in existing designs. Although these gaps strongly motivate blockchain-based approaches that could improve transparency and privacy, the review by Capper et al. does not analyze how blockchain could address them at the pricing-mechanism level. Similarly, Faia et al. [2] review LEM developments and outline benefits, barriers, and regulatory considerations for local markets. Their discussion treats blockchain as one of several enabling technologies for LEMs rather than examining in detail how bidding and pricing would be executed on-chain. In summary, existing surveys underscore both the potential of blockchain to support new energy-market models and the importance of trust, transparency, and security, yet none systematically analyzes the price-formation stage itself. This survey distinguishes itself by organizing and reviewing the literature through the lens of pricing mechanisms and by explaining how blockchain techniques are applied in each category to address the challenges noted above.

III. THEORETICAL FOUNDATION

A. *Pricing Mechanism*

Price formation in energy markets is commonly classified into three canonical families: auction-based, game-theoretic, and optimization-based. These families are largely non-overlapping, encompass the dominant designs in electricity and related sub-markets, and align cleanly with network physics and uncertainty.

Auction-Based Pricing. In auction-based markets, participants submit bids and asks; a market rule maps these messages to traded quantities, and a payment rule determines transfers. Foundational results in auction theory and mechanism design show that welfare-maximizing clears can approximate competitive outcomes in large markets, whereas with finitely many participants the standard trade-offs among allocative efficiency, incentive compatibility, individual rationality, and budget balance arise. Representative formats include sealed-bid uniform-price auctions, continuous double auctions, and network-aware or other constraint-aware designs.

Contemporary electricity markets set day-ahead (DA) and real-time (RT) prices via sealed-bid, batch-cleared auctions. Similar clears produce prices for operating reserves and capacity, while distribution-level and peer-to-peer (P2P) settings often employ continuous double auctions to form transaction prices. Across these applications, the auction maps bids to dispatch and payments, embedding congestion and scarcity signals into settlements.

Game-Theoretic Mechanisms. Prices are determined as equilibrium outcomes of strategic interaction among agents. Canonical formulations include Stackelberg pricing, Nash bargaining, mean-field games, population games, and learning-in-games dynamics. Existence, and under additional regularity also uniqueness, of equilibrium prices typically follow from fixed-point arguments with convex best-response mappings, and comparative statics characterize how network constraints, risk preferences, and information asymmetries shift equilibria. Unlike auction-based designs, these mechanisms do not precommit a payment rule; prices emerge as equilibrium objects that jointly support agents' optimality and system feasibility.

Game-theoretic mechanisms are applied at the pricing stage to predict how strategic bidding and contracting translate into

