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# Blockchain Interoperability in Decentralized Energy Systems: A Performance Comparison of On-Chain and Cross-Chain Transactions in Cosmos-Based Microgrids

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Master Thesis

presented as partial requirement for obtaining a Master’s Degree in Data Science and Advanced Analytics

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# STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism, any form of undue use of information or falsification of results along the process leading to its elaboration. I further declare that I have fully acknowledged the Rules of Conduct and Code of Honor from the NOVA Information Management School.

Lisbon, 3rd of June 2025

Jannik Himmelsbach

# DEDICATION

This work is dedicated to all my loved ones. My mother, father, family, friends and colleagues.

# ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my family and friends for their unwavering support and encouragement throughout my academic journey. Their belief in me has been a constant source of motivation. I am also deeply indebted to NOVA IMS for providing an inspiring learning environment and to all my professors for their invaluable guidance and mentorship. A special thank you goes to my supervisor, Professor Mijail Naranjo-Zolotov, for his insightful advice, patience, and dedication.

# ABSTRACT

Blockchain interoperability is critical for decentralized peer-to-peer energy trading in interconnected microgrids, yet the performance trade-offs of single-chain versus multi-chain architectures remain poorly understood. This study evaluates the feasibility and efficiency of Cosmos-based blockchain setups for energy transactions, comparing on-chain execution with cross-chain transfers using the Hermes relayer. Through experimental simulations with synthetic energy data, cross-chain transactions demonstrated a 24% increase in gas costs compared to on-chain operations. However, absolute costs remained low, suggesting practical viability despite overheads. These findings highlight a trade-off: multi-chain architectures enable decentralized flexibility across microgrids at modest operational costs, though scalability and security require further optimization. The study provides a foundational framework for evaluating blockchain interoperability in energy systems, underscoring the need for future work integrating real-world datasets and heterogeneous blockchain ecosystems to advance resilient, decentralized energy markets.

# KEYWORDS

Blockchain Interoperability; Peer-to-Peer Energy Trading; Microgrid; Decentralized Energy Resources; Cosmos; Inter-Blockchain Communication Protocol (IBC)

## Sustainable Development Goals (SDG):

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| | |
|---|---|
| BAILIF | Blockchain Agnostic Interoperability Framework |
| BMG | The Brooklyn Microgrid |
| BSMG | Blockchain Enabled Smart Microgrid |
| DER | Distributed Energy Resources |
| DET | Distributed Energy Trading |
| DNS | Decentralized Notary Service |
| HTLC | Hashed Time Lock Contracts |
| IBC | Inter-Blockchain Communication |
| ILP | Interledger Protocol |
| ISGF | India Smart Grid Forum |
| LEM | Local Energy Market |
| NFT | Non-Fungible Tokens |
| P2P | Peer-to-Peer |
| PoW | Proof of Work |
| REC | Renewable Energy Certificates |
| RES | Renewable Energy Sources |
| SPV | Simplified Payment Verification |
| TPS | Transactions per Second |
| XCAV | Cross-Chain Attestation Protocol |

# 1. Introduction

The rise of blockchain technology has sparked a technological revolution, promising to reshape industries by providing decentralized, transparent, and secure solutions. Initially popularized by cryptocurrencies like Bitcoin, blockchain has since expanded its reach into various sectors, including finance, supply chain, healthcare, and energy (Choobineh et al., 2022). This technology's potential lies in its ability to create immutable records, facilitate trustless transactions, and enable decentralized governance (Bao et al., 2021), all of which are critical for the future of digital economies.

In the energy sector, blockchain technology is promising in various contexts, one of them is Microgrids. Microgrids, which are localized energy systems that can operate independently or in conjunction with the traditional grid, are becoming increasingly important as the world transitions towards renewable energy sources (RES). These systems offer numerous benefits, including increased energy resilience, reduced transmission losses, and the ability to integrate distributed energy resources (DERs) such as solar panels and wind turbines (Saeed et al., 2024).

Through blockchain, prosumers, individuals, or entities that both produce and consume energy, can trade excess energy directly with each other (Peer-to-Peer, P2P), bypassing traditional intermediaries. This P2P trading model provides energy efficiency but also fosters community resilience and economic benefits. For instance, in a microgrid homeowners with solar panels can sell surplus energy to neighbors, thus creating a local energy market (LEM) (Okwuibe et al., 2020).

However, the rise of various blockchain types and applications has also introduced complexity. Different blockchain platforms and protocols often operate in silos, making it challenging to achieve seamless interoperability. This lack of interoperability is a significant barrier to the widespread adoption of blockchain technology in the energy sector, particularly in Distributed Energy Trading (DET) where multiple (blockchain) networks need to interact (Karumba, Sethuvenkatraman, et al., 2023).

Moreover, despite the growing interest in blockchain for energy trading, there is a noticeable gap in research on blockchain interoperability protocols in that context. Existing studies (Ali et al., 2022; Aloqaily et al., 2020; Okwuibe et al., 2020; Saeed et al., 2024) have primarily focused on the technical aspects of P2P energy trading within the same blockchain network or system. These studies have explored how prosumers within a single, unified blockchain environment can efficiently trade energy. Still unexplored is how interconnected microgrids, each potentially utilizing different blockchain technologies, can communicate, collaborate, and trade energy effectively (Dinesha & Balachandra, 2022).

This study aims to address this research gap by conducting a performance comparison of existing blockchain interoperability protocols for energy trading in a multi-microgrid environment. By doing so, it seeks to explore how different microgrids, despite running on separate blockchains, can achieve seamless communication, collaboration, and energy exchange through interoperability protocols. This research is essential to advancing the practical application of blockchain in the energy sector, particularly in scenarios where multiple microgrids need to interact and share resources in a decentralized and efficient manner.

# 2. Literature Review

## 2.1. P2P Energy Trading

P2P energy trading is a decentralized approach to energy transactions where individuals or entities, known as prosumers, can directly buy and sell excess energy with one another, bypassing traditional utility companies or centralized energy markets. This model is facilitated by digital platforms that enable participants to trade surplus energy generated from renewable sources such as solar panels or wind turbines. Key components of P2P energy trading include prosumers, energy management systems, smart meters, and blockchain technology. Prosumers, who both produce and consume energy, generate renewable energy and sell any surplus to other consumers in the network. Energy management systems monitor energy production, consumption, and trading activities, while smart meters provide real-time data for accurate trading and billing.

