Development of Peer-to-Peer Solar Energy Trading Simulation System using Solana Smart Contract
(Anchor Framework Permissioned Environments)

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Abstract—This paper presents a performance evaluation of GridTokenX, a decentralized Peer-to-Peer (P2P) energy trading platform built on a private Solana cluster. We propose a "blockchainified" adaptation of the TPC-C benchmark to surely test the platform's capabilities under high-contention energy market scenarios. Our results demonstrate that the platform achieves 21,101 tpmC (transactions per minute Type C) with a p99 latency of 20ms, identifying a minimal "Trust Premium" of 5.65x compared to centralized baselines. Furthermore, we detail the specific low-level optimizations—including integer-only arithmetic and lazy state updates—that enable this throughput while maintaining strict mathematical invariants for energy conservation.

Index Terms—Blockchain, Energy Trading, Solana, TPC-C, Performance Benchmarking, Smart Contracts

I. Introduction

The decentralization of energy systems through Distributed Energy Resources (DERs) necessitates robust trading infrastructures capable of handling high-frequency micro-transactions [2]. Traditional centralized utility models suffer from single-point-of-failure risks and lack transparency in pricing. Blockchain technology offers a solution but is often criticized for scalability limitations [4].

This research evaluates GridTokenX, which leverages Solana's Sealevel parallel runtime [3] to overcome these bottlenecks. The objectives of this study are:

1) To study and present the architecture of a P2P energy trading simulation system using Solana (Anchor) in a Permissioned (PoA) environment.
2) To develop and prove the concept (Proof-of-Concept) of a prototype system capable of simulating GRID Token exchange using an AMI Simulator.
3) To evaluate and analyze the performance of the proposed architecture in terms of processing speed (Throughput) and transaction latency (Latency).

II. System Architecture

The platform is implemented as a suite of five interconnected Anchor smart contracts on Solana: 1. **Registry**: Manages user identity and meter assets. 2. **Oracle**: Validates off-chain sensor data. 3. **Energy Token**: SPL-compliant token representing 1 kWh. 4. **Trading**: Order book and settlement engine. 5. **Governance**: Configuration and DAO parameters.

III. Methodology

A. TPC-C Mapping

We map standard TPC-C transactions [1] to Energy Trading equivalents to create a realistic workload profile:

TABLE I
TPC-C to Energy Trading Mapping

TPC-C Transaction	Mix	GridTokenX Function
New Order	45%	`create_sell_order` / `create_buy_order`
Payment	43%	`transfer_tokens` (Settlement)
Order Status	4%	`get_order_status` (RPC Read)
Delivery	4%	`match_orders` (Batch Execution)
Stock Level	4%	`get_balance` (Energy Audit)

B. Mathematical Models

1) VWAP Pricing Mechanism: To ensure fair market value, the platform employs a Volume-Weighted Average Price (VWAP) discovery algorithm. The clearing price $P_{clearing}$ is calculated dynamically:

$$P_{base} = \frac{P_{bid} + P_{ask}}{2} \tag{1}$$

$$P_{clearing} = P_{base} + \left(P_{base} \times \min\left(\frac{V_{trade}}{V_{total}}, 1.0 \right) \times \delta_{max} \right) \tag{2}$$

Where V_{trade} is the current match volume, V_{total} is the historical volume, and δ_{max} is the maximum price elasticity factor (10%).

2) Token Conservation Invariant: The system enforces a strict conservation of energy. Tokens ($\Delta Supply_{GRID}$) can only be minted when physically generated energy is mathematically settled:

$$\Delta Supply_{GRID} = \max(0, (E_{produced} - E_{consumed}) - E_{settled}) \quad (3)$$

3) System Optimizations: To maximize throughput within the Solana Compute Unit (CU) limit, we implemented three critical optimizations:

A. Integer-Only Arithmetic: Floating-point operations (`f64`) are computationally expensive and discouraged in Solana programs. We replaced the VWAP calculation with fixed-point integer math:

$$W = \min\left(\frac{V \times 1000}{V_{total}}, 1000\right) \quad (4)$$

This reduction saved approximately 10,000 CUs per trade execution.

B. Lazy State Updates: Instead of serializing the full price history array (100+ entries) on every transaction, updates are "lazily" committed only when the price deviation exceeds 5% or every 60 seconds. This reduced the serialization overhead by 90%.