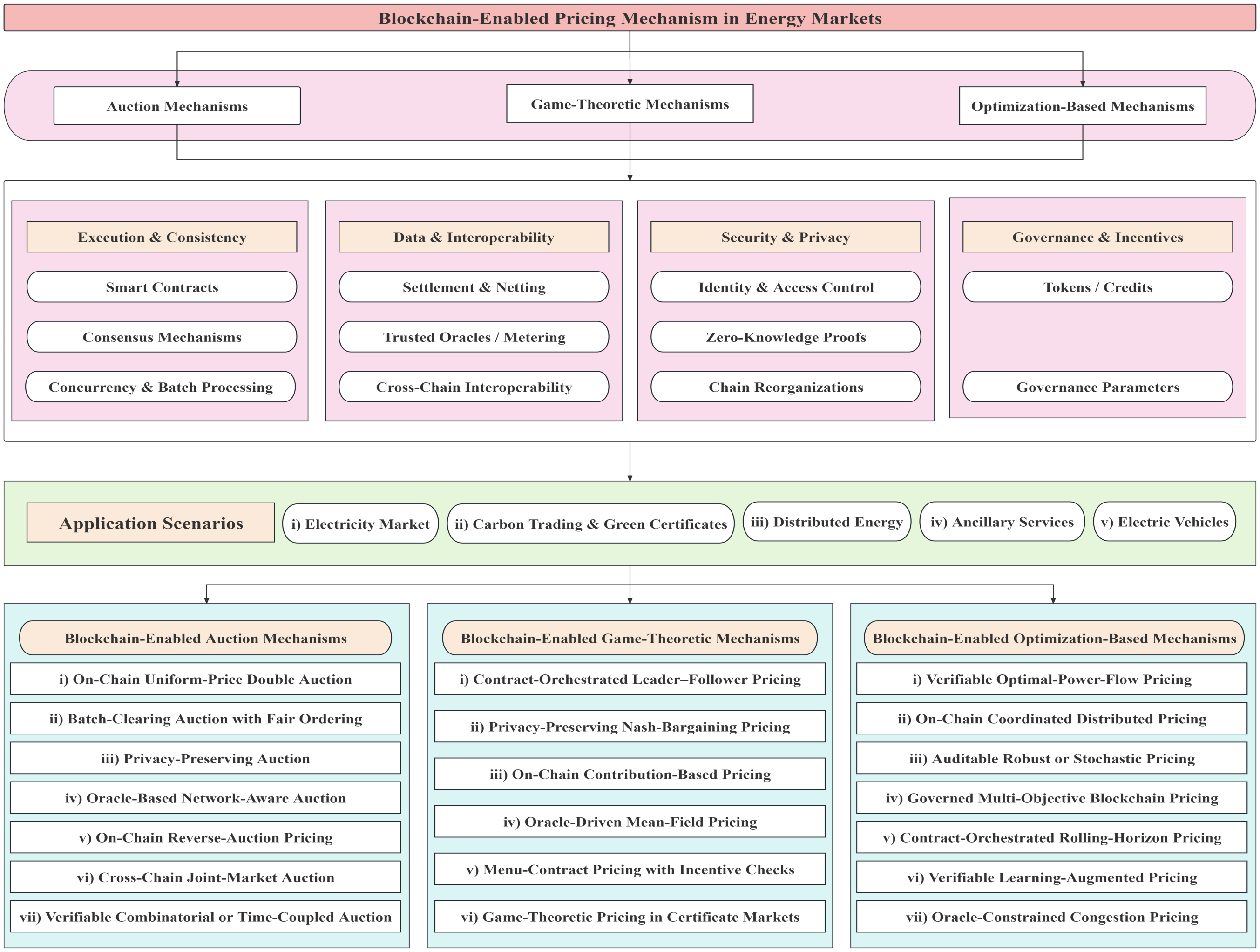

Fig. 1. Framework of Blockchain-Enabled Pricing Mechanism in Energy Markets.

equilibrium prices under limited competition and decentralized decision making. Supply-function and Cournot formulations yield equilibrium price–quantity pairs and markups; leader–follower models underpin posted tariffs by anticipating consumer or aggregator responses; bargaining models produce bilateral contract prices for energy, reserves, and flexibility services. In P2P settings, large-population and evolutionary models generate endogenous price signals that coordinate many small actors while respecting network or capacity limits.

Optimization-Based Mechanisms. Prices are obtained as the dual variables of a system optimization, typically a social-welfare maximization or a cost-minimization subject to physical and operational constraints such as security-constrained economic dispatch and OPF. The Lagrange multipliers on nodal power-balance and network limits define locational marginal prices and scarcity premia, and these shadow prices decentralize the system optimum by conveying marginal signals consistent with feasibility. Uncertainty can be incorporated through stochastic programming, robust optimization, or chance-constrained formulations, and multi-objective programs yield Pareto-efficient price vectors when cost, reliability, and emissions are considered jointly. For large-scale or multi-area clears, distributed primal–dual methods and the alternating direction method of multipliers (ADMM) enable coordinated clearing across operators or zones while preserving the interpretation of prices as dual variables.

Day-ahead and real-time prices are computed by solving a network-constrained welfare or cost optimization and the associated dual variables yield locational marginal prices together with congestion components. The same optimization-based clearing co-optimizes operating reserves and other ancillary services, so reserve prices equal the shadow values of the corresponding reliability constraints. At the distribution level, operator tariffs and peer-to-grid settlements increasingly apply OPF-based pricing to distributed energy resources, thereby preserving the interpretation of prices as dual variables.

B. Blockchain-Related Technologies

Execution & Consistency. Smart contracts are deterministic programs executed on-chain: given inputs and the current state, they apply a specified state-transition function and emit verifiable outputs. Consensus protocols provide ordering and finality: Proof-of-Authority (PoA) employs a fixed validator set to produce blocks at short, predictable intervals, while Istanbul Byzantine Fault Tolerant finalizes blocks via quorum voting among validators, offering immediate finality under partial synchrony. To minimize persistent storage, stateless-contract patterns keep ephemeral computation off-chain and commit results via cryptographic hashes; event logs supply append-only, indexable receipts for audit and off-chain integration without mutating contract state.

Security & Privacy. The commit-reveal pattern hides inputs by first posting a cryptographic commitment and later revealing the preimage for verification. Threshold encryption allows a designated committee to jointly decrypt ciphertexts after a deadline or trigger, preventing early access by any single party. Zero-knowledge proofs (ZKPs) attest the correctness of computations without disclosing private inputs. Adversarial transaction ordering can create maximal extractable value via front-running; verifiable random function-based or otherwise randomized proposer selection reduces ordering predictability and mitigates such attacks. Identity and access control rely on public-key infrastructure or decentralized identifiers with verifiable credentials to authenticate roles and authorize actions.

Data & Interoperability. Oracles provide authenticated ingestion of metering and supervisory control and data acquisition measurements to the chain, signing payloads and timestamps. Merkle-tree commitments (Merkle roots) record a succinct, tamper-evident commitment to large datasets; later, inclusion proofs verify individual records without publishing the entire dataset. Cross-chain bridges and relays transmit state either by verifying light-client proofs (on-chain validation of headers and membership proofs) or by multisignature notarization performed by a designated committee.

Governance & Incentives. Protocol governance employs multisignature controls and timelocks to gate parameter changes and contract upgrades, while on-chain voting updates validator sets and policy parameters under quorum and threshold rules. Settlement rails use permissioned stablecoins or internal credit tokens and support atomic delivery-versus-payment, ensuring simultaneous transfer of energy rights and funds. To reduce cash and messaging overhead, periodic netting aggregates obligations prior to settlement, and state channels together with rollups provide high-frequency, low-latency settlement with batched finalization on the base layer.