The general process of P2P energy trading involves several steps. Prosumers generate energy using renewable sources and monitor their production through smart meters. Participants connect to a P2P energy trading platform, built on blockchain technology, to facilitate transactions. The platform matches buyers and sellers based on their energy needs and availability, allowing prosumers to list excess energy for sale and consumers to browse available offers. Blockchain-enabled smart contracts automate the trading process, ensuring that transactions are executed when predefined conditions are met, such as energy delivery. Once the energy is delivered, the transaction is recorded on the blockchain, and payments are settled automatically, using cryptocurrency or digital tokens.

P2P energy trading increases autonomy for prosumers, allowing them to control their energy production and consumption while monetizing excess energy (Karumba, Sethuvenkatraman, et al., 2023). Consumers can access cheaper energy prices by purchasing directly from peers rather than through traditional utility companies (Okwuibe et al., 2020). P2P trading reduces the burden on centralized grids, enhancing grid resilience and reliability, especially during peak demand periods and avoids long distance transmission losses (Aloqaily et al., 2020). By incentivizing the generation and consumption of renewable energy, P2P trading supports the transition to a more sustainable energy system (Aloqaily et al., 2020).

## 2.2. Blockchain Technology Applications in Microgrids

Microgrids are local energy systems that can operate independently or in conjunction with the traditional centralized grid. It typically consists of DERs such as solar panels, wind turbines, energy storage systems, and controllable loads. P2P energy trading within microgrids enables localized energy transactions, allowing prosumers to directly exchange excess energy with neighbors or other consumers. Compared to conventional systems, microgrids offer multiple benefits, including cost reduction by eliminating intermediaries and lowering energy prices through competitive trading (Saeed et al., 2024). They increase efficiency by optimizing energy distribution and consumption, minimizing losses, and enhancing renewable energy utilization (Van Leeuwen et al., 2020). Moreover, microgrids enhance reliability by providing backup power during grid outages and reducing dependence on centralized power plants (Saeed et al., 2024).

Although theoretical benefits of blockchain adoption in P2P energy trading within microgrids are widely recognized in literature, successful real world implementations are yet rather uncommon to find. Roth et al., (2022) states that literature is very positive but in the same time hypothetical. Furthermore they argue that the existing technological challenges such as the lack of interoperability, technical standards, scalability and security are the most dominant in literature but also the easiest to address. On the other hand organizational and, in particular, regulatory challenges appeared to be treated with minor importance, while those turn out to be serious hurdles for many blockchain projects.

That said, there are still existing real world use cases and pilot projects implementing P2P energy trading in microgrids using blockchain technology. In *Table 1*, successful examples will be briefly presented.

*Table 1: P2P Energy Trading Real World Projects*

| Project Name | Location & Scope | Blockchain Details / Technology | Key Achievements / Findings | Challenges | Scale (Initial / Current) |
|---|---|---|---|---|---|
| Brooklyn Microgrid (BMG) (Mengelkamp et al., 2018) | Brooklyn, USA; Community-based energy market | Private blockchain (Tendermint protocol); TransActive Grid smart meters | First recorded blockchain energy transaction; Proven feasibility of P2P energy trading in real-world settings. | Regulatory hurdles (lack of legal frameworks); Integration with existing grid infrastructure. | Initial: 5 prosumers, 5 consumers. Current: >300 houses/businesses, ~50 PV prosumers, 1 wind turbine. |
| Quartierstrom (Meeuw et al., 2020) | Walenstadt, Switzerland; P2P energy market for 37 households + 1 retirement home | Blockchain-based; User interface for trading | Traded 70 MWh solar energy in 1 year; Demonstrated technical feasibility of P2P trading; Addressed privacy with self-sovereign identity. | Integration with existing smart meter infrastructure; Establishing viable business models under current regulations; Participants favored increased automation. | 37 households, 1 retirement home. |
| Powerledger (*Power Ledger Whitepaper*, 2019) | Australia (Company); Global (Pilot Projects) | Dual token ecosystem (POWR & Sparkz); Decentralized & transparent platform | Demonstrated technical feasibility and benefits for prosumers/consumers in pilot projects (e.g., India with ISGF). | Existing regulatory frameworks; Need for enhanced metering infrastructure. | Pilot in India: 12 participants (9 prosumers, 3 consumers). |

These case studies — Brooklyn Microgrid, Quartierstrom, and Powerledger — collectively illustrate the nascent but promising real-world application of blockchain technology in peer-to-peer (P2P) energy trading. While demonstrating the technical feasibility and potential benefits of such systems, they consistently highlight common challenges, primarily related to regulatory frameworks, the need for smarter metering infrastructure, and the development of sustainable business models. Despite these hurdles, these projects pave the way for more decentralized, efficient, and renewable energy markets.

## 2.3. Blockchain Interoperability

The concept of blockchain interoperability is still in its early stage of maturity. Never the less, research about this topic has been significantly intensified over the past few years (Belchior et al., 2022). The survey of Belchior et al., 2022 defines interoperability as "the ability of a source blockchain to change the state of a target blockchain (or vice versa), enabled by cross-chain or cross-blockchain transactions, spanning across a composition of homogeneous and heterogeneous blockchain systems." Essentially, it allows different blockchains to communicate and work together. This capability would solve the problem that blockchains operate in silos, unable to communicate with one another effectively which limits their potential and creates isolated data and value systems.

According to Ren et al., 2023 the current existing blockchain interoperability approaches can be classified into five main categories: 1 – Sidechains, 2 – Notary Schemes, 3 – Hashed Time Lock Contracts (HTLC), 4 – Relays, and 5 – Blockchain Agnostic Protocols.

**Sidechains:** These independent blockchains operate alongside a mainchain, enabling bidirectional asset transfers. Assets are locked on the mainchain, verified on the sidechain, and then equivalent assets are minted. Sidechains can employ distinct consensus protocols and validator networks. Two-way pegs, which allow asset movement in both directions, can be centralized (relying on a single trusted party), federated (distributing trust among a group of validators), or utilize Simplified Payment Verification (SPV) for trust-minimized transactions by verifying block headers and Merkle proofs (Belchior et al., 2022; Nakamoto, 2008). Examples include Rootstock (RSK) for Bitcoin and Zendoo (Garoffolo et al., 2020; Lerner, 2019).

