Blockchain-Enabled Market Clearing Mechanism for Peer-to-Peer Energy Storage Sharing

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***Abstract*—This paper first classifies blockchain-based shared energy storage studies into three deployment modes, namely community sharing, cloud sharing, and peer-to-peer (P2P) sharing, and summarizes how blockchain reshapes market mechanisms and data governance in these settings. Building on these insights, we develop a blockchain-enabled P2P market framework that tokenizes time-sliced capacity rights and clears a uniform capacity price through a sealed-bid commit–reveal process. The proposed framework establishes a privacy-preserving market microstructure where sellers and buyers submit piecewise capacity bids across delivery windows, and smart contracts execute commitment verification, convex welfare-based capacity clearing, and auditable settlement. The clearing problem is formulated as a convex social-welfare optimization and reduced to a one-dimensional dual problem, yielding closed-form expressions for the uniform price and primal allocations. Furthermore, the framework specifies deposit rules and capacity-right tokenization to ensure verifiable settlement. Future research directions include degradation-aware pricing, real-time capacity verification, and streaming settlement aligned with realized energy delivery.**

***Index Terms*—Blockchain-based shared energy storage, peer-to-peer (P2P) market framework, sealed-bid commit–reveal process, uniform capacity price, convex social-welfare optimization.**

I. INTRODUCTION

With the depletion of conventional energy resources and the deterioration of the environment, the use of renewable energy has increasingly come to dominate the future energy market [1]. Due to their abundant availability and clean, pollution-free nature, renewable energy sources are gradually aligning with global "dual-carbon" (carbon peak/carbon neutrality) goals. However, renewables such as photovoltaic (PV) and wind power are characterized by randomness, volatility, and intermittency, which may threaten the voltage stability of power systems and make it more challenging to maintain real-time supply and demand balance [2]. In this context, the need for flexible resources in power systems has become increasingly salient. Energy Storage Systems (ESS), with their bidirectional and flexible power regulation capability, offer an effective means to address the challenges brought by high-penetration renewables. On the grid side, storage enhances the safety margin of renewable-rich networks through peak shaving, valley filling, fast frequency response, and voltage support [3]. On the load side, storage enables users to perform price arbitrage and demand management, significantly improving utilization efficiency and reducing overall energy costs [4]. On the generation side, storage absorbs surplus renewable output during high-production periods and releases it during high-demand or high-price intervals, thereby reducing curtailment, smoothing power fluctuations, and increasing renewable accommodation and plant revenue [5]. Qiu et al. [6] reviewed cloud energy storage (CES) and summarized aggregated service models and operation methods for multi-user storage, while Liu et al. [7] quantified the accommodation prospect of shared storage under China's carbon-peaking targets.

In traditional individual distributed energy storage (ES) frameworks, each storage unit serves a single user independently. As a result, the operating time at full capacity is limited, since users make decisions based solely on their own interests. This fragmented operation leads to high investment and maintenance costs. Furthermore, the limited variety of storage products and the dynamic, uncertain nature of users' demand make it difficult to achieve efficient capacity matching between users and storage systems, especially for small-scale residential consumers [8]. Under such circumstances, there is an urgent need for more aggregated and efficient utilization of ESS and for cost-effective access to shared storage services.

To overcome the limitations of the individual distributed storage framework, shared energy storage (SES) has been proposed as a novel architecture that introduces new economic opportunities. Zhang et al. [9] provided a comprehensive SES review contrasting individual ownership with sharing schemes and reporting utilization and cost advantages of aggregation, and Chen et al. [10] surveyed shared-economy applications in smart grids, detailing SES market structures and pricing mechanisms that enable better matching. As defined by Kang et al. [11], SES decouples the ownership and usage rights of storage assets. Customers can lease storage capacity from owners according to their own needs, while owners can rent out their idle capacity during specific periods to obtain additional revenue. This business model inherently aligns with

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large-scale energy storage serving multiple users. Prior surveys indicate that SES studies typically fall into three deployment scenarios, namely community sharing, cloud ESS, and peer-to-peer sharing, and two research strands, namely market mechanism design and security and data governance. Moreover, Song et al. [12] proposed a barriers and prospects framework that highlights gaps in trusted metering, privacy-preserving settlement, and interoperable governance, which motivates a blockchain-enabled perspective. Consequently, exploring more efficient and diversified blockchain-based SES designs has become a major focus of academic research.

The structure of shared energy storage (SES) aligns closely with the architecture of blockchain. SES involves multiple independent participants such as storage owners, aggregators, operators, and users, who share physical assets while maintaining distinct interests and control. This distributed ownership corresponds to decentralized consensus and a replicated ledger in which transactions are transparently recorded and collectively verified. The time-coupled and event-driven workflow of SES, including bidding, scheduling, and settlement, aligns well with programmable smart contracts that sequence and enforce operations. Each step from capacity leasing to energy delivery can be represented as a verifiable on-chain record of rights and outcomes. Therefore, the decentralization, traceability, and programmability of blockchain make it a natural foundation for secure, transparent, and autonomous SES ecosystems.

In shared energy storage, credible coordination requires not only transparent pricing and verifiable exchange but also strong guarantees on identity, integrity, privacy, and auditability. Evidence from blockchain deployments in IoT data valuation and incentives [13], [14], community-based reputation in Web3 [15], and generative art markets shows that programmable pricing [16], incentive-aligned matching, and tamper-evident settlement are already operational at scale. Building on these capabilities, SES can price and allocate capacity rights on chain while settling against authenticated metering and at the same time strengthening security. Decentralized identity and verifiable credentials provide fine-grained access control for users, aggregators, meters, and batteries. Device-signed telemetry and authenticated oracles bind AMI, BMS, and SCADA measurements to on-chain state to achieve nonrepudiation and traceable reconciliation. Zero-knowledge proofs and secure multiparty computation enable verification of delivered energy, location constraints, or state of health without exposing raw profiles. Permissioned Byzantine fault-tolerant chains offer auditable high-throughput coordination for community and cloud deployments, while public chains and layer 2 channels support low-fee P2P microtransactions. Together, these properties deliver transparent pricing and allocation, automated and dispute-resistant settlement, trustworthy scheduling and metering, and auditable compliance for SES.

A detailed examination of existing literature reveals several key limitations. First, current Blockchain-based SES studies are fragmented, lacking a unified analytical structure across different sharing architectures. Second, most blockchain-enabled trading frameworks fail to ensure verifiable fairness and privacy under decentralized coordination. Third, existing market-clearing models are largely heuristic or simulation-based, without analytical tractability or interpretability.