C. Application Scenarios

Blockchain-enabled pricing mechanisms apply where bids must be collected, cleared, and published with auditability and tamper evidence. Representative domains include wholesale electricity markets; carbon markets and renewable energy certificates (RECs); distributed or P2P energy trading; ancillary services procurement; and electric-vehicle (EV) charging.

i) Electricity Market. Pricing covers interval energy and, when networks bind, location-dependent components for congestion and losses, with settlements addressing imbalances.

ii) Carbon Trading & Green Certificates. Prices apply to emission allowances and renewable certificates across issuance and secondary trades, with terms for banking, borrowing, and retirement.

iii) Distributed Energy. Pricing targets peer-to-peer exchanges and local flexibility from storage and controllable loads, including availability, activation, and curtailment.

iv) Ancillary Services. Prices reflect capacity and delivered performance for regulation, reserves, voltage/VAR support, and black start, with penalties and bonuses.

v) Electric Vehicles. Pricing includes charging tariffs, time-slot reservations, idle and congestion fees at stations, and compensation for vehicle-to-grid discharge or flexibility.

IV. BLOCKCHAIN-ENABLED PRICING MECHANISM

A. Blockchain-Enabled Auction Mechanisms

i) On-Chain Uniform-Price Double Auction. This design employs smart contracts to collect bids and asks and then to clear a double-sided market at a single uniform price, while verification and settlement are anchored on the blockchain. Foti and Vavalis [13] present a decentralized, real-time, uniform-price double auction whose operating rules are specified in an Ethereum smart contract; they prototype and evaluate three Ethereum-based implementation approaches, show that selected computation modules can be offloaded to edge devices to reduce on-chain overhead. Vieira and Zhang [14] build two Ethereum-backed peer-to-peer trading frameworks, which respectively perform matching with on-chain execution and record offers and settlements on-chain while clearing in batches off-chain, thereby demonstrating privacy, throughput, and gas-cost trade-offs between continuous and uniform-price double-auction realizations.

ii) Batch-Clearing Auction with Fair Ordering. In this design, buy and sell orders are accumulated within a fixed interval and cleared simultaneously, and allocation rules such as pro-rata sharing among tied orders are used to eliminate first-in-first-out (FIFO) advantages. Graf, Kuppelwieser, and Wozabal [15] propose frequent batch auctions for intraday electricity markets and demonstrate that they reduce liquidity costs and generate more stable price signals. Complementary evidence by Kuppelwieser and Wozabal [16] shows that Italy's auction-based intraday market exhibits lower round-trip liquidity costs than Germany's continuous market, which highlights efficiency gains from batch-cleared designs.

iii) Privacy-Preserving Auction. These designs conceal bids and participant identities during submission and clearing by using techniques such as commit–reveal, secure multiparty computation, homomorphic aggregation, and zero-knowledge proofs, while still enabling verifiable determination of winners and clearing prices. In power-market settings, Sarenche et al. [17] present a privacy-preserving double auction for smart grids that performs bid matching and payment computation without disclosing individual offers. Zhang et al. [18] develop a linkable ring-signature approach for P2P uniform-price double auctions in microgrid day-ahead markets, ensuring payment privacy while preserving the auditability of transactions.

iv) Oracle-Based Network-Aware Auction. These designs ingest authenticated grid-feasibility data, such as smart-meter measurements, network limits, and outputs from OPF and distribution locational marginal pricing (DLMP), via on-chain oracles, so that clearing and settlement remain auditable while respecting network constraints. Condon et al. [19] implement a peer-to-peer microgrid auction on a permissioned Ethereum network with a Chainlink oracle that retrieves smart-meter data for settlement, demonstrating end-to-end oracle integration in a working testbed. Amanbek et al. [20] develop a DLMP-driven transactive-energy framework in which an OPF-based auction schedules trades under distribution constraints; although realized off-chain, its DLMP and allocation outputs are oracle-compatible for on-chain/off-chain clearing patterns.

v) On-Chain Reverse-Auction Pricing. In a reverse auction, sellers submit asks for energy or flexibility, and the clearing is performed in batches by a smart contract that implements either uniform-price or pay-as-bid payments on-chain; when required, oracle feeds and privacy mechanisms are incorporated. Abou El Houda et al. [21] implement a blockchain-based reverse-auction mechanism for vehicle-to-vehicle energy trading, where smart contracts conduct winner determination and settlement. Husain et al. [22] introduce BlockCharge, a smart-contract–deployable framework employing a repeated single-minded reverse auction to allocate mobile charging stations to electric vehicles, thereby encouraging truthful bidding and ensuring transparent on-chain execution.