**Notary Schemes:** These rely on trusted intermediaries (a single entity or a group) to validate and relay transactions between blockchains. Notaries confirm events on one chain and, for asset transfers, lock or burn assets on the source chain to issue new ones on the destination chain (Karumba, Sethuvenkatraman, et al., 2023; Xue & Herlihy, 2021). While simpler to implement, they introduce risks of centralization or malicious behavior.

**Hashed Time Lock Contracts (HTLCs):** A fundamental mechanism for trustless atomic swaps, HTLCs use cryptographic constraints: a hash lock (requiring a secret code) and a time lock (a deadline). This ensures transactions are atomic, meaning they either fully execute or revert, eliminating the need for intermediaries (Nolan, 2013; Ren et al., 2023). HTLCs are applied in protocols like TierNolan and for asset transfers via the Burn-to-Claim protocol (Pillai et al., 2021).

**Relays:** These facilitate cross-chain communication by transmitting and verifying transaction data. Trustless relays, often leveraging SPV, validate transactions without storing full blockchain histories. Trusted relays rely on authorized entities to replicate blockchain data and execute cross-chain smart contracts. Unlike notary schemes, relays focus on continuous data synchronization (Ren et al., 2023). Examples include BTCRelay for Bitcoin-Ethereum interoperability and XCLAIM for atomic swaps (*BTC Relay*, 2017; Zamyatin et al., 2019).

**Blockchain Agnostic Protocols:** These universal frameworks enable seamless interaction across diverse blockchains by abstracting technical complexities. They eliminate the need for custom bridges, allowing users to operate across multiple ledgers through a single interface (Belchior et al., 2022). The Interledger Protocol (ILP) is a key example, enabling cross-chain payments via "connectors" to securely transfer assets between blockchains (Interledger Foundation, 2025).

Beyond these approaches, dedicated blockchain interoperability platforms are emerging. For public blockchains, Polkadot connects heterogeneous "parachains" via a central Relay Chain for shared security and cross-chain transactions (Wood, 2016). Cosmos aims to be an "Internet of Blockchains," linking independent chains ("zones") through a central "hub" using its IBC protocol (Kwon & Buchman, 2016). For private blockchains, Hyperledger Cactus offers modular tools for cross-chain transactions without system changes, supporting diverse ledgers through plugins (Somogyvari & Montgomery, 2021). YUI, a Hyperledger Labs project, adapts Cosmos's IBC for permissioned chains, enabling secure asset transfers and data sharing ("YUI," 2022).

## 2.4. Challenges of Blockchain Interoperability

Blockchain interoperability faces significant hurdles due to inherent technical heterogeneity, security vulnerabilities, and privacy concerns (Ren et al., 2023). Fundamental architectural differences exist between public blockchains, characterized by open and flexible systems like Ethereum, and private chains employing stricter controls like Hyperledger, creating trust barriers when they interact (Ren et al., 2023). Security is a paramount challenge, as cross-chain systems managing valuable assets are prime targets for exploits like double-spending, where attackers leverage validation discrepancies between connected chains; solutions such as confirmation delays mitigate but do not eliminate this risk (Ren et al., 2023). Furthermore, vulnerabilities in smart contract code remain a critical attack vector (Ren et al., 2023). Privacy is also problematic: while blockchains typically conceal identities, cross-chain tools (e.g., transaction trackers) can inadvertently expose sensitive data, particularly when private information like medical records traverses public networks; encryption helps, yet balancing privacy with necessary transparency proves difficult (Ren et al., 2023). Effective interoperability necessitates both asset transfer and data exchange between chains, requiring the conversion of an asset's value from the source chain to the destination chain without loss or gain (Dinesha & Patil, 2023). Verifying transaction status in a trustless environment is another core challenge, as chains struggle to independently confirm external transactions (Dinesha & Patil, 2023). Consequently, interoperability methods must adhere to key criteria: supporting diverse platform types, avoiding disruptive modifications to existing technology (like forking or smart contract changes for new links), minimizing manual user intervention, reducing reliance on off-chain infrastructure, and preserving the performance and security of participating chains (Dinesha & Patil, 2023). The absence of generalized standards means multiple vertical-specific standards are likely to emerge and potentially be reused across industries, though this heterogeneity complicates regulation across jurisdictions (Belchior et al., 2022). Despite advances, a significant gap persists between theoretical interoperability concepts and practical implementations, hindering scalability and adoption; enforcing correct executions in a fully trust-free manner across different blockchains remains highly challenging (Belchior et al., 2022). Platform fragmentation, especially in complex applications like IoT using tailored public, private, or consortium chains, creates management overhead and intensifies discoverability issues (locating assets and routing transactions) and governance complexities, particularly in community-driven public blockchain projects (Belchior et al., 2022). While interoperability reduces single-chain dependency risks, it introduces inherent cross-chain communication complexity and governance hurdles (Belchior et al., 2022). Key open issues thus include bridging the theory-practice gap, solving discoverability, ensuring robust privacy and security (including GDPR compliance challenges like the 'right-to-forget'), and establishing effective governance models (Belchior et al., 2022).

## 2.5. Blockchain Interoperability State of Art in the Energy Sector

Blockchain could transform energy trading, but its growth is slowed by poor compatibility between systems. Researchers agree that interoperability is crucial but underdeveloped, with no common standards for linking different platforms (Ahl et al., 2022; Leong et al., 2024; Perrons & Cosby, 2020). For example, energy systems with solar panels, wind farms, and electric cars often use multiple blockchains, requiring seamless coordination (Choobineh et al., 2022). Recent projects aim to fix this. Zhang & Hou, (2021) tested a multi-chain model that splits energy networks into smaller chains (e.g., solar/wind) linked by a central relay. While this worked in simulations, it struggled to balance speed and decentralization. Another tool, BAILIF (Karumba, Jurdak, et al., 2023), allows energy data and assets to move between blockchains like Ethereum and Hyperledger. It hit 666 transactions per second in tests but faces issues like scaling up and securing validator nodes.

