

# GridTokenX

## Blockchain Performance Analysis for P2P Energy Trading

### Master's Thesis Defense

*December 2024*

# Research Motivation

- Renewable energy adoption accelerating
- Prosumers need peer-to-peer trading capability
- Blockchain provides decentralized trust
- **Challenge:** Can blockchain meet performance requirements?

# Research Questions

1. Can blockchain achieve **production-level** performance for energy trading?
2. What is the **Trust Premium** (cost of decentralization)?
3. How does GridTokenX compare to **existing platforms**?

# Methodology

## BLOCKBENCH + TPC Benchmark Suite

Layer	Benchmark	Purpose
Consensus	DoNothing	Measure pure consensus overhead
Execution	CPUHeavy	Smart contract computation
Data Model	IOHeavy	State read/write operations
Application	TPC-C/E/H, Smallbank, YCSB	Real workloads

# Platform Architecture

## GridTokenX Technology Stack

- **Blockchain:** Solana-based
- **Consensus:** Proof of Authority (PoA)
- **Framework:** Anchor 0.32.1
- **Smart Contracts:** 5 programs + BLOCKBENCH
- **Testing:** LiteSVM in-process simulator

# Core Components

## 5 Smart Contract Programs

Program	Lines	Purpose
Registry	782	User & meter registration, balance settlement
EnergyToken	441	GRX token minting, transfer, burning
Trading	879	Order book, matching, batch execution
Oracle	434	AMI data ingestion, validation
Governance	343	PoA, ERC certification, emergency controls

# How Anchor Programs Work

## Anchor Framework v0.32.1

Feature	Description
IDL Generation	Auto-generate TypeScript/Rust clients
Account Validation	Compile-time constraints ( <code>#[account]</code> )
Error Handling	Custom error codes with messages
Events	On-chain event emission for indexers
CPI Helpers	Cross-program invocation wrappers

# Account Model (PDAs)

## Program Derived Addresses

```
#[account(  
  init,  
  payer = payer,  
  space = 8 + User::INIT_SPACE,  
  seeds = [b"user", owner.key().as_ref()],  
  bump  
)]  
pub user: Account<'info, User>,
```

- **Deterministic:** Derived from seeds + program ID
- **Keyless:** No private key required
- **Secure:** Only owning program can sign



# Cross-Program Invocation (CPI)

## Program Interaction Pattern

```
sequenceDiagram
    participant Client
    participant Registry
    participant EnergyToken
    participant Trading

    Client->>Registry: settle_and_mint_tokens()
    Registry->>Registry: Calculate net generation
    Registry->>EnergyToken: CPI: mint_tokens_direct()
    EnergyToken-->>Registry: Tokens minted
    Registry-->>Client: Success
```

# CPI Implementation

## Registry → EnergyToken Mint

```
// Registry calls EnergyToken via CPI
let cpi_ctx = CpiContext::new_with_signer(
    ctx.accounts.energy_token_program.to_account_info(),
    MintTokensDirect {
        mint: ctx.accounts.grid_mint.to_account_info(),
        destination: ctx.accounts.user_token_account.to_account_info(),
        authority: ctx.accounts.registry_authority.to_account_info(),
    },
    signer_seeds, // PDA signs for registry
);
energy_token::cpi::mint_tokens_direct(cpi_ctx, mint_amount)?;
```

# Trading Workflow

## Order Lifecycle

```
stateDiagram-v2
    [*] --> Created: create_sell_order()
    Created --> Active: ERC validated
    Active --> Matched: match_orders()
    Matched --> Settled: Token transfer
    Settled --> [*]
    Active --> Cancelled: cancel_order()
    Cancelled --> [*]
```

# Program Dependencies

## Inter-Program Relationships

Caller	Callee	CPI Purpose
Registry	EnergyToken	Mint GRX on settlement
Trading	Governance	Validate ERC for sell orders
Trading	EnergyToken	Transfer tokens on match
Oracle	Registry	Update meter readings

# Registry Program

## User & Meter Management

- **User Registration:** Prosumer/Consumer classification
- **Meter Registration:** Smart meter linking with MeterType
- **Reading Updates:** Oracle-authorized energy data (kWh)
- **Balance Settlement:** Net generation → GRID token minting

```
settle_and_mint_tokens() // CPI to energy_token program
```

# Energy Token Program

## GRX Token Lifecycle

- **Token 2022:** Anchor SPL Token interface
- **Mint:** Authority-controlled for verified meters
- **Transfer:** P2P energy settlement
- **Burn:** Consumption tracking

```
mint_tokens_direct(amount: u64) // Verified meter → tokens
```

# Trading Program

## P2P Order Book Engine

Feature	Implementation
Order Types	Buy/Sell limit orders
Matching	Price-priority FIFO
VWAP	Integer-only calculation (~10K CU saved)
Batch Execution	~40% overhead reduction
Market Depth	10-level bid/ask tracking