vi) Cross-Chain Joint-Market Auction. These designs aggregate orders from multiple ledgers (e.g., electricity, carbon, and tradable green certificates, TGCs) and execute a harmonized market clear that typically respects network constraints, while atomic and auditable settlement is performed on each chain via cross-chain protocols. Wang et al. [23] propose a day-ahead collaborative electricity–carbon–TGC market that redesigns each market's chain architecture and uses cross-chain messaging to coordinate sequential clears so that prices and allocations internalize cross-market influences; case studies on a modified IEEE-30 system report lower emissions and improved revenues for low-carbon resources. Zheng et al. [24] develop a relay-chain–centric framework for virtual power plants that couples electricity, carbon, and green-certificate trading with on-chain verifiability, synchronizing market states across chains to support joint trading and settlement.

vii) Verifiable Combinatorial or Time-Coupled Auction. Bidders submit package bids across nodes or products, as well as intertemporal blocks, and the market clears jointly by solving a welfare-maximizing mixed-integer linear program (MILP) under network limits. The explicit order definitions and clearing conditions make outcomes transparent and reproducible, and primal–dual optimality checks can certify the results. In the European day-ahead setting, Madani and Van Vyve [25] develop computationally efficient MIP/MILP formulations that clear block and complex orders with documented and reproducible outcomes. Dourbois and Biskas [26] present a market-coupling algorithm that incorporates transmission constraints together with clearing conditions for multiple block and complex order types, thereby exemplifying intertemporal and network-aware joint clearing.

B. Blockchain-Enabled Game-Theoretic Mechanisms

i) Contract-Orchestrated Leader–Follower Pricing. A Stackelberg game can be orchestrated by smart contracts in which the leader posts tariffs and admissibility constraints on-chain to time-stamp commitment, followers submit verifiable responses, and the contract checks feasibility and executes settlement; oracle feeds and privacy extensions are incorporated when required. In one realization, Moti et al. [27] design a blockchain-based electricity marketplace and a two-stage Stackelberg retail-pricing model in which leader prices are learned via reinforcement learning, while the blockchain provides commitment and transaction recording. Xiao et al. [28] develop a blockchain-assisted framework where the electricity market serves as the Stackelberg leader and electric-vehicle charging operators act as followers; a reinforcement-learning solver computes equilibrium prices and demands, and the chain secures trading records and data integrity.

ii) Privacy-Preserving Nash-Bargaining Pricing. Prices are obtained by maximizing a Nash product under market and network constraints, while private utilities and reservation values are protected through cryptographic commitments, secure multiparty computation, homomorphic encryption, and zero-knowledge proofs, and smart contracts provide commitment and auditable disclosure. In networked microgrids, Mohseni et al. [29] design a distributed, privacy-preserving bargaining mechanism that computes fair trading prices without revealing agent data. For cross-carrier coordination, Zhang et al. [30] propose a two-stage robust Nash-bargaining scheme for electricity–hydrogen trading that exchanges only boundary information and derives bargaining prices via a privacy-preserved alternating direction method of multipliers procedure.

iii) On-Chain Contribution-Based Pricing. Cooperative fair-sharing rules are encoded in smart contracts: metered deliveries and credibility indices drive participant-specific settlements computed via Shapley-value or marginal-contribution allocations, or credit-weighted formulas, with transparent, auditable on-chain execution. In a community P2P setting, Wang et al. [31] develop a consortium-blockchain sharing scheme in which a two-level incentive mechanism and an individual credit index shape prices and rewards for prosumers. Zhang et al. [32] design smart contracts with an entropy-weighted credit model that prioritizes trustworthy users and governs contribution-sensitive matching and settlement.

iv) Oracle-driven mean-field pricing. A smart contract encodes a tariff function, where authenticated oracles supply aggregate statistics, such as system demand, state-of-charge distributions, and congestion or DLMP proxies, which drive price updates. Agents best respond to posted prices, and the mechanism iterates toward a fixed point under network constraints, while settlement and disclosure remain auditable on-chain. Mean-field formulations capture the feedback between population behavior and prices in electricity systems [33].

v) Menu-Contract Pricing with Incentive Checks. A leader posts a screening menu of contracts (e.g., energy quota, response time, reliability tier), and agents self-select by type; smart contracts encode the menu and settlement, and oracle-fed metering triggers bonuses and penalties that enforce individual rationality (IR) and incentive compatibility (IC) with auditable execution. Demonstrations include a consortium-blockchain mechanism for the Internet of Electric Vehicles with optimized, on-chain–enforced menus [34], and a permissioned energy-blockchain scheme in which contracts govern electric-vehicle charging while delegated Byzantine-fault-tolerant consensus ensures reliable settlement [35].

vi) Game-Theoretic Pricing in Certificate Markets. Generators and obligated buyers strategically quote for RECs and related attributes, and prices are determined as equilibrium outcomes, for example Nash bargaining or learning in games, that are encoded in smart contracts; oracle-fed issuance and compliance data enable auditable on-chain settlement. A representative design is the GC-TS architecture, which integrates multi-agent Nash strategies with Q-learning and implements the trading and clearing logic in smart contracts, yielding equilibrium quotes and verified execution [36]. Complementary blockchain renewable energy certificate platforms, including DAG-based ledgers, provide privacy-preserving and scalable rails on which such equilibrium contract scripts can run [37].