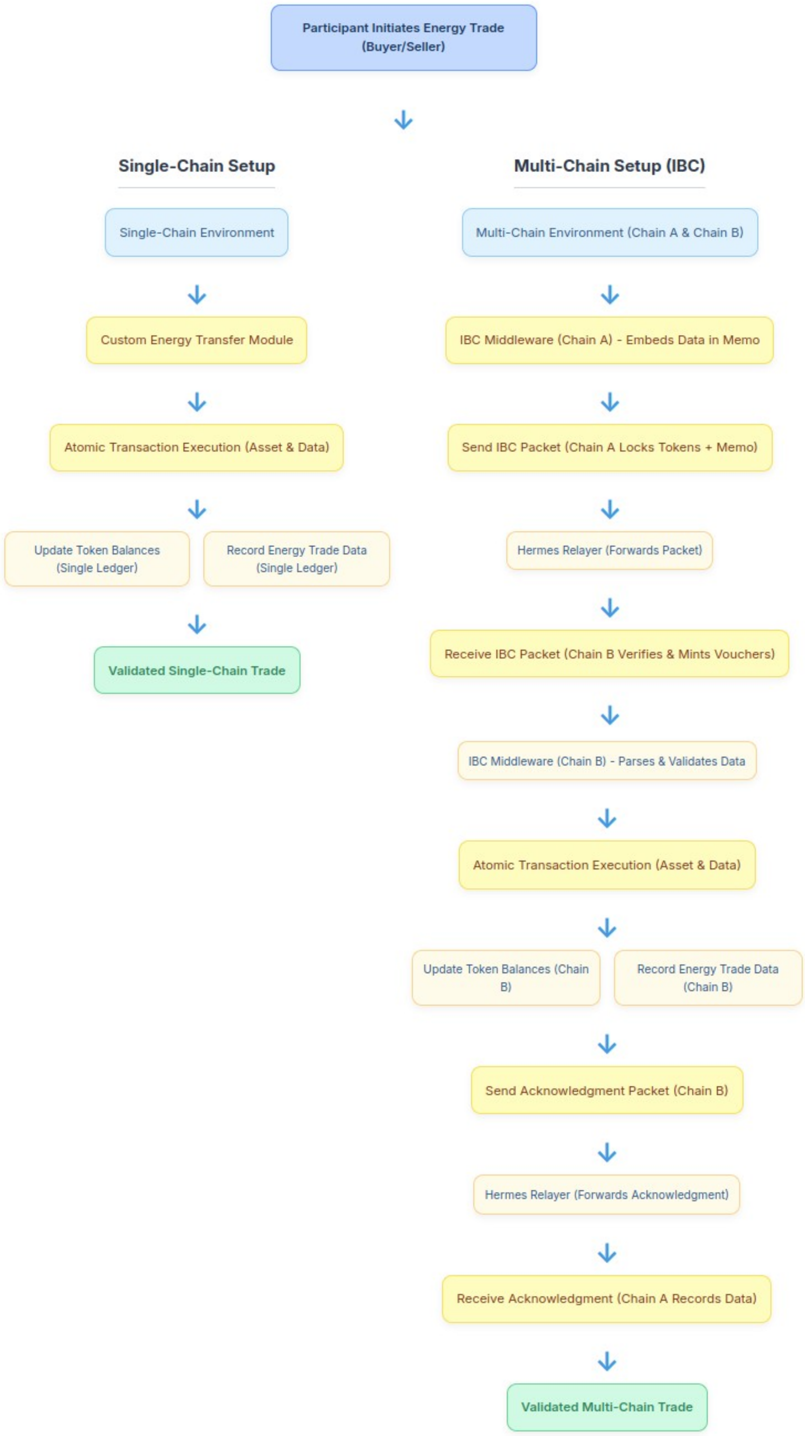
Cross-chain protocols like Cosmos IBC and Polkadot parachains are also being explored for energy systems (Choobineh et al., 2023; Dinesha & Patil, 2023). However, adapting these tools for real-world energy grids is still unproven. For instance, aligning governance rules between blockchains remains a hurdle (Dinesha & Patil, 2023). Many proposed solutions, like the BSMG framework (Dinesha & Balachandra, 2022), lack real-world testing. Most energy projects still rely on single-blockchain setups, limiting their flexibility (Dinesha & Patil, 2023).

# 3. Methodology/Experiment Implementation

The methodology of this research employs a comparative experimental framework to evaluate the performance and feasibility of peer-to-peer energy trading systems within single-chain and multi-chain blockchain architectures, representing single-microgrid and multi-microgrid setups. Central to this investigation is the examination of atomic transactions involving both *data* and *asset transfers* under two distinct setups: (1) a single-chain environment, where transactions occur on a unified blockchain, and (2) a multi-chain environment, where transactions span two interconnected blockchains via the IBC protocol. Asset transfers adhere to the ICS-20 standard, a token transfer specification enabling fungible token interoperability across Cosmos-based chains (Cosmos, 2025c), while energy-related data, including buyer/seller identifiers, energy quantity (kWh), pricing, token amounts, and source/destination chain metadata (in cross-chain cases), is embedded within transaction packets. To ensure atomicity and consistency, transactions are only valid if *both* asset and data transfers succeed.

For the single-chain setup, a custom module executes combined transfers on a single ledger. In cross-chain scenarios, IBC packets relayed via the Hermes relayer tool facilitate transfers, with energy data encapsulated in the packet's memo field. This design ensures a single packet per transfer, employing IBC's inherent transaction integrity mechanisms and packet lifecycle stages (send, relay, and confirm (Cosmos, 2025b)), ensuring that transfers either execute fully or revert entirely, with no partial state changes. Both setups undergo simulations with scalable variables, account numbers and transaction volumes, to measure gas consumption, enabling quantitative comparison. The conceptual workflow is illustrated in *Figure 1*.

The primary objective focuses on identifying the actual technical feasibility of deploying interoperable blockchain systems in energy microgrids, as well as possible performance disparities (e.g., gas cost) between single-chain and multi-chain architectures and assessing the viability of IBC for decentralized energy markets. Additionally, the comparative analysis of gas consumption between single-chain and multi-chain setups serves as a foundational dataset for subsequent economic analysis. By quantifying the resource overhead of IBC transfers, the results will show potential cost disadvantages inherent to cross-chain architectures, such as relayer fees or cross-chain gas pricing models.