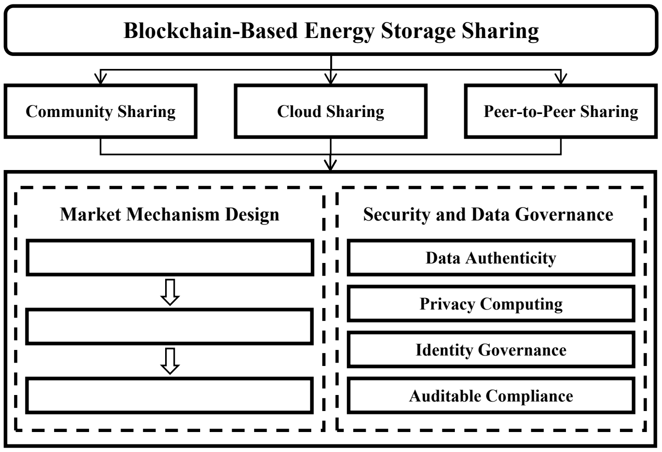

Fig. 1. Framework of Blockchain-Based Energy Storage Sharing.

To address these gaps, this paper makes the following contributions:

- **Unified framework for Blockchain-Based Shared Storage.** We establish a structured analytical framework that classifies blockchain-enabled shared storage into three deployment architectures, namely Community Sharing, Cloud Sharing, and P2P Sharing, and clarify how blockchain reshapes market mechanisms, coordination logic, and security governance within each architecture.
- **Blockchain-based Peer-to-Peer sharing mechanism.** We design a blockchain-based P2P sharing mechanism that employs a commit–reveal process to prevent front-running and ensure fair capacity trading. The mechanism achieves transparent pricing, secure settlement, and decentralized coordination among participants.
- **Analytical market-clearing formulation.** We reformulate capacity clearing as a convex social-welfare optimization and reduce it to a one-dimensional dual problem, yielding closed-form uniform prices. The model provides a provably optimal equilibrium and interpretable linkage between aggregate supply–demand and market outcomes.

The remainder of this paper is organized as follows. Section II analyzes existing studies on Blockchain-Based Shared Energy Storage and outlines the unified framework. Section III presents the proposed blockchain-based P2P sharing mechanism and its analytical market-clearing model. Section IV discusses potential extensions and future research directions. Finally, Section V concludes the paper with closing remarks.

II. BLOCKCHAIN-BASED ENERGY STORAGE SHARING

The research on Blockchain-Based Shared Energy Storage is typically categorized into three primary application scenarios: Community Energy Storage, Cloud-ESS, and P2P Energy Storage. Regardless of the scenario, existing studies on blockchain-based SES generally focus on two main aspects:

Market Mechanism Design and Security and Data Governance. The Market Mechanism and Design module governs the economic process of shared energy storage through three sequential stages. Pricing & Allocation determines uniform clearing prices and assigns time-windowed capacity rights based on supply and demand bids. Settlement & Revenue executes payments and revenue distribution via smart contracts, ensuring fairness and enforcing performance guarantees through deposits or slashing. Finally, Scheduling & Auditing converts cleared rights into dispatch schedules, verifies execution with metering data, and enables transparent post-event reconciliation. In parallel, the Security and Data Governance module ensures the reliability and trust of market operations. Data Authenticity links metering data to on-chain states, Privacy Computing protects sensitive information, Identity Governance manages decentralised authentication, and Auditable Compliance provides traceable and regulator-ready transaction records. Together, these two modules ensure that SES markets are transparent, secure, and verifiable.

A. *Community Energy Storage Sharing*

Community Energy Storage focuses on sharing storage devices within a specific geographic area, typically managed by community organizations, property managers, or energy service companies (ESCOs). In this model, users access storage capacity on demand without the need for individual investments in energy storage systems. The main advantage of this model lies in its ability to reduce users' capital expenditures while improving the overall utilization of storage devices through centralized management and scheduling. Community energy storage is well-suited for residential areas, small commercial districts, and industrial parks, facilitating functions such as demand response and peak shaving.

Market Mechanism and Design. For community energy storage, market design must specify how shared capacity is priced and allocated, how revenues and penalties are calculated and settled against metering, and how scheduled activations are verified and paid. It should also prevent strategic timing, align incentives among residents and the community battery operator, and interoperate with local network or service constraints. Damisa et al. [17] proposed a smart contract double auction that allocates time or power slices of the community battery with commit and reveal plus on chain sequencing to preclude front running, and writes winning bids and payments to the ledger for transparent settlement. Thomas et al. [18] encoded a local market for storage sharing where clearing rules, contribution based revenue splitting, and penalty clauses are implemented as contract logic, so pricing, allocation, and payouts follow verifiable procedures. Ali et al. [19] integrated a community battery with a blockchain based local market that aligns community level clearing with resident to resident trades, and disperses revenue automatically according to measured participation. Yu et al. [20] linked economic dispatch to on-chain transactions by feeding clearing price, activation windows, and performance scores from the optimiser to contracts that execute settlement and benchmarking, which reduces reconciliation overhead and operator discretion. In a flexible demand setting, Xiang et al. [21] introduced on chain incentives and settlement for local electric vehicles coordinated with the community battery, improving the aggregability and traceability of demand response.

Security and Data Governance. Security and data governance in community storage must control who can access devices and market roles, ensure that metering and telemetry are authentic and nonrepudiable, provide privacy preserving verification so that compliance can be checked without exposing raw traces, and maintain auditable records that support dispute resolution and regulation. Umar et al. [22] presented a decentralised energy management scheme that uses distributed identity and verifiable credentials to authorise users, aggregators, meters, and community batteries without a single credential authority. Demidov et al. [23] developed an energy management system in which devices sign telemetry and authenticated oracles bind AMI, BMS, and SCADA measurements to on chain state, enabling settlement and arbitration over nonrepudiable events. Wang et al. [24] designed a power battery data monitoring and sharing system on a consortium chain that records lifecycle and state information with integrity guarantees and traceable accountability across owners and operators. Zhang et al. [25] built a real time blockchain anchored state estimation system for battery storage that ties estimates to signed measurements and publishes verifiable states to the ledger, increasing trust in operational data used for scheduling and safety checks.

B. *Cloud Energy Storage Systems Sharing*

Cloud energy storage systems sharing (Cloud ESS) is a platform-based large-scale shared storage model that aggregates multiple storage units via a centralized ES service platform. Users can rent storage resources on an hourly or capacity basis. This model leverages economies of scale to reduce the unit cost of storage by sharing the investment cost of large storage facilities. Cloud energy storage systems sharing not only enables arbitrage in peak and off-peak electricity pricing but also provides grid support services. This model is particularly applicable to large-scale distributed storage systems, where more efficient resource scheduling and management are achieved through the cloud platform.