C. Blockchain-Enabled Optimization-Based Mechanisms

i) Verifiable Optimal-Power-Flow Pricing. Settlements and locational marginal prices (LMPs) or distribution locational marginal prices (DLMPs) are computed from an alternating-current/direct-current optimal power flow (AC OPF/DC OPF), and a public certificate, such as primal–dual or Karush–Kuhn–Tucker (KKT) checks or a succinct cryptographic proof, allows auditing of feasibility and optimality without re-solving the OPF. Oustry et al. [38] develop certified and accurate semidefinite programming (SDP) bounds for AC OPF that serve as optimality and feasibility certificates, thereby supporting verifiable OPF-based settlements.

ii) On-Chain Coordinated Distributed Pricing. Market clearing is executed via distributed optimization orchestrated by smart contracts, for example consensus schemes based on ADMM. Agents solve local subproblems and post iterates on-chain, the contract updates dual variables, enforces residual-based stopping tests, and commits nodal prices (e.g., DLMPs) under oracle-fed network constraints with full auditability. In energy systems, Münsing et al. [39] implement a smart-contract–coordinated ADMM for decentralized OPF that recovers DLMPs and verifiable schedules, and Yang and Wang [40] design a blockchain contract that updates ADMM multipliers to coordinate distributed energy resources, demonstrating trustworthy distributed price coordination.

iii) Auditable Robust or Stochastic Pricing. Market settlements and nodal prices are computed from distributionally robust optimization or scenario-based stochastic programs, and public artifacts, such as primal–dual or KKT checks and cryptographic commitments, enable third-party or on-chain verification without re-solving the problem. Zavala et al. [41] formulate a stochastic market-clearing model with consistent pricing that guarantees bounded price distortions, revenue adequacy, and zero expected uplifts. Franke et al. [42] design an uncertainty-aware local market cleared via Consensus-ADMM with secure multiparty computation and ElGamal commitments, which supports verifiable settlement.

iv) Governed Multi-Objective Blockchain Pricing. Markets are cleared through an explicitly multi-objective formulation that may include cost, reliability, carbon, and equity, and an on-chain governance layer implemented via smart contracts specifies and revises the policy vector, which includes objective weights, targets, and guardrails; oracle-supplied measurements support transparent settlement and auditing. As a concrete realization, Saeed et al. [43] integrate energy and carbon-credit trading for multi-microgrid systems on-chain, provide tunable cost–emissions objectives via contract parameters, and realize auditable clearing with updatable policies.

v) Contract-Orchestrated Rolling-Horizon Pricing. Smart contracts orchestrate look-ahead, multi-interval clearing in which authenticated oracles stream forecasts and network states, a sliding-window optimization is solved at each step, the first interval is settled on-chain, and indicative prices for later intervals are rolled forward. Optional multi-interval settlement preserves incentives and price consistency. Feng et al. [44] design a rolling-horizon, multi-interval settlement for real-time spot pricing that tightens incentives and reduces deviations. Zade et al. [45] implement smart contracts that maintain a “rolling-horizon array” of metering and settlement prices for LEMs, enabling auditable, periodic on-chain clearing.

vi) Verifiable Learning-Augmented Pricing. Market clearing incorporates machine learning (ML) forecasts or policy surrogates and releases auditable evidence, either by feeding ML outputs to an OPF solver that emits primal–dual or KKT checks, or by proving on-chain ML inference via zero-knowledge machine learning (zkML), so that allocations and prices remain rule-compliant. Rahman et al. [46] develop a learning-augmented alternating-current OPF that accelerates solves while retaining OPF-based settlement and price recovery. Fan et al. [47] demonstrate zkML-backed peer-to-peer trading in which smart contracts verify ML inference, thereby making learning-driven pricing auditable on-chain.

vii) Oracle-Constrained Congestion Pricing. Tariffs derive from network-aware models, such as LMP and DLMP, and smart contracts ingest authenticated grid limits, including transfer capacities, power-transfer distribution factors (PTDFs), and dynamic line ratings (DLR), while recording settlements to enable on-chain audit without re-solving the OPF. As a blockchain implementation, Hu et al. [48] encode sealed bidding and congestion checks in smart contracts and enforce line-capacity constraints via energy-transfer distribution factors by adjusting clearing queues and prices, which yields congestion-aware and auditable settlements.

V. VISION

Verifiable and Transparent Optimization-Based Pricing. Emerging pricing schemes in energy markets increasingly leverage verifiability to build trust. Complex optimization-based pricing, including optimal power flow and multi-objective tariff design, can be made transparent by combining cryptographic proofs with auditable computation. For example, zero-knowledge proof frameworks and trusted oracles allow market participants to verify that computed prices or allocations are correct without revealing sensitive inputs. The research trajectory is nascent but promising; recent studies demonstrate that verifiable-computation techniques, such as zkSNARKs, can be applied to energy-market optimizations, addressing privacy and performance bottlenecks. A key vision is to incorporate verifiability into optimization-based pricing at scale so that regulators, operators, and prosumers can independently confirm outcomes. This agenda raises open questions of scalability and integration, since real-time verification of grid-wide optimizations will require efficient proof generation and possibly layered architectures. Developing lightweight, zero-knowledge-enabled pricing algorithms that provide mathematical guarantees of correctness is a forward-looking direction to strengthen transparency in blockchain-based energy markets.