Participant Initiates Energy Trade (Buyer/Seller)
Single-Chain Setup
Multi-Chain Setup (IBC)
Single-Chain Environment
Custom Energy Transfer Module
Atomic Transaction Execution (Asset & Data)
Update Token Balances (Single Ledger)
Record Energy Trade Data (Single Ledger)
Validated Single-Chain Trade
Multi-Chain Environment (Chain A & Chain B)
IBC Middleware (Chain A) - Embeds Data in Memo
Send IBC Packet (Chain A Locks Tokens + Memo)
Hermes Relayer (Forwards Packet)
Receive IBC Packet (Chain B Verifies & Mints Vouchers)
IBC Middleware (Chain B) - Parses & Validates Data
Atomic Transaction Execution (Asset & Data)
Update Token Balances (Chain B)
Record Energy Trade Data (Chain B)
Send Acknowledgment Packet (Chain B)
Hermes Relayer (Forwards Acknowledgment)
Receive Acknowledgment (Chain A Records Data)
Validated Multi-Chain Trade

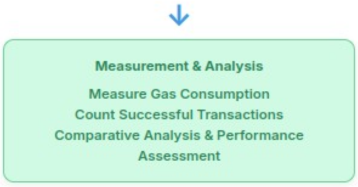



*Figure 1: Illustration of Simulation Workflow, Single-Chain vs Multi-Chain Setup.*

## 3.1. Setup

The experimental setup involves two distinct blockchain configurations, single-chain and multi-chain, both scaffolded using the *Ignite CLI* framework, a toolchain for building Cosmos SDK-based blockchains. Ignite CLI standardizes chain development by automating boilerplate code generation, ensuring identical foundational parameters (e.g., consensus protocol, block time, governance modules) across all chains. Each chain employs the Tendermint consensus algorithm with a fixed block time of 1 second and a minimal validator set (1 validator per chain) to prioritize simplicity and reproducibility. By maintaining uniformity in chain specifications, such as gas limits, staking parameters, and module configurations, the setup minimizes variables that could distort performance comparisons between single-chain and multi-chain architectures.

**Single-Chain Configuration:** For on-chain energy trading, a custom module was developed to handle atomic *data* and *asset transfers*. This module defines an *EnergyTransfer* transaction type containing the following fields:

- *buyer* (sender address)
- *seller* (recipient address),
- *energy_amount* (kWh traded),
- *price* (token/kWh rate),
- *token_amount* (ICS-20 tokens to transfer).

A *create-energytransfer* function executes the transaction, deducting the specified *token_amount* from the buyer's account, crediting it to the seller, and simultaneously recording the energy trade metadata (e.g., price, kWh) on-chain. If either the token transfer or data recording fails, the entire transaction is reverted.

**Multi-Chain Configuration:** For cross-chain transactions, an *IBC middleware* was implemented atop the Cosmos SDK's native *ibc-transfer* module, which facilitates ICS-20 token transfers. In Cosmos, an IBC middleware is a modular layer that intercepts and processes IBC packets before they reach core modules, enabling custom logic (e.g., parsing metadata) without modifying the underlying protocol. Here, the middleware extracts energy data from the memo field of ICS-20 token transfers, a free-form text field often used for attaching transaction-specific metadata. The memo field is structured as a JSON object containing:

- *amount* (kWh traded)
- *price* (token/kWh rate)
- *buyer* (sender address)
- *buyerchain* (chain-id of chain where *buyer's* account exists)

- *seller* (receiver address)
- *sellerchain* (chain-id of chain where *seller's* account exists)

When a user initiates a cross-chain transfer from Chain A to Chain B, the middleware on Chain A injects the energy metadata into the memo field. Upon receipt, the middleware on Chain B parses this data, validates it, and records the energy trade details on Chain B's ledger. If successful Chain B sends an acknowledgment to Chain A which middleware then records the energy trade details on Chain A's ledger. The ICS-20 token transfer itself is handled by the native ibc-transfer module, which follows IBC's packet lifecycle:

1. *Send Packet:* Chain A locks tokens and emits a packet containing the memo field.
2. *Relay Packet:* The Hermes relayer detects and forwards the packet to Chain B.
3. *Receive Packet:* Chain B verifies the packet, mints vouchers for the tokens, and processes the memo data via the middleware.
4. *Acknowledge/Timeout:* If successful, Chain B returns an acknowledgment to Chain A, which then processes the memo data via the middleware and finalizes the transfer. If Chain B rejects the packet or the relayer detects a timeout, tokens are refunded to the sender.

If either the token transfer fails on Chain B or the metadata processing encounters an error, the middleware triggers a rollback, reverting all state changes. Upon success, the energy trade entry is persisted on both chains, ensuring synchronized records.

**Simulation Initialization:** All chains were initialized with pre-funded accounts to enable transaction execution. For scalability testing, three participant scales were simulated:

- *4 participants:* Single-chain (4 accounts) vs. multi-chain (2 accounts per chain).
- *10 participants:* Single-chain (10 accounts) vs. multi-chain (5 accounts per chain).
- *20 participants:* Single-chain (20 accounts) vs. multi-chain (10 accounts per chain).

A Python script generated synthetic energy trade data (randomized kWh, price, token amounts) and executed transactions sequentially. For each simulation **1000 transactions** were generated and executed. The script interfaced with chain nodes via REST endpoints, submitting transactions, monitoring inclusion in blocks, and logging metrics (gas consumed, success/failure rates). After each simulation it will confirm that token balances and energy trade records matched expected post-transaction states.

## 3.2. Tools

The experimental framework relies on a suite of specialized tools to implement, deploy, and evaluate the blockchain architectures and interoperability mechanisms. Below is a detailed overview of the tools and their roles in this study:

**Ignite CLI (v28.8.2):** Ignite CLI (Ignite, 2025) is a developer toolkit for scaffolding, building, and deploying Cosmos SDK-based blockchains. It automates boilerplate code generation, enabling rapid chain initialization with preconfigured modules (e.g., staking, governance) and standardized consensus parameters. For this experiment, Ignite CLI was used to scaffold both single-chain and multi-chain configurations, ensuring identical foundational setups (e.g., Tendermint consensus, default gas limits) across all chains. This consistency minimizes variability, ensuring fair comparisons between single-chain and cross-chain transaction performance.

**Cosmos SDK (v0.50.13) and Go (v1.23.8):** The Cosmos SDK (Cosmos, 2025a) is a modular framework for building application-specific blockchains, offering prebuilt modules for core functionalities like token transfers and governance. Custom modules, such as the *EnergyTransfer* transaction handler for single-chain atomic transfers and the IBC middleware for cross-chain data processing, were developed using Go, a statically typed programming language optimized for performance-critical blockchain logic. The Cosmos SDK's modularity allowed seamless integration of custom transaction types and middleware layers while leveraging the SDK's native security and consensus mechanisms.