Market Mechanism and Design. For cloud energy storage, market design must specify how pooled capacity is offered as multiple services, how cloud operators coordinate bids from heterogeneous users, and how revenues from energy, frequency response, and ramping products are dispersed in a rule bound manner. Luo et al. [26] formulated a blockchain based sharing mechanism that lets a cloud pool participate in a joint market and clears bids on chain so that pricing, allocation, and settlement are tamper-evident . Truong et al. [27] studied multi use coordination of stationary batteries and showed how smart contracts can divide pooled capacity across concurrent services with explicit priorities and compensation rules . Ochoa et al. [28] proposed a blockchain as a service architecture for battery fleets that exposes metering, dispatch instructions, and performance records to contracts, enabling automated settlement at cloud scale. Chinnasamy et al. [29] designed a decentralised optimisation framework where a consortium ledger disseminates clearing results and activation windows to participating nodes, which reduces reconciliation overhead and operator discretion. In industrial parks, Hou et al. [30] embedded local storage into a blockchain based trading system so that cloud nodes can allocate capacity to tenants and settle against authenticated telemetry. Bird et al. [31] further examined how governance and revenue dispersal for cloud scale storage investments can be codified on a ledger to provide transparent payouts to investors and users.

Security and Data Governance. Security and data governance in cloud settings must control identities and permissions across many organisations, guarantee authenticity and non repudiation of telemetry, protect sensitive battery and user data during verification, and maintain auditable histories for compliance. Aenugu et al. [32] built a blockchain based battery data management and analytics platform that tracks lifecycle events and supports provenance aware analysis for fleets. Gong et al. [33] designed a consortium chain system for power battery monitoring and sharing that enforces fine grained access while preserving data integrity across owners and operators. Wang et al. [34] introduced a proxy signature based management model so that operation rights on SES can be delegated and audited without exposing private keys. Wang et al. [35] combined blockchain with secure multi party computation to verify delivery and cost sharing without releasing raw traces, showing a privacy preserving path for cloud level settlement. Jiang et al. [36] proposed a secure multi party computation scheme for shared storage indices that records proofs on-chain for verifiable calculation. Meng et al. [37] presented SFedChain, a blockchain supported federated energy data sharing framework that enables cross domain learning with data sovereignty. Sun et al. [38] developed a blockchain enhanced energy sharing framework for large electric vehicle groups that binds device signed telemetry to ledger state for high confidence metering. Huang et al. [39] studied distributed collaborative regulation based on blockchain and state awareness, demonstrating how authenticated measurements can drive trustworthy control in integrated energy systems.

C. Peer-to-Peer Energy Storage Sharing

The P2P model enables users to trade energy or storage capacity directly, without a central broker. Smart contracts record bids, match trades, and trigger payments on a shared ledger, which provides transparency and near real-time execution. The model favors autonomy and locality, making it suitable for distributed users and small businesses.

Market Mechanism and Design. Recent P2P studies center on on-chain pricing, allocation, and automated clearing. Zekiye et al. [40] design a blockchain-assisted market across microgrids where smart contracts coordinate bidding, clearing, and payoff under realistic demand and battery constraints. Their follow-up work realizes a decentralized market that trades both electricity and capacity with game-theoretic price formation on-chain [41]. Kim et al. [42] enable vehicle-to-vehicle negotiation using decentralized identifiers so that bilateral trades of ES are verifiable and resistant to manipulation. Sun et al. [43] couple a P2P pricing interface with demand-response based configuration of SES, allowing the contract layer to execute capacity scheduling and settlement.

Security and Data Governance. Security focuses on authentic metering, controlled participation, and auditable settlement without a trusted intermediary. In [40], metering and dispatch events are signed by nodes and validated through consensus, yielding tamper-evident accounting among peers. The decentralized market in [41] adds on-chain identity and permission control to restrict who can advertise capacity and trigger operations. [42] use decentralized identifiers to preserve participant privacy while keeping transactions traceable. [43] anchor demand-response actions and usage records on-chain to support transparent settlement and compliance auditing.

III. MARKET MECHANISM AND ANALYTICAL MODELING

In this section, we propose a blockchain-enabled market clearing mechanism for P2P energy storage sharing. The mechanism establishes a decentralized and transparent trading environment in which storage capacities are securely tokenized and exchanged among participants without relying on centralized intermediaries. By integrating smart contracts and mathematical market modeling, the proposed framework ensures both operational transparency and economic optimality.

To enable fine-grained ownership and verifiable transactions, large ES capacities are divided and tokenized into discrete tradable units represented by Non-Fungible Tokens (NFTs). Each NFT encapsulates essential attributes such as capacity size, ownership, and time validity, enabling automated verification and transfer through smart contracts. This tokenization process enhances market liquidity and traceability, ensuring that every storage unit is auditable on-chain.

Building upon this architecture, we formulate a blockchain-constrained market clearing model to derive an equilibrium solution between storage supply and demand. The model integrates participants' bidding strategies and smart-contract-based settlement rules, ensuring that the market reaches a stable, incentive-compatible, and economically efficient equilibrium. The blockchain ensures verifiable compliance with the clearing results, preventing manipulation and enhancing trust.

A. Bidding Model and Sealed Submission Mechanism.

To ensure effective scheduling and prevent congestion in energy transactions, we define a set of delivery windows $\tau \in \mathcal{W}$, where $\mathcal{W}$ represents the collection of all possible delivery time slots. Each delivery window corresponds to a specific time period during which ES capacity can be traded. This approach allows for organized transaction execution, ensuring that trading activities occur at different intervals, reducing system overload, and improving market scalability.

Both sellers and buyers submit sealed capacity quotations to the smart contract for each delivery window $\tau \in \mathcal{W}$. The goal is to construct a verifiable but private order book that