Strategic Behavior and Game-Theoretic Pricing. A key direction is to design pricing mechanisms that anticipate and mitigate strategic behavior by rational agents. Game-theoretic models provide a foundation for understanding how prosumers and utilities bid or adjust consumption in response to pricing rules. Blockchain platforms can enhance these models by providing a transparent and tamper-evident environment in which participants access the same information, thereby approximating a complete-information game setting. The next step is to embed incentive alignment and mechanism-design principles into smart contracts, for example by automatically enforcing truth-telling or penalizing manipulation. Future research should pursue incentive-compatible and strategy-proof pricing that remains robust when participants attempt to game the system, including smart-contract–based enforcement of pricing rules and tokenized penalty or reward that deter free-riding and collusion. By combining blockchain transparency with rigorous game theory, energy markets can be designed so that strategic manipulation is checked by the pricing.

Privacy and Cryptographic Auction Mechanisms. Auction-based pricing in energy trading can gain substantially from strong cryptographic guarantees. A forward-looking objective is to operate auctions in which bid privacy, fairness, and integrity are enforced by the infrastructure with mathematical assurance. Recent developments show that sealed bids can remain confidential while the outcome remains verifiable on-chain. Techniques including commit–reveal protocols, homomorphic encryption, and interactive zero-knowledge proofs enable privacy-preserving auctions without a trusted auctioneer. Beyond privacy, research addresses collusion and fairness, and one prototype demonstrates a collusion-resistant double auction with bidder anonymity and an on-chain dispute-resolution contract that certifies correctness and fairness of the result. Building on these ideas, future energy markets can implement verifiable sealed-bid auctions for electricity or carbon credits, where smart contracts automatically enforce clearing and winner determination with cryptographic assurance. Realizing this vision requires scalability to handle high bid volumes and reductions in cryptographic overhead for practical deployment.

VI. CONCLUSION

This survey classifies blockchain-enabled pricing into auction-based, game-theoretic, and optimization-based families and analyzes how blockchain technology influences price formation in energy markets. Across pilots and prototypes, on-chain auctions enhance the auditability of settlement, game-theoretic designs leverage contract-coded commitment and rewards to sustain equilibrium behavior, and optimization-based clears, such as OPF-derived nodal pricing, gain verifiable correctness and distributed coordination through certificates and contract-orchestrated algorithms. The main challenges are to integrate privacy with public verifiability, to embed network physics through authenticated oracles, to scale clearing without compromising fairness or latency, and to align with regulatory standards and governance. Blockchain is not a panacea, but when co-designed with market rules and grid operations it can deliver credible, transparent, and automatable pricing modules that complement system-operator markets. We hope this review provides a compact basis for future work on verifiable, privacy-preserving, and interoperable pricing mechanisms.

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REFERENCES

[1] International Energy Agency, “World energy outlook 2024,” Paris, 2024. [Online]. Available: https://www.iea.org/reports/world-energy-outlook-2024

[2] R. Faia, J. Soares, M. Vasirani, and Z. Vale, “Local electricity markets: A review on benefits, barriers, and design options,” *Renewable and Sustainable Energy Reviews*, vol. 188, p. 113912, 2024.

[3] M. Yang, E. C. H. Ngai, X. Hu, B. Hu, J. Liu, and E. Gelenbe, “Digital phenotyping and feature extraction on smartphone data for depression detection,” *Proceedings of the IEEE*, vol. 112, no. 12, pp. 819–845, 2024.

[4] X. Shi and H. Duan, “Data valuation and pricing in internet of things: Survey and vision,” in *Proc. IEEE Int. Conf. Smart Internet of Things (SmartIoT)*, Shenzhen, China, Nov. 2024.

[5] Y. Peng and H. Duan, “Blockchain-based incentive mechanism in internet of things: Survey and vision,” in *Proc. IEEE Int. Conf. Smart Internet of Things (SmartIoT)*, Shenzhen, China, Nov. 2024.

[6] H. Duan, A. E. Saddik, and W. Cai, “Incentive mechanism design towards a win–win situation for generative art trainers and artists,” *IEEE Trans. Comput. Social Syst.*, 2024.

[7] W. A. H. Ahmed, E. Lughofer, and M. Sayed-Mouchaweh, “Blockchain-enabled supply chain traceability – how wide? how deep?” *International Journal of Production Economics*, vol. 260, p. 108891, 2023.

[8] T. K. Agrawal, A. Kumar, R. Pal, L. Wang, and Y. Chen, “Blockchain-based framework for supply chain traceability: A case of textile and clothing industry,” *Computers & Industrial Engineering*, vol. 154, p. 107130, 2021.

[9] M. Andoni, V. Robu, D. Flynn, S. Abram, D. Geach, D. Jenkins, P. McCallum, and A. Peacock, “Blockchain technology in the energy sector: A systematic review of challenges and opportunities,” *Renewable and Sustainable Energy Reviews*, vol. 100, pp. 143–174, 2019.