**IBC-Go (v8.5.1):** IBC-Go (Cosmos, 2025b) is the canonical implementation of the IBC protocol for the Cosmos SDK. It provides standardized modules (e.g., *ibc-transfer* for ICS-20 token transfers) and interfaces for building cross-chain applications. In this experiment, IBC-Go facilitated the creation of IBC-enabled channels between chains, managing packet encoding/decoding, proof verification, and state machine synchronization. The middleware layer built atop IBC-Go extended the protocol to parse and validate energy metadata embedded in token transfer packets.

**Hermes Relayer (v1.10.5):** Hermes (Informal Systems, 2025) is a production-grade IBC relayer that monitors and forwards IBC packets between chains. It detects pending packets on source chains, submits them to destination chains, and handles acknowledgments or timeouts. For cross-chain simulations, Hermes was configured to relay energy token transfers and metadata between the two test chains, ensuring atomicity by enforcing IBC's packet lifecycle (send, relay, receive, acknowledge).

**Python (v3.12.8):** Python served as the orchestration layer for simulations to automate transaction generation, submission, and metric collection. A custom Python script generated synthetic energy trading data (randomized kWh, price, token amounts), executed sequential transactions across test scenarios, and logged performance metrics (gas consumption, success rates).

**System Configuration:** All blockchains and tools were deployed locally on a Lenovo Yoga Slim 7 laptop equipped with an AMD Ryzen 5 4500U processor (6 cores), 7.1GB available RAM, and a 512GB SSD, running Linux Mint 22.1 Cinnamon. Each blockchain operated in development mode as a single-node network, with chains in the multi-chain setup assigned unique ports (e.g., Chain A: port 26657, Chain B: port 26658) to avoid conflicts. Resource constraints (e.g., limited RAM) were mitigated by sequential execution of simulations and disabling non-essential background processes.

## 3.3. Metrics

To quantitatively evaluate the performance and reliability of single-chain and multi-chain energy trading architectures, two core metrics were systematically collected during simulations:

**Gas Consumption**: In blockchain systems, gas represents the computational resources required to execute operations, with users paying fees proportional to gas usage. For each transaction, the gas consumed (measured in gas units) was extracted by querying the blockchain's REST API using the transaction hash, enabling calculation of *average*, *minimum*, *maximum*, and *standard deviation* values. Gas consumption directly correlates with operational costs, making it a key indicator of economic efficiency, particularly when comparing the overhead of cross-chain IBC transfers versus on-chain transactions.

**Successful Transaction Count**: The absolute number of transactions that completed atomically (i.e., both asset and data transfers succeeded) was tracked to assess system reliability.

# 4. Results and Discussion

## 4.1. Verification of Single-Chain Setup

Prior to evaluating the gas consumption (simulation scenarios) of on-chain transactions, the functional correctness of the single-chain setup was validated. This verification encompassed three phases: (1) blockchain initialization and account creation, (2) execution of a test transaction, and (3) confirmation of ledger integrity and asset transfers.

**Chain Initialization and Account Configuration:** The Cosmos-based blockchain was instantiated using Ignite CLI, with predefined parameters allocating initial token balances to two test accounts: *User_1* (100,000 tokens) and *User_2* (200,000 tokens). As depicted in *Figure 2* and *Figure 3*, the chain startup logs confirm successful genesis block creation and node synchronization. While the initial balances are not explicitly displayed in the runtime logs, they were programmatically embedded in the chain's genesis configuration.

```
[IGNITE]
[IGNITE] ✔ Added account user_1 with address cosmos1x2ww3ds9gfv7ay7qad33d8d4stmv43wjczl9es and mnemonic:
[IGNITE] rookie soft grass zero drip consider meadow column dwarf monster stadium dynamic alter wreck emotion rotate aco
ustic crowd order fancy evoke dignity empty notice
[IGNITE]
[IGNITE] ✔ Added account user_2 with address cosmos1hnlcwmcc59m0nmg4my20ngentxhmxskxpnre53 and mnemonic:
[IGNITE] deliver squirrel lunar vocal outdoor require item gas idle pony wonder raven casino act solve stem devote pictu
re soda famous label degree happy fragile
```

*Figure 2: Logs of successful account initialization for the single-chain setup*

```
[IGNITE] 🌍 Tendermint node: http://0.0.0.0:26657
[IGNITE] 🌍 Blockchain API: http://0.0.0.0:1317
[IGNITE] 🌍 Token faucet: http://0.0.0.0:4500
[IGNITE] ⋆ Data directory: /home/jannik/.singlegrid
[IGNITE] ⋆ App binary: /home/jannik/go/bin/singlegridd
```

*Figure 3: Logs of successful chain initialization for the single-chain setup*

**On-Chain Transaction Execution:** A peer-to-peer energy transfer transaction was initiated to validate the chain's operational logic. *User_1* submitted a request to purchase 40 energy units from *User_2* at a rate of 50 tokens per unit, resulting in a total transfer of 70 tokens. The transaction, illustrated in *Figure 4*, returned a success code (code: 0), indicating its inclusion in a validated block.

```
jannik@jannik-yoga-slim-7:~/NOVA_IMS/Master_Thesis/Code/singlegrid$ singlegridd tx singletransfer create-singleenergytra
nsfer cosmos1x2ww3ds9gfv7ay7qad33d8d4stmv43wjczl9es cosmos1hnlcwmcc59m0nmg4my20ngentxhmxskxpnre53 40 50 70token --from c
osmos1x2ww3ds9gfv7ay7qad33d8d4stmv43wjczl9es
```

*Figure 4: Command for energy transfer on-chain in single-chain setup*

**Ledger and Balance Validation:** To verify the transaction's atomicity and state consistency, the blockchain ledger was queried for energy transfer records. As shown in *Figure 5*, the query returned a structured entry detailing the energy quantity (40 units), price (50 tokens/unit), sender (buyer) and receiver (seller) addresses, and the amount of tokens transferred.

```
jannik@jannik-yoga-slim-7:~/NOVA_IMS/Master_Thesis/Code/singlegrid$ singlegridd query singletransfer list-singleenergytr
ansfer
Singleenergytransfer:
- amount: "40"
  buyer: cosmos1x2ww3ds9gfv7ay7qad33d8d4stmv43wjczl9es
  creator: cosmos1x2ww3ds9gfv7ay7qad33d8d4stmv43wjczl9es
  price: "50"
  seller: cosmos1hnlcwmcc59m0nmg4my20ngentxhmxskxpnre53
  transfer: 70token
pagination:
  total: "1"
```