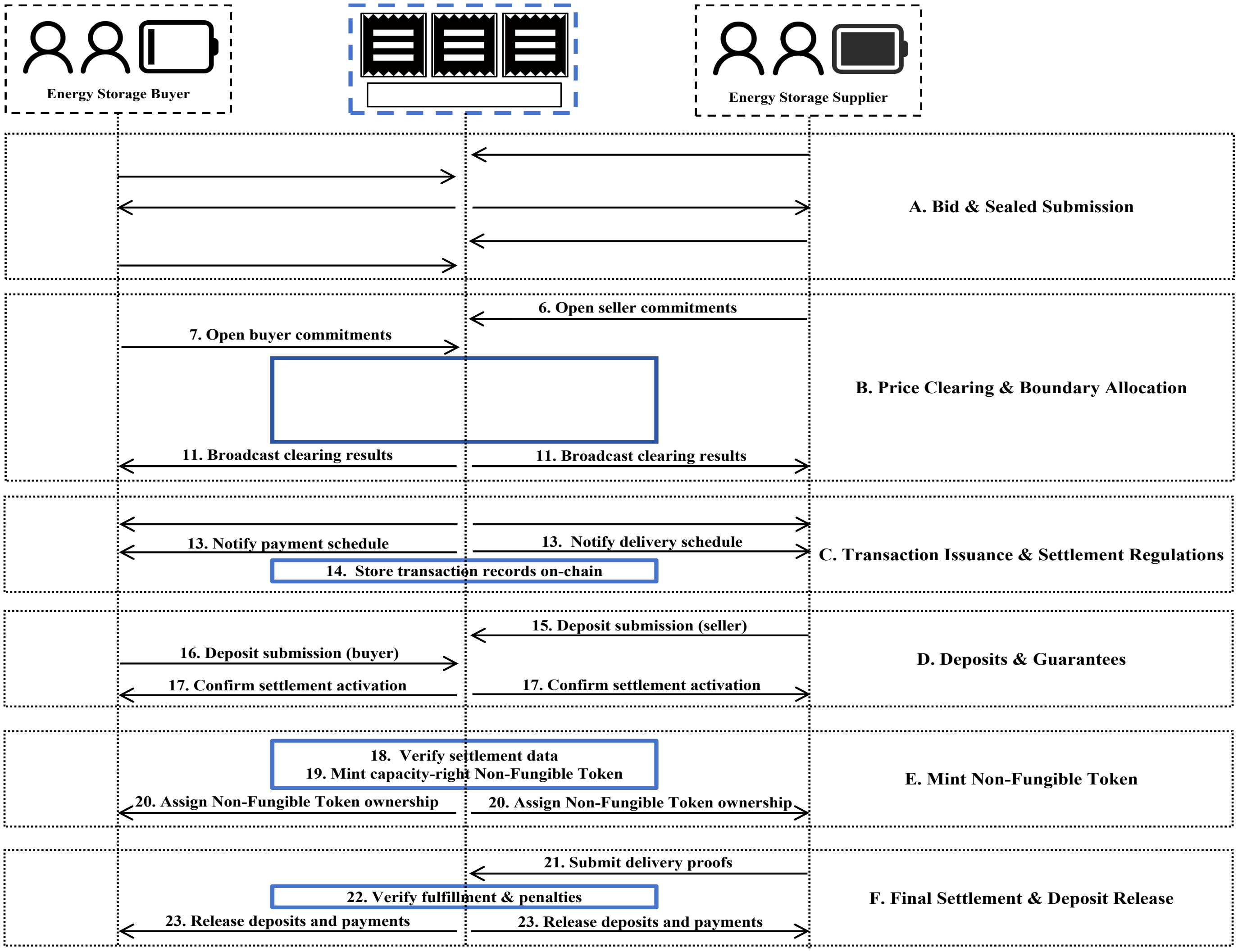

Fig. 2. Blockchain-Enabled Market-Clearing Workflow for Peer-to-Peer Shared Energy Storage.

prevents front–running and late manipulation. At this step only cryptographic commitments and timestamps are recorded on chain; the economic plaintext is revealed in the opening phase.

On the seller side, each storage owner $i \in \mathcal{S}$ declares the admissible capacity-right bound $q_{i,\tau} \in [0, Q^{\max}_{i,\tau}]$ for delivery window τ, where

$$0 \le q_{i,\tau} \le Q^{\max}_{i,\tau} = \min\Big\{\bar{E}_i,\ \sum_{t\in\tau} \bar{p}^{\tau}_{i,t}\,\Delta t\Big\}. \tag{1}$$

Here, $\bar{E}_i$ denotes the usable energy of storage unit i, $\bar{p}^{\tau}_{i,t}$ is the export power cap at time slot t, and Δt is the slot length. The term "capacity-right" represents the tradable discharge entitlement of storage capacity within window τ, constrained by both energy and power limits.

Each seller reports a nondecreasing piecewise-linear marginal willingness-to-accept function over the admissible range $[0, Q^{\max}_{i,\tau}]$, parameterized by $K_{i,\tau}$ breakpoints and corresponding price levels:

$$0 = q^{(0)}_{i,\tau} < q^{(1)}_{i,\tau} \le \cdots \le q^{(K)}_{i,\tau} = Q^{\max}_{i,\tau}, \qquad \mu^{(1)}_{i,\tau} \le \cdots \le \mu^{(K)}_{i,\tau}.$$

Each $\mu^{(k)}_{i,\tau}$ is a fixed bid parameter provided by the seller, representing a constant marginal willingness-to-accept within the corresponding quantity segment. The resulting marginal and total capacity ask functions are defined respectively as

$$\pi^{\mathrm{cap}}_{i,\tau}(q) = \mu^{(k)}_{i,\tau}, \quad \text{if } q^{(k-1)}_{i,\tau} < q \le q^{(k)}_{i,\tau}, \tag{2}$$

$$\Pi^{\mathrm{cap}}_{i,\tau}(q) = \int_0^q \pi^{\mathrm{cap}}_{i,\tau}(z)\,dz = \sum_{k=1}^{K_{i,\tau}} \mu^{(k)}_{i,\tau}\Big(\min\{q, q^{(k)}_{i,\tau}\} - q^{(k-1)}_{i,\tau}\Big)^{+}, \tag{3}$$

where $(x)^{+}$ ensures non-negativity. The marginal function $\pi^{\mathrm{cap}}_{i,\tau}(q)$ captures the seller's incremental willingness-to-accept per unit capacity, while $\Pi^{\mathrm{cap}}_{i,\tau}(q)$ represents the cumulative cost associated with offering q units of capacity.

On the buyer side, each consumer $j \in \mathcal{B}$ declares the admissible purchase bound $y_{j,\tau} \in [0, Y^{\max}_{j,\tau}]$ for delivery window τ, where $Y^{\max}_{j,\tau}$ denotes the buyer's maximum admissible purchase bound determined by its demand requirement or technical limitation. Each buyer submits a nonincreasing piecewise-linear marginal willingness-to-pay function over $[0, Y^{\max}_{j,\tau}]$, parameterized by $L_{j,\tau}$ breakpoints and the corresponding value levels:

$$0 = y^{(0)}_{j,\tau} < y^{(1)}_{j,\tau} \le \cdots \le y^{(L)}_{j,\tau} = Y^{\max}_{j,\tau}, \qquad \nu^{(1)}_{j,\tau} \ge \cdots \ge \nu^{(L)}_{j,\tau}.$$

Here, each $\nu^{(l)}_{j,\tau}$ is a fixed bid parameter provided by the buyer, representing a constant marginal willingness-to-pay within the corresponding quantity segment. The resulting marginal and total value functions are defined respectively as

$$V'_{j,\tau}(y) = \nu^{(l)}_{j,\tau}, \quad \text{if } y^{(l-1)}_{j,\tau} < y \le y^{(l)}_{j,\tau}, \tag{4}$$

$$V_{j,\tau}(y) = \int_0^y V'_{j,\tau}(z)\,dz = \sum_{l=1}^{L_{j,\tau}} \nu^{(l)}_{j,\tau} \Big(\min\{y, y^{(l)}_{j,\tau}\} - y^{(l-1)}_{j,\tau} \Big)^+, \tag{5}$$

The function $V'_{j,\tau}(y)$ represents the buyer's marginal valuation per unit of purchased capacity right, while $V_{j,\tau}(y)$ gives the total valuation of acquiring y units of capacity rights. This construction yields a concave total value function, consistent with the economic principle of diminishing marginal utility with respect to additional capacity rights.