[10] M. L. D. Silvestre, P. Gallo, J. M. Guerrero, R. Musca, E. R. Sanseverino, G. Sciumè, and G. Zizzo, “Blockchain for power systems: Current trends and future applications,” *Renewable and Sustainable Energy Reviews*, vol. 119, p. 109585, 2020.

[11] M. Choobineh, A. Arabnya, B. Sohrabi, A. Khodaei, and A. Paaso, “Blockchain technology in energy systems: A state-of-the-art review,” *IET Blockchain*, vol. 3, no. 1, pp. 35–59, Mar. 2023.

[12] M. Capper, J. Parra, and J. Salom, “A systematic literature review of p2p, community self-consumption and transactive energy market models,” *Renewable and Sustainable Energy Reviews*, vol. 162, p. 112403, 2022.

[13] E. Foti and M. Vavalis, “Blockchain based uniform price double auctions for energy markets,” *Applied Energy*, vol. 254, p. 113604, Nov. 2019.

[14] G. Vieira and J. Zhang, “Peer-to-peer energy trading in a microgrid leveraged by smart contracts,” *Renewable and Sustainable Energy Reviews*, vol. 143, p. 110900, 2021.

[15] C. Graf, T. Kuppelwieser, and D. Wozabal, “Frequent auctions for intraday electricity markets,” *The Energy Journal*, vol. 45, no. 1, pp. 231–256, 2024.

[16] T. Kuppelwieser and D. Wozabal, “Liquidity costs on intraday power markets: Continuous trading versus auctions,” *Energy Policy*, vol. 154, p. 112299, 2021.

[17] R. Sarenche, M. Salmasizadeh, M. H. Ameri, and M. R. Aref, “A secure and privacy-preserving protocol for holding double auctions in smart grid,” *Information Sciences*, vol. 557, pp. 108–129, 2021.

[18] S. Zhang, X. Ying, and B. Wang, “A privacy protection scheme based on linkable ring signature for user payment of peer-to-peer uniform-price double auction transaction in the microgrid day-ahead market,” *International Journal of Electrical Power & Energy Systems*, vol. 147, p. 108806, 2023.

[19] F. Condon, P. Franco, J. M. Martínez, A. M. Eltamaly, Y.-C. Kim, and M. A. Ahmed, “Energyauction: Iot-blockchain architecture for local peer-to-peer energy trading in a microgrid,” *Sustainability*, vol. 15, no. 17, p. 13203, 2023.

[20] Y. Amanbek, A. Kalakova, S. Zhakiyeva, K. Kayisli, N. Zhakiyev, and D. Friedrich, “Distribution locational marginal price based transactive energy management in distribution systems with smart prosumers—a multi-agent approach,” *Energies*, vol. 15, no. 7, p. 2404, 2022.

[21] Z. A. E. Houda, A. S. Hafid, and L. Khoukhi, “Blockchain-based reverse auction for v2v charging in smart grid environment,” in *Proc. IEEE International Conference on Communications (ICC)*, 2021, pp. 1–6.

[22] Z. Husain, T. H. M. El-Fouly, S. Singh, R. Mizouni, H. Otrok, and E. F. El-Saadany, “Blockcharge: A blockchain-based auction framework for ev charging via mobile stations,” *Applied Energy*, vol. 377, p. 124638, 2025.

[23] Y. Wang, H. Xie, X. Sun, L. Tang, and Z. Bie, “A cross-chain enabled day-ahead collaborative power–carbon–tgc market,” *Energy*, vol. 258, p. 124881, 2022.

[24] C. Zheng, W. Huang, S. Zhai, K. Pan, X. He, X. Liu, S. Su, C. Shen, and Q. Ai, “Blockchain-enabled cross-chain coordinated trading strategy for electricity–carbon–green certificate in virtual power plants: Multi-market coupling and low-carbon operation optimization,” *Energies*, vol. 18, no. 13, p. 3443, 2025.

[25] M. Madani and M. V. Vyve, “Computationally efficient mip formulation and algorithms for european day-ahead electricity market auctions,” *European Journal of Operational Research*, vol. 242, no. 2, pp. 580–593, 2015.

[26] G. A. Dourbois and P. N. Biskas, “European market coupling algorithm incorporating clearing conditions of block and complex orders,” in *2015 IEEE Eindhoven PowerTech*, 2015.

[27] M. M. M. A. Moti, R. S. Uddin, M. A. Hai, T. B. Saleh, M. G. R. Alam, M. M. Hassan, and M. R. Hassan, “Blockchain based smart-grid stackelberg model for electricity trading and price forecasting using reinforcement learning,” *Applied Sciences*, vol. 12, no. 10, p. 5144, 2022.

[28] Y. Xiao, Y. Lei, F. Zhao, X. Liu, J. Tang, B. Qin, and Y. He, “Blockchain-assisted secure energy trading in electricity markets: A tiny deep reinforcement learning-based stackelberg game approach,” *Electronics*, vol. 13, no. 18, p. 3647, 2024.