C. Batch Order Matching: The `match_orders` instruction was refactored to handle batch execution, allowing multiple non-overlapping limit orders to be settled in a single atomic transaction, significantly improving the "fills per second" rate.

IV. EXPERIMENTAL SETUP

Benchmarks were conducted on a high-performance Solana localnet cluster to eliminate internet latency variables.

- **Hardware**: Apple M-Series (8-core), 16GB RAM.
- **Cluster**: Solana Test Validator v1.18.
- **Client**: Multi-threaded Rust workload generator.

V. PERFORMANCE EVALUATION

A. Throughput Analysis

The platform achieved a peak throughput of **21,101 tpmC** (352 TPS). This high throughput is directly attributed to the *Sealevel* parallel runtime, which allows non-overlapping transactions (e.g., trades between different pairs of users) to execute simultaneously. In a traditional EVM-based blockchain, these transactions would be serialized, creating a bottleneck.

In our latest benchmark run, 23,848 total transactions were processed with 23,817 successful (99.9% success rate). For a regional P2P market with 10,000 households, assuming each smart meter submits a reading every 15 minutes, the required throughput is approximately 11 TPS. The observed 352 TPS provides a **32x safety margin**, proving the architecture can scale to city-wide deployments without congestion. This linear scalability is maintained up to 200 concurrent users (tested limit), with no significant degradation in p99 latency.

B. Latency Analysis

Transaction latency differs significantly from "confirmation time" in this permissioned PoA environment.

1) **Average Latency (11.30ms)**: Represents the time for the leader node to process the instruction and update the in-memory state.
2) **p50 Latency (11.00ms)**: Median transaction processing time.
3) **p95 Latency (18.00ms)**: 95th percentile under normal load.
4) **p99 Latency (20.00ms)**: Represents the worst-case processing time under heavy load.

The consistently low latency (<20ms) is critical for "Real-Time" energy pricing. Unlike public mainnets wherever finality may take seconds, the permissioned nature of the GridTokenX cluster allows for near-instant block propagation and deterministic finality, minimizing the "Trust Premium" to just **5.65x** over a centralized database.

C. Concurrency Analysis

Under high contention (multiple orders against the same market state), the Sealevel runtime effectively linearized conflicting transactions while processing non-overlapping requests in parallel. The observed MVCC (Multi-Version Concurrency Control) conflict rate was low at 1.5%, largely due to the atomic nature of the `match_orders` instruction.

D. The "Trust Premium"

We define "Trust Premium" as the performance cost incurred to achieve distributed consensus in a private network compared to a centralized baseline (PostgreSQL).

$$TrustPremium = \frac{Latency_{Blockchain}}{Latency_{Baseline}} = \frac{11.30ms}{2.00ms} \approx 5.65x \quad (5)$$

This 5.65x latency overhead is negligible for energy trading applications, where settlement typically takes days or weeks in traditional systems.

VI. CROSS-PLATFORM EVALUATION FRAMEWORK

To strictly compare GridTokenX with other blockchain platforms (e.g., Ethereum, Hyperledger Fabric) [4], we propose the *Standardized Energy Trading Workload (SETW)*. Researchers must follow three steps to replicate this methodology:

A. Equivalent Contract Implementation

Target platforms must implement the core logic defined in Table I. Specifically, the "Order Match" function must be atomic, ensuring that the trade execution and token settlement occur in the same cryptographic state transition.

B. Workload Injection Profile

The load generator must maintain the specific TPC-C mix:

- **Write Heavy (88%)**: New Orders + Payments. This stresses the consensus engine's state contention.
- **Read Light (12%)**: Status checks. This tests the RPC query performance.

C. Metric Normalization

Results must be reported in **tpmC** (transactions per minute Type-C). For blockchains with probabilistic finality (e.g., PoW), latency must include the time to reach k-block confirmation depth to be comparable with Solana's deterministic leader schedule.

VII. CONCLUSION

GridTokenX demonstrates that private blockchain technology is ready for real-time P2P energy trading. By achieving over 20,000 tpmC with sub-second latency, the platform proves that the "Trust Premium" is a worthy trade-off for the transparency, security, and automation benefits provided by the Solana blockchain in a managed consortium environment.

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