To ensure privacy preserving and verifiable bid submission, both sellers and buyers employ binding and hiding commitments to submit their encrypted offers to the blockchain. Let

$$m^{\text{sell}}_{i,\tau} = \mathrm{Enc}\big(\{q^{(k)}_{i,\tau}, \mu^{(k)}_{i,\tau}\}_k, H_i\big),$$

$$m^{\text{buy}}_{j,\tau} = \mathrm{Enc}\big(\{y^{(l)}_{j,\tau}, \nu^{(l)}_{j,\tau}\}_l, Y^{\max}_{j,\tau}, H_j\big),$$

where $\mathrm{Enc}(\cdot)$ denotes a binding and hiding encryption (commitment) function that guarantees bid confidentiality before the opening phase while allowing verifiable decryption through on-chain commitments. The auxiliary hash $H_i = \mathrm{Hash}(\bar{E}_i, \bar{p}^r_i, \bar{p}^t_i, \{\bar{p}^{\text{out}}_{i,t}\}_{t\in\tau}, \eta_c, \eta_d)$ fingerprints static device parameters for later feasibility checks.

The on-chain artifacts are implemented as Pedersen commitments, expressed as

$$C^{\text{sell}}_{i,\tau} = g^{m^{\text{sell}}_{i,\tau}} h^{r^{\text{sell}}_{i,\tau}}, \qquad C^{\text{buy}}_{j,\tau} = g^{m^{\text{buy}}_{j,\tau}} h^{r^{\text{buy}}_{j,\tau}}, \tag{6}$$

where (g, h) are public generators of a cyclic group, and $r^{\text{sell}}_{i,\tau}$ and $r^{\text{buy}}_{j,\tau}$ are independent random blinders. A Pedersen commitment $C = g^m h^r$ ensures both computational binding, meaning that the committed message m cannot be altered without knowing r, and statistical hiding, which keeps the bid content private until the blinding factor is revealed.

At the opening phase, each participant discloses its corresponding (m, r) pair. The smart contracts verify equation (6) on-chain and extract the plaintext schedules for market clearing. This unified sealed bid interface forms a privacy preserving, timestamped supply demand book per delivery window and enables subsequent capacity right minting and settlement.

B. Smart Contract-Based Price Clearing and Boundary Capacity Allocation.

At the bid deadline of window $\tau \in \mathcal{W}$, the smart contract enters a common opening phase. Each seller $i \in \mathcal{S}$ and buyer $j \in \mathcal{B}$ reveals its plaintext pair $(m^{\text{sell}}_{i,\tau}, r^{\text{sell}}_{i,\tau})$ and $(m^{\text{buy}}_{j,\tau}, r^{\text{buy}}_{j,\tau})$, respectively. The smart contracts verify the sealed bids against the on-chain commitments posted in Step A as

$$C^{\text{sell}}_{i,\tau} \overset{?}{=} \mathrm{Com}(m^{\text{sell}}_{i,\tau}, r^{\text{sell}}_{i,\tau}), \qquad C^{\text{buy}}_{j,\tau} \overset{?}{=} \mathrm{Com}(m^{\text{buy}}_{j,\tau}, r^{\text{buy}}_{j,\tau}), \tag{7}$$

and discard any mismatched bids. Here, $\mathrm{Com}(m, r)$ denotes the Pedersen commitment function defined in (6), which generates the on-chain commitment $C = g^m h^r$ based on message m and blinding factor r. This function enables the smart contracts to verify the authenticity of the opened bids during the commitment verification stage. If multiple bids lie on the same marginal price (ties), the smart contract selects a deterministic order using a publicly verifiable randomness seed. Both the seed and a short log of the tie-breaking order are recorded as on-chain events for auditability.

After the commitment verification, the smart contract executes the capacity clearing program for each delivery window $\tau \in \mathcal{W}$. The clearing problem determines the optimal allocation of traded storage capacities between sellers and buyers to maximize social welfare, defined as the total valuation of buyers minus the total cost of sellers.

Let $\Pi^{\text{cap}}_{i,\tau}(\cdot)$ denote the convex piecewise-linear total ask function of seller i, and $V_{j,\tau}(\cdot)$ denote the concave piecewise-linear total value function of buyer j. The capacity clearing for window τ is formulated as

$$\begin{aligned} \max_{\{q_{i,\tau},\, y_{j,\tau}\}} \quad & \sum_{j\in\mathcal{B}} V_{j,\tau}(y_{j,\tau}) - \sum_{i\in\mathcal{S}} \Pi^{\text{cap}}_{i,\tau}(q_{i,\tau}) \\ \text{s.t.} \quad & \sum_j y_{j,\tau} \le \sum_i q_{i,\tau}, \\ & 0 \le q_{i,\tau} \le Q^{\max}_{i,\tau}, \quad 0 \le y_{j,\tau} \le Y^{\max}_{j,\tau}. \end{aligned} \tag{8}$$

This program maximizes social welfare by jointly determining the optimal allocation of traded capacity and the corresponding equilibrium price for each delivery window, while satisfying both supply and demand constraints.

To analyze the mathematical properties of the above clearing model and ensure the existence of an equilibrium solution, we first examine its convexity and strong duality. The convexity and strong duality of problem (8) are verified as follows.

Proof of Convexity and strong duality. Problem (8) is a convex optimization problem. For every seller $i \in \mathcal{S}$, the total capacity ask $\Pi^{\text{cap}}_{i,\tau}(\cdot)$ is convex and piecewise linear on $[0, Q^{\max}_{i,\tau}]$. For every buyer $j \in \mathcal{B}$, the total value $V_{j,\tau}(\cdot)$ is concave and piecewise linear on $[0, Y^{\max}_{j,\tau}]$. Hence the objective function is concave. All constraints in (8) are linear and define a polyhedral feasible set. Therefore (8) is a convex optimization problem in the sense of [44].