[29] S. Mohseni, M. S. Pishvaee, and R. Dashti, “Privacy-preserving energy trading management in networked microgrids via data-driven robust optimization assisted by machine learning,” *Sustainable Energy, Grids and Networks*, vol. 34, p. 101011, 2023.

[30] W. Zhang, G. Qiu, H. Gao, T. Liu, J. Liu, Y. Li, S. Yang, J. Yan, and W. Mao, “Two stage robust nash bargaining based energy trading between hydrogen-enriched gas and active distribution networks,” *arXiv preprint arXiv:2310.05999*, 2023.

[31] Y. Wang, Y. Cao, Y. Li, L. Jiang, Y. Long, Y. Deng, Y. Zhou, and Y. Nakanishi, “Modelling and analysis of a two-level incentive mechanism based peer-to-peer energy sharing community,” *International Journal of Electrical Power & Energy Systems*, vol. 133, p. 107202, 2021.

[32] L. Zhang, R. Huang, M. Jiao, Q. Lu, and Y. Yang, “Distributed power trading mechanism based on blockchain smart contracts,” *Energies*, vol. 18, no. 8, p. 2040, 2025.

[33] B. Djehiche, J. Barreiro-Gomez, and H. Tembine, “Price dynamics for electricity in smart grid via mean-field-type games,” *Dynamic Games and Applications*, vol. 10, no. 4, pp. 798–818, Dec. 2020.

[34] Z. Zhou, B. Wang, Y. Guo, and Y. Zhang, “Blockchain and computational intelligence inspired incentive-compatible demand response in internet of electric vehicles,” *IEEE Transactions on Emerging Topics in Computational Intelligence*, vol. 3, no. 3, pp. 205–216, 2019.

[35] Z. Su, Y. Wang, Q. Xu, M. Fei, Y.-C. Tian, and N. Zhang, “A secure charging scheme for electric vehicles with smart communities in energy blockchain,” *IEEE Internet of Things Journal*, vol. 6, no. 3, pp. 4601–4613, 2019.

[36] Q. He, J. Wang, R. Shi, Y. He, and M. Wu, “Enhancing renewable energy certificate transactions through reinforcement learning and smart contracts integration,” *Scientific Reports*, vol. 14, p. 10838, 2024.

[37] W. Liu, W. Chiu, and W. Hua, “Blockchain-enabled renewable energy certificate trading: A secure and privacy-preserving approach,” *Energy*, vol. 290, p. 130110, 2024.

[38] A. Oustry, C. D'Ambrosio, L. Liberti, and M. Ruiz, “Certified and accurate SDP bounds for the ACOPF problem,” *Electric Power Systems Research*, vol. 212, p. 108278, 2022.

[39] E. Munsing, J. Mather, and S. J. Moura, “Blockchains for decentralized optimization of energy resources in microgrid networks,” in *Proc. 2017 IEEE Conference on Control Technology and Applications (CCTA)*, 2017.

[40] Q. Yang and H. Wang, “Exploring blockchain for the coordination of distributed energy resources,” *arXiv preprint arXiv:2103.06046*, 2021. [Online]. Available: https://arxiv.org/abs/2103.06046

[41] V. M. Zavala, K. Kim, M. Anitescu, and J. R. Birge, “Stochastic market clearing with consistent pricing,” *arXiv preprint arXiv:1510.08335*, 2015. [Online]. Available: https://arxiv.org/abs/1510.08335

[42] M. Franke, O. Stanojev, L. Mitridati, and G. Hug, “Privacy-preserving distributed market mechanism for active distribution networks,” *Electric Power Systems Research*, vol. 234, p. 110616, 2024.

[43] N. Saeed, F. Wen, and M. Z. Afzal, “A unified flc-blockchain framework for optimized carbon credit trading in multi-microgrid systems,” *Scientific Reports*, vol. 15, 2025. [Online]. Available: https://www.nature.com/articles/s41598-025-12562-x

[44] Q. Feng, X. Dong, and J. Wang, “Multi-interval settlement system of rolling-horizon scheduling for electricity spot market,” *Frontiers in Energy Research*, vol. 11, p. 1170138, 2023.

[45] M. Zade, M. Feroce, A. Guridi, S. D. Lumpp, and P. Tzscheutschler, “Evaluating the added value of blockchains to local energy markets—comparing the performance of blockchain-based and centralised implementations,” *IET Smart Grid*, vol. 5, no. 4, pp. 234–245, 2022.

[46] J. Rahman, C. Feng, and J. Zhang, “A learning-augmented approach for ac optimal power flow,” *International Journal of Electrical Power & Energy Systems*, vol. 130, p. 106908, 2021.

[47] C. Fan, A. Sohrabbeig, and P. Musilek, “Zero-knowledge machine learning models for blockchain peer-to-peer energy trading,” *Internet of Things*, vol. 32, p. 101638, 2025.

[48] W. Hu, Y. W. Hu, W. H. Yao, W. Q. Lu, H. H. Li, and Z. W. Lv, “A blockchain-based smart contract trading mechanism for energy power supply and demand network,” *Advances in Production Engineering & Management*, vol. 14, no. 3, pp. 284–296, 2019.