*Figure 5: Response of query for energy transfers records on-chain in single-chain setup*

Subsequently, token balance updates were audited. *Figure 6* demonstrates that *User_1*'s balance decreased by 70 tokens (from 100,000 to 99,930), while *User_2*'s balance increased commensurately (from 200,000 to 200,070).

```
jannik@jannik-yoga-slim-7:~/NOVA_IMS/Master_Thesis/Code/singlegrid$ singlegridd query bank spendable-balances cosmos1x2w
w3ds9gfv7ay7qad33d8d4stmv43wjczl9es
balances:
- amount: "99930"
  denom: token
pagination:
  total: "1"
jannik@jannik-yoga-slim-7:~/NOVA_IMS/Master_Thesis/Code/singlegrid$ singlegridd query bank spendable-balances cosmos1hnl
cwmcc59m0nmg4my20ngentxhmxskxpnre53
balances:
- amount: "200070"
  denom: token
pagination:
  total: "1"
```

*Figure 6: Response of queries for user account balances in single-chain setup*

The single-chain setup operates as designed: accounts initialize with configured balances, transactions are processed atomically, and both energy trade metadata and token balances are accurately reflected in the ledger. The next subsection evaluates the cross-chain setup's interoperability via IBC and the Hermes relayer.

## 4.2. Verification of Multi-Chain Setup

The multi-chain setup verification process included four stages: (1) independent chain initialization (grid_one and grid_two), (2) IBC channel establishment, (3) cross-chain transaction execution, and (4) multi-chain ledger and balance reconciliation.

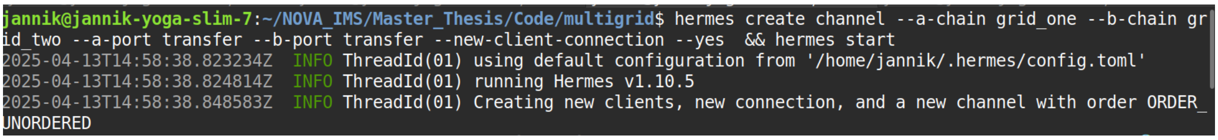
**Independent Chain Initialization:** Both *grid_one* (Chain 1) and *grid_two* (Chain 2) were instantiated using Ignite CLI with distinct genesis configurations. As shown in *Figure 7, 8, 9, 10, 11* the startup logs confirm successful initialization of accounts and network readiness for both chains. *User_1* on *grid_one* was allocated 100,000 tokens, while *User_3* on *grid_two* received 300,000 tokens, as defined in their respective genesis files. Although initial balances are not explicitly visible in runtime logs, subsequent balance queries (discussed later) validate the deterministic initialization.

```
[IGNITE]
[IGNITE] ✔ Added account user_1 with address cosmos1x2ww3ds9gfv7ay7qad33d8d4stmv43wjczl9es and mnemonic:
[IGNITE] rookie soft grass zero drip consider meadow column dwarf monster stadium dynamic alter wreck emotion rotate aco
ustic crowd order fancy evoke dignity empty notice
```

*Figure 7: Logs of  successful account initialization for chain ‘grid_one’ in the multi-chain setup*

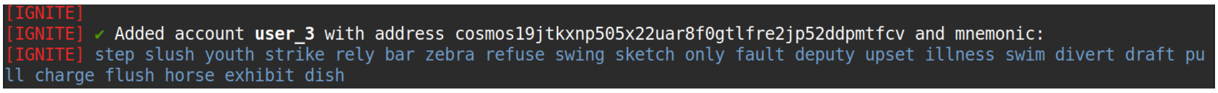
```
[IGNITE] 🌍 Tendermint node: http://0.0.0.0:26657
[IGNITE] 🌍 Blockchain API: http://0.0.0.0:1317
[IGNITE] 🌍 Token faucet: http://0.0.0.0:4500
[IGNITE] · Data directory: /home/jannik/.grid_one
[IGNITE] · App binary: /home/jannik/go/bin/multigridd
```

*Figure 8: Logs of successful chain initialization of chain 'grid_one' in the multi-chain setup*



```
jannik@jannik-yoga-slim-7:~/NOVA_IMS/Master_Thesis/Code/multigrid$ hermes create channel --a-chain grid_one --b-chain gr
id_two --a-port transfer --b-port transfer --new-client-connection --yes  && hermes start
2025-04-13T14:58:38.823234Z  INFO ThreadId(01) using default configuration from '/home/jannik/.hermes/config.toml'
2025-04-13T14:58:38.824814Z  INFO ThreadId(01) running Hermes v1.10.5
2025-04-13T14:58:38.848583Z  INFO ThreadId(01) Creating new clients, new connection, and a new channel with order ORDER_
UNORDERED
```

*Figure 9: Command and first logs of channel creation between 'grid_one' and 'grid_two'*



```
[IGNITE]
[IGNITE] ✔ Added account user_3 with address cosmos19jtkxnp505x22uar8f0gtlfre2jp52ddpmtfcv and mnemonic:
[IGNITE] step slush youth strike rely bar zebra refuse swing sketch only fault deputy upset illness swim divert draft pu
ll charge flush horse exhibit dish
```

*Figure 10: Logs of  successful account initialization for chain ‘grid_two’ in the multi-chain setup*

```
[IGNITE] 🌍 Tendermint node: http://0.0.0.0:26666
[IGNITE] 🌍 Blockchain API: http://0.0.0.0:1318
[IGNITE] 🌍 Token faucet: http://0.0.0.0:4501
[IGNITE] · Data directory: /home/jannik/.grid_two
[IGNITE] · App binary: /home/jannik/go/bin/multigridd
```

*Figure 11: Logs of successful chain initialization of chain 'grid_two' in the multi-grid setup*

**IBC Channel Establishment:** A bidirectional IBC channel was created between *grid_one* and *grid_two* using the Hermes relayer. The command output in *Figure 12* confirms the creation of a channel (*channel-0*) on the *transfer* port, with a final state of *OPEN*. This channel will be used for packet relaying and trustless communication between the chains. The Hermes logs in *Figure 9* further verify the handshake completion, confirming the channel’s readiness for cross-chain operations.

```
2025-04-13T14:59:39.611164Z  INFO ThreadId(01) # Chain: grid_one
  - Client: 07-tendermint-0
    * Connection: connection-0
      | State: OPEN
      | Counterparty state: OPEN
      + Channel: channel-0
        | Port: transfer
        | State: OPEN
        | Counterparty: channel-0
# Chain: grid_two
  - Client: 07-tendermint-0
    * Connection: connection-0
      | State: OPEN
      | Counterparty state: OPEN
      + Channel: channel-0
        | Port: transfer
        | State: OPEN
        | Counterparty: channel-0
```