Since all upper bounds $Q^{\max}_{i,\tau}$ and $Y^{\max}_{j,\tau}$ are finite and nonnegative, one can choose strictly feasible quantities such that

$$0 < q_{i,\tau} < Q^{\max}_{i,\tau}, 0 < y_{j,\tau} < Y^{\max}_{j,\tau}, \sum_j y_{j,\tau} < \sum_i q_{i,\tau}.$$

Hence Slater's condition holds. By the standard strong duality result for convex programs with a strictly feasible point [44],

[45], the duality gap of (8) is zero and the optimal value of the primal problem equals that of its dual.

Given that the clearing problem is convex and satisfies strong duality, we can now derive its dual formulation and corresponding optimality conditions.

Let $\lambda_\tau \geq 0$ be the Lagrange multiplier of the market-balance constraint. The Fenchel–Rockafellar dual of (8) reduces to a one-dimensional convex optimization:

$$\min_{\lambda_\tau \geq 0} \Phi_\tau(\lambda_\tau) = \sum_{i \in \mathcal{S}} \Pi^{\text{cap}*}_{i,\tau}(\lambda_\tau) + \sum_{j \in \mathcal{B}} V^*_{j,\tau}(\lambda_\tau), \tag{9}$$

$$\Pi^{\text{cap}*}_{i,\tau}(\lambda) = \max_{0 \leq q \leq Q^{\max}_{i,\tau}} \big\{\lambda q - \Pi^{\text{cap}}_{i,\tau}(q)\big\}, \tag{10}$$

$$V^*_{j,\tau}(\lambda) = \max_{0 \leq y \leq Y^{\max}_{j,\tau}} \big\{V_{j,\tau}(y) - \lambda y\big\}. \tag{11}$$

Because $\Pi^{\text{cap}}_{i,\tau}$ is convex and $V_{j,\tau}$ is concave, both conjugates are convex and piecewise-linear; hence Φ_τ is convex and piecewise-linear on $\mathbb{R}_+$.

Define the step responses induced by a price λ:

$$\begin{aligned} q_{i,\tau}(\lambda) &= \arg\max_{0 \leq q \leq Q^{\max}_{i,\tau}} \big\{\lambda q - \Pi^{\text{cap}}_{i,\tau}(q)\big\}, \\ y_{j,\tau}(\lambda) &= \arg\max_{0 \leq y \leq Y^{\max}_{j,\tau}} \big\{V_{j,\tau}(y) - \lambda y\big\}. \end{aligned} \tag{12}$$

For the piecewise-linear models, (12) admits closed forms. If the seller's marginal ask $\pi^{\text{cap}}_{i,\tau}(q)$ has breakpoints $0 = q^{(0)}_{i,\tau} < \cdots < q^{(K)}_{i,\tau}$ with levels $\mu^{(1)}_{i,\tau} \leq \cdots \leq \mu^{(K)}_{i,\tau}$, then

$$q_{i,\tau}(\lambda) = \max\big\{q \;\big|\; \pi^{\text{cap}}_{i,\tau}(q) \leq \lambda\big\} \tag{13}$$

$$= \sum_{k=1}^{K} \big(q^{(k)}_{i,\tau} - q^{(k-1)}_{i,\tau}\big)\, \mathbf{1}\Big\{\mu^{(k)}_{i,\tau} \leq \lambda\Big\}. \tag{14}$$

Similarly, if the buyer's marginal value $V'_{j,\tau}(y)$ has breakpoints $0 = y^{(0)}_{j,\tau} < \cdots < y^{(L)}_{j,\tau}$ with levels $\nu^{(1)}_{j,\tau} \geq \cdots \geq \nu^{(L)}_{j,\tau}$, then

$$y_{j,\tau}(\lambda) = \max\big\{y \;\big|\; V'_{j,\tau}(y) \geq \lambda\big\} \tag{15}$$

$$= \sum_{l=1}^{L} \big(y^{(l)}_{j,\tau} - y^{(l-1)}_{j,\tau}\big)\, \mathbf{1}\Big\{\nu^{(l)}_{j,\tau} \geq \lambda\Big\}. \tag{16}$$

Let the aggregate step functions be

$$S_\tau(\lambda) \triangleq \sum_i q_{i,\tau}(\lambda), \qquad D_\tau(\lambda) \triangleq \sum_j y_{j,\tau}(\lambda), \tag{17}$$

where S_τ is nondecreasing and right-continuous, while D_τ is nonincreasing and right-continuous. By subgradient optimality for (9), any minimizer λ^*_τ satisfies

$$0 \in \partial\Phi_\tau(\lambda^*_\tau) \iff D_\tau(\lambda^*_\tau) - S_\tau(\lambda^*_\tau) = 0. \tag{18}$$

Closed-Form Characterization of the Uniform Capacity Price:

$$\lambda^*_\tau \;=\; \inf\big\{\lambda \geq 0 \;\big|\; S_\tau(\lambda) \geq D_\tau(\lambda)\big\}. \tag{19}$$

If the crossing occurs on a flat interval $[\lambda^-_\tau, \lambda^+_\tau]$ with $S_\tau(\lambda) = D_\tau(\lambda)$ for all λ therein, any $\lambda \in [\lambda^-_\tau, \lambda^+_\tau]$ solves (9); the smart contracts selects one deterministically using the public randomness seed.

Given λ^*_τ, define the marginal cohorts

$$\begin{aligned} \mathcal{I}^{=}_\tau &= \big\{\, i \;\big|\; \exists k : \mu^{(k)}_{i,\tau} = \lambda^*_\tau \,\big\}, \\ \mathcal{J}^{=}_\tau &= \big\{\, j \;\big|\; \exists l : \nu^{(l)}_{j,\tau} = \lambda^*_\tau \,\big\}. \end{aligned} \tag{20}$$

Let $q^{<}_{i,\tau} \triangleq q_{i,\tau}(\lambda^*_\tau-)$ and $y^{<}_{j,\tau} \triangleq y_{j,\tau}(\lambda^*_\tau+)$, and define the residual $R_\tau \triangleq \sum_j y^{<}_{j,\tau} - \sum_i q^{<}_{i,\tau} \geq 0$. For any $\theta_i \in [0,1]$ such that $\sum_{i \in \mathcal{I}^{=}_\tau} \theta_i \Delta q^{=}_{i,\tau} = R_\tau$ (with $\Delta q^{=}_{i,\tau} \triangleq q^{(k_i)}_{i,\tau} - q^{(k_i-1)}_{i,\tau}$), set

$$q^*_{i,\tau} \;=\; \begin{cases} q^{<}_{i,\tau} + \theta_i \Delta q^{=}_{i,\tau}, & i \in \mathcal{I}^{=}_\tau, \\ q_{i,\tau}(\lambda^*_\tau), & i \notin \mathcal{I}^{=}_\tau. \end{cases} \tag{21}$$