# Oracle Program

## AMI Data Bridge

- **API Gateway:** Authorized meter reading submission
- **Validation:** Anomaly detection, range checks
- **Market Trigger:** Automated clearing initiation
- **Quality Score:** Data reliability tracking

```
submit_meter_reading(meter_id, energy_produced, energy_consumed)
```



# Governance Program

## PoA & ERC Certification

- **Proof of Authority:** Single REC authority model
- **ERC Issuance:** Renewable certificate generation
- **ERC Validation:** Trading authorization
- **ERC Transfer:** Certificate ownership transfer
- **Emergency Controls:** Pause/unpause system

# Core Features Overview

## End-to-End Energy Trading Platform

```
flowchart LR
```

```
  A[Smart Meter] --> B[Oracle]
```

```
  B --> C[Registry]
```

```
  C --> D[Energy Token]
```

```
  D --> E[Trading]
```

```
  E --> F[Settlement]
```

```
  G[Governance] --> E
```

# Feature 1: P2P Energy Trading

## Decentralized Order Matching

Capability	Specification
Sell Orders	ERC-validated producers only
Buy Orders	Registered consumers
Matching	Automatic price-priority
Settlement	Atomic token transfer
Batch Processing	Up to N orders per tx

# Feature 2: ERC Certification

## Renewable Energy Certificates

1. **Meter Reading** → Oracle validates production
2. **ERC Issuance** → Governance mints certificate
3. **ERC Validation** → Trading authorization
4. **Trade Execution** → Only validated ERC holders

Prevents double-claiming via `claimed_erc_generation` tracker

# Feature 3: Smart Metering Integration

## AMI Data Pipeline

- **Data Ingestion:** Real-time meter readings
- **Validation Rules:** Min/max bounds, deviation checks
- **Net Settlement:**  $\text{Generation} - \text{Consumption} = \text{Mintable}$
- **Token Bridge:** Registry CPI  $\rightarrow$  EnergyToken mint

# Feature 4: Market Clearing

## Automated Trading Operations

- **Trigger:** Oracle-initiated clearing cycles
- **Price Discovery:** VWAP from order book
- **Depth Tracking:** 10-level bid/ask updates
- **Fee Collection:** Configurable market fee (BPS)

# BLOCKBENCH Micro-benchmark Results

## Layer-by-Layer Analysis

Layer	Benchmark	TPS	Latency
Consensus	DoNothing	225	2.5ms
Execution	CPUHeavy	231	2.5ms
Data Model	IOHeavy-Write	192	3.0ms
Data Model	IOHeavy-Mixed	192	3.0ms

# YCSB Workload Results

## Application Layer Performance

Workload	Profile	ops/s	Latency
YCSB-A	50% read, 50% update	290	2.7ms
YCSB-B	95% read, 5% update	442	1.8ms
YCSB-C	100% read	391	2.1ms

Smallbank OLTP: 1,714 TPS @ 5.8ms



# TPC Benchmark Results

## Industry-Standard Performance Metrics

Benchmark	Primary Metric	Latency	p99
TPC-C	2,111 tpmC	117ms	216ms
TPC-E	306 tpsE	7.9ms	17ms
TPC-H	250,486 QphH	71ms	147ms

# Comparative Analysis

## Platform Comparison

Platform	Smallbank TPS	Latency	Trust Premium
GridTokenX	1,714	5.8ms	58x
Hyperledger Fabric	400	150ms	175x
Ethereum	30	12,000ms	6,000x
PostgreSQL	5,000	2ms	1x

# Trust Premium Analysis

**|** Trust Premium = Blockchain Latency / Centralized Baseline Latency

- GridTokenX TPC-C: **58.28x** (117ms vs 2ms baseline)
- Hyperledger Fabric: 175x
- Ethereum: 6,000x

**GridTokenX achieves ~3x better Trust Premium than Hyperledger**

# Scalability Results

## Concurrency & Duration Tests

Test	Result	Stability
Peak TPS (1 thread)	443 TPS	100%
32 concurrent threads	398 TPS	90% retained
60-second sustained	416 TPS	Stable
1,000 accounts	220 TPS	Linear degradation

# Key Contributions

1. **BLOCKBENCH Layer Analysis** for Solana/Anchor
2. **TPC-C/E/H Adaptation** for blockchain
3. **Trust Premium Quantification**: 58x vs 175x (Fabric)
4. **Scalability Validation**: Stable under load

# Limitations

- LiteSVM simulation (not network)
- Single-validator PoA configuration
- No real smart meter integration
- Limited geographic distribution

# Future Work

- Multi-validator PoA cluster deployment
- Real network latency measurements
- Smart meter IoT integration
- Zero-knowledge privacy extensions

# Conclusion

- GridTokenX achieves **2,111 tpmC** TPC-C
- **1,714 TPS** Smallbank throughput
- **Trust Premium of 58x** vs PostgreSQL baseline
- **Stable performance** under concurrency


**Blockchain is viable for P2P energy trading**



# Thank You

## Questions?

 Benchmark Data: `test-results/`

 Charts: `test-results/charts/`

 Full Results: `docs/thesis/chapter4-results.tex`