*Figure 12: Logs of successful channel creation between 'grid_one' and 'grid_two'*

**Cross-Chain Transaction Execution:** A cross-chain energy trade was initiated, where *User_1* (Chain 1) purchased 40 energy units from *User_3* (Chain 2) at price of 37 units, resulting in a 20-token payment. The transaction command *Figure 13* included metadata in its memo field, specifying buyer/seller addresses, energy quantities, and chain identifiers. The transaction returned a success code (*code: 0*), indicating successful execution.

```
jannik@jannik-yoga-slim-7:~/NOVA_IMS/Master_Thesis/Code/multigrid$ multigridd tx ibc-transfer transfer transfer channel-
0 cosmos19jtkxnp505x22uar8f0gtlfre2jp52ddpmtfcv 20token --from cosmos1x2ww3ds9gfv7ay7qad33d8d4stmv43wjczl9es --chain-id
grid_one --home ~/.grid_one --node "tcp://localhost:26657" --memo  '{"amount": "40", "price": "37", "buyerchain": "grid_
one", "sellerchain": "grid_two"}'
```

*Figure 13: Command for cross-chain energy transfer in the multi-chain setup*

**Ledger and Balance Verification:** To verify atomicity, both chains' ledgers were queried for energy transfer records. *Figure 14 (Chain: grid_one)* and *Figure 15 (Chain: grid_two)* show identical entries for the transaction, including energy quantities, pricing, and participant addresses and their corresponding chains.

```
jannik@jannik-yoga-slim-7:~/NOVA_IMS/Master_Thesis/Code/multigrid$ multigridd query multitransfer list-multienergytransf
er --node tcp://localhost:26666
Multienergytransfer:
- amount: "40"
  buyer: cosmos1x2ww3ds9gfv7ay7qad33d8d4stmv43wjczl9es
  buyerchain: grid_one
  price: "37"
  seller: cosmos19jtkxnp505x22uar8f0gtlfre2jp52ddpmtfcv
  sellerchain: grid_two
pagination:
  total: "1"
```

*Figure 14: Response of query for energy transfers records on chain 'grid_two' in multi-chain setup*

```
jannik@jannik-yoga-slim-7:~/NOVA_IMS/Master_Thesis/Code/multigrid$ multigridd query multitransfer list-multienergytransf
er --node tcp://localhost:26657
Multienergytransfer:
- amount: "40"
  buyer: cosmos1x2ww3ds9gfv7ay7qad33d8d4stmv43wjczl9es
  buyerchain: grid_one
  price: "37"
  seller: cosmos19jtkxnp505x22uar8f0gtlfre2jp52ddpmtfcv
  sellerchain: grid_two
pagination:
  total: "1"
```

*Figure 15: Response of query for energy transfers records on chain 'grid_one' in multi-chain setup*

Token balances were then audited to confirm cross-chain asset transfers. Querying *User_1*'s address on *grid_one Figure 16* revealed a 20-token deduction (100,000 → 99,980), while *User_3*'s address on *grid_two Figure 17* reflected a 20-token increase of IBC-denominated tokens. Notably, the received tokens on *grid_two* are represented as IBC-denominated tokens (*ibc/...*), which are cryptographic vouchers proving the escrowed origin of assets from *grid_one*. These vouchers can later be redeemed for native tokens through a reverse IBC transaction.

```
jannik@jannik-yoga-slim-7:~/NOVA_IMS/Master_Thesis/Code/multigrid$ multigridd query bank spendable-balances cosmos1x2ww3
ds9gfv7ay7qad33d8d4stmv43wjczl9es --node tcp://localhost:26657
balances:
- amount: "99980"
  denom: token
pagination:
  total: "1"
```

*Figure 16: Response of query for account balance of user_1 on chain 'grid_one'*

```
jannik@jannik-yoga-slim-7:~/NOVA_IMS/Master_Thesis/Code/multigrid$ multigridd query bank spendable-balances cosmos19jtkx
np505x22uar8f0gtlfre2jp52ddpmtfcv --node tcp://localhost:26666
balances:
- amount: "20"
  denom: ibc/B5CB286F69D48B2C4F6F8D8CF59011C40590DCF8A91617A5FBA9FF0A7B21307F
- amount: "300000"
  denom: token
pagination:
  total: "2"
```

*Figure 17: Response of query for account balance of user_3 on chain 'grid_two'*

The multi-chain setup operates as intended: IBC channels relay packets reliably, cross-chain transactions atomically update both ledgers, and asset transfers are securely represented via IBC tokens.

## 4.3. Comparative Performance Analysis of On-Chain and Cross-Chain Transactions

Following the functional verification of both blockchain architectures, each setup was tested in three different rounds executing each round at each chain-setup 1000 transactions, as stated in the Methodology section previously. The results of those simulations are presented in this section.

**Transaction Success Rates:** Both architectures demonstrated flawless reliability across all simulation scenarios. As shown in *Table 2*, 100% of transactions (1,000 per round) completed atomically in all test cases, regardless of participant scale (4, 10, or 20 users) or architecture type.

*Table 2: Successful transaction rate, single-chain setup vs. multi-chain setup*

| Successful Transaction Rate | Single-Chain | Multi-Chain |
|---|---|---|
| Round 1 (4 User) | 100% | 100% |
| Round 2 (10 User) | 100% | 100% |
| Round 3 (20 User) | 100% | 100% |

**Gas Consumption Patterns:** Gas usage analysis reveals a consistent performance disparity between architectures. As illustrated in *Figure 18*, cross-chain transactions consumed approximately 78,000 gas units on average, 24% higher than single-chain transactions (60,000 gas units). This overhead stems from IBC's multi-step packet lifecycle (send, relay, receive, acknowledge), which introduces additional computational steps compared to single-chain operations.

Notably, the participant count influenced gas variability more than absolute consumption. While average gas usage remained stable within each architecture (±0.5% variation across scales), multi-chain transactions exhibited wider fluctuations. For instance, at 20 users, multi-chain gas consumption ranged from 77,964 to 105,070 units (27,106-unit spread), compared to single-chain's 59,959–73,449 range (13,490-unit spread).