Analogously, choose $\phi_j \in [0,1]$ satisfying $\sum_{j \in \mathcal{J}^{=}_\tau} \phi_j \Delta y^{=}_{j,\tau} = R_\tau$ (with $\Delta y^{=}_{j,\tau} \triangleq y^{(l_j)}_{j,\tau} - y^{(l_j-1)}_{j,\tau}$), and set

$$y^*_{j,\tau} \;=\; \begin{cases} y^{<}_{j,\tau} + \phi_j \Delta y^{=}_{j,\tau}, & j \in \mathcal{J}^{=}_\tau, \\ y_{j,\tau}(\lambda^*_\tau), & j \notin \mathcal{J}^{=}_\tau. \end{cases} \tag{22}$$

Then $\sum_j y^*_{j,\tau} = \sum_i q^*_{i,\tau}$ and the Karush–Kuhn–Tucker(KKT) relations $V'_{j,\tau}(y^*_{j,\tau}) = \lambda^*_\tau = \pi^{\text{cap}}_{i,\tau}(q^*_{i,\tau})$ hold for all interior participants. The smart contracts record λ^*_τ, $\{q^*_{i,\tau}\}_i$, and $\{y^*_{j,\tau}\}_j$, and forwards $(\tau,\, q^*_{i,\tau},\, \lambda^*_\tau)$ to NFT minting.

C. Transaction Issuance and Settlement Regulations

After the market clearing phase, the equilibrium results, including the uniform clearing price λ^*_τ and the traded storage capacities $(q^*_{i,\tau}, y^*_{j,\tau})$, have been determined in the previous step. In this stage, the smart contracts utilize these precomputed results to issue official transaction records and enforce corresponding deposit and settlement regulations for both energy storage suppliers and buyers.

For each delivery window $\tau \in \mathcal{W}$, the smart contracts retrieve the equilibrium parameters $\{\lambda^*_\tau, q^*_{i,\tau}, y^*_{j,\tau}\}$ and communicate them to the corresponding market participants. For the ES supplier, the smart contract specifies the amount of capacity $q^*_{i,\tau}$ to be delivered during window τ, together with the payment amount calculated from the clearing price λ^*_τ. The settlement and deposit rules are explicitly published on-chain, ensuring that each supplier fully understands the payment and deposit requirements. All records are immutably stored on-chain to guarantee transparency, traceability, and auditability.

Similarly, for the ES buyer, the smart contract communicates the confirmed purchase quantity $y^*_{j,\tau}$ and the total payment obligation based on the same market clearing price λ^*_τ. Upon receiving this information, the buyer completes payment through the on-chain settlement module. This guarantees that the payment strictly conforms to the market-clearing outcome, thereby ensuring fairness and preventing any payment manipulation or dispute.

Through these automated issuance and settlement procedures, the framework finalizes the exchange of ES capacity and monetary assets according to predefined market rules. The entire transaction cycle is executed under smart-contract control, ensuring full decentralization and verifiable accountability.

D. Deposits and Guarantees

Following the issuance of settlement instructions, both suppliers and buyers are required to submit deposits to the smart contract to secure the execution of the transaction. The deposit mechanism ensures that all participants fulfill their market commitments based on the previously determined equilibrium results, namely the clearing price λ_τ^* and the traded capacities $(q_{i,\tau}^*, y_{j,\tau}^*)$ obtained from the market-clearing model.

For the energy storage supplier S, the deposit serves as a financial guarantee to ensure the reliable provision of the committed energy storage capacity. The deposit mitigates the risk of non-performance or default by making the supplier's commitment financially backed. The required deposit amount is determined as a function of the agreed storage capacity and market-clearing price, given by

$$D_S = \alpha_S \, q_{i,\tau}^* \lambda_\tau^*, \tag{23}$$

where $\alpha_S \in (0, 1]$ is the supplier's deposit coefficient encoded in the smart contract. The coefficient can be predefined by the market governance entity or dynamically adjusted according to the supplier's past reliability or reputation score. The deposit D_S is transferred to the smart contract and held in escrow until the transaction is completed. Once the delivery of ES capacity is verified, the deposit is released automatically.

Similarly, for the energy storage buyer B, a deposit is submitted to the smart contract to guarantee payment compliance with the agreed capacity purchase. The buyer's deposit prevents the participant from withdrawing after market clearing and ensures that the payment obligation is financially secured. The deposit amount is calculated as

$$D_B = \alpha_B \, y_{j,\tau}^* \lambda_\tau^*, \tag{24}$$

where $\alpha_B \in (0, 1]$ is the buyer's deposit coefficient. This deposit is also held in escrow and automatically released after successful payment and capacity verification. The smart contract verifies that both deposits align with the market-clearing results and enforces their release conditions on-chain, ensuring fairness and accountability of the entire transaction.

E. Mint Non-Fungible Tokens (Capacity Rights)

After the settlement and deposit stages, the system proceeds to the on-chain registration phase, where the verified market-clearing results are tokenized through the minting of NFTs. The NFTs represent the verified capacity rights for energy storage sharing and serve as cryptographically verifiable digital asset within the blockchain network. This stage finalizes the transaction cycle by transforming the previously computed equilibrium outcomes into immutable, auditable, and tradable on-chain records.

The minting process is implemented by smart contracts as a deterministic state transition function, mapping the verified market-clearing results and the associated deposits into an on-chain digital asset. The input parameters include the token identifier, the digital identity (DID) of the participant, the delivery window τ, the cleared energy storage capacity $q_{i,\tau}^*$ or $y_{j,\tau}^*$, the uniform clearing price λ_τ^*, and the corresponding deposits D_S and D_B that have been secured in the previous stage. These parameters ensure that the resulting token reflects both the physical trading outcome and the underlying financial guarantees. The formal expression of the minting function is given as

$$\begin{aligned}\mathrm{NFT}_{\mathrm{mint}}(&\mathrm{tokenId}, \mathrm{DID}, \tau, q_{i,\tau}^* \text{ or } y_{j,\tau}^*, \\ &\lambda_\tau^*, D_S, D_B, \text{transaction conditions}),\end{aligned} \tag{25}$$

where $\mathrm{NFT}_{\mathrm{mint}}(\cdot)$ denotes the on-chain function executed by the smart contract that generates and records the NFT.

During minting, the smart contract collects and verifies all transaction data, including the agreed capacity, price, deposit amounts, and settlement conditions. Once verified, the NFT is permanently recorded on the blockchain ledger, ensuring that the ownership and attributes of the capacity right cannot be altered. The NFT thus acts as a digital certificate of verified energy storage capacity, embedding both economic and operational credibility within the decentralized market.

In addition to providing an immutable proof of transaction, the minted NFT also enables traceability and secondary trading. Because the NFT contains verifiable identifiers such as $\{\mathrm{DID}, \tau, q_{i,\tau}^*, \lambda_\tau^*\}$ and the deposit-related parameters $\{D_S, D_B\}$, it can be freely transferred, exchanged, or verified by any participant through on-chain queries. This mechanism ensures that the transaction record is transparent, publicly auditable, and economically secured by collateralized deposits. As a result, the NFT-based capacity right serves as a trusted and tradable digital representation of the energy storage asset in the blockchain-enabled market.

F. Final Settlement and Deposit Release

After the verification of delivery and payment conditions for each delivery window τ, the smart contracts execute the final settlement for all participants. Once both the energy storage supplier and the buyer have fulfilled their contractual obligations, the contract releases a proportional amount of the locked deposits and finalizes the payment based on the cleared capacity and market price. The released deposit and final settlement payments are computed as

$$P_S = \beta_S D_S, \qquad P_B = \beta_B D_B, \tag{26}$$

where P_S and P_B denote the released deposits for the supplier and the buyer, respectively, D_S and D_B are the locked deposits defined in the deposit stage, and $\beta_S, \beta_B \in (0, 1]$ are the release coefficients determined by the smart contract. This ensures that all payments and deposit releases are consistent with the verified delivery quantities and the uniform clearing price λ_τ^*.

After settlement, the verified results, including digital identities, cleared quantities, market price, and released deposits, are permanently recorded on the blockchain as a final NFT:

$$\begin{aligned}\mathrm{NFT}_{\mathrm{final}}(&\mathrm{tokenId}, \mathrm{DID}, \tau, q_{i,\tau}^*, y_{j,\tau}^*, \\ &\lambda_\tau^*, P_S, P_B, \text{payment details}).\end{aligned} \tag{27}$$

This step ensures transparency, verifiability, and the completion of the blockchain-based energy storage transaction cycle.

IV. FUTURE DIRECTIONS AND PRACTICAL EXTENSIONS

A. Incorporating Degradation-Aware Supply Pricing

In the current design, sellers submit piecewise-constant marginal ask functions, which simplify capacity clearing but neglect the physical degradation of batteries. A practical improvement is to incorporate degradation-aware marginal costs that reflect both cycle wear and calendar aging effects. For seller i, the unit degradation cost can be formulated as

$$c^{\deg}_{i,\tau}(q;\theta_i) = a_i + b_i q + \phi_i(\mathrm{DOD}, T, u_i), \tag{28}$$

where $\theta_i = (a_i, b_i, \phi_i)$ captures the parameters related to linear throughput cost and nonlinear degradation as functions of depth-of-discharge (DOD), temperature T, and utilization rate u_i. The total cost function then becomes

$$\Pi^{\mathrm{cap}}_{i,\tau}(q;\theta_i) = \int_0^q c^{\deg}_{i,\tau}(z;\theta_i)\, dz. \tag{29}$$

This enhancement enables pricing to more accurately reflect the real wear-and-tear of battery assets, guiding market participants toward sustainable operation and prolonging the life cycle of SES. Future work can empirically estimate θ_i from operating data $\mathcal{D} = \{(\mathrm{DOD}_t, T_t, u_{i,t}, \Delta\mathrm{SOH}_t)\}_t$ by minimizing degradation prediction errors. Such data-driven calibration allows capacity pricing to align with physical performance, producing more credible market equilibria.

B. Real-Time Verification of Delivered Capacity

The current market settles on a scheduled basis at the end of each delivery window. To improve accountability, real-time verification mechanisms can be integrated using metered discharge data. Let $e_{i,\tau} = \sum_{t\in\tau} u_{i,t}$ denote the actual discharged energy from seller i and define the fulfillment ratio as

$$\rho_{i,\tau} = \frac{e_{i,\tau}}{\eta_i q^*_{i,\tau} \Delta_\tau}, \tag{30}$$

where η_i is the contractual efficiency, $q^*_{i,\tau}$ is the cleared capacity right, and Δ_τ is the delivery duration. A fulfillment-adjusted payment can then be expressed as

$$\mathrm{AdjPay}_{i,\tau} = \lambda^*_\tau q^*_{i,\tau} \rho_{i,\tau}. \tag{31}$$

This real-time validation links financial settlements directly to metered performance, ensuring that payments correspond to actual energy provision. It enhances market credibility, discourages under-delivery, and transforms smart contracts into compliance tools without altering the core pricing structure.

C. Streaming Settlement Based on Actual Usage

Traditional settlement aggregates all payments at the window boundary, delaying cash flows and increasing settlement risk. Future extensions can adopt a streaming settlement mechanism that continuously processes payments based on real-time utilization. Dividing τ into smaller subslots $t \in \mathcal{T}_\tau$ (e.g., every 5 minutes), the streaming settlement can be defined as

$$\mathrm{dPay}_{i,t} = \lambda^*_\tau u_{i,t}, \qquad \sum_{t\in\tau} \mathrm{dPay}_{i,t} = \lambda^*_\tau e_{i,\tau}. \tag{32}$$

This continuous settlement approach aligns cash flow timing with real energy delivery, reduces counterparty risk, and enables adaptive payment streaming for dynamic market environments. It effectively bridges the gap between market clearing signals and physical dispatch, paving the way for executable, real-time blockchain-based energy transactions.

V. CONCLUSION

This paper presented a unified blockchain enabled framework for shared energy storage and introduced a peer to peer market for capacity rights that integrates sealed bid privacy, on chain verifiability, and analytical market clearing. By representing sellers' asks and buyers' values as piecewise capacity curves over delivery windows, the proposed mechanism enables the smart contract to verify commitments, maximize social welfare, and compute a uniform clearing price with Karush-Kuhn-Tucker feasible allocations. The framework further supports transparent settlement through deposit escrows and capacity right tokenization, ensuring both fairness and auditability. Compared with simulation driven or purely numerical approaches, this design provides a provably optimal and verifiable clearing mechanism. In addition, the framework accommodates practical deployment choices such as permissioned ledgers for high throughput community or cloud settings and public networks or payment channels for low fee peer to peer transactions, while preserving a consistent security and audit model. It also supports interoperability with electricity, renewable certificate, and carbon accounting records so that settlement can reconcile across markets. Future research will extend the market microstructure to incorporate degradation aware supply pricing, post trade verification using metered delivery data, and streaming, usage aligned settlement to further enhance fairness, accountability, and operational reliability, and will validate scalability and governance in field pilots with real users and devices.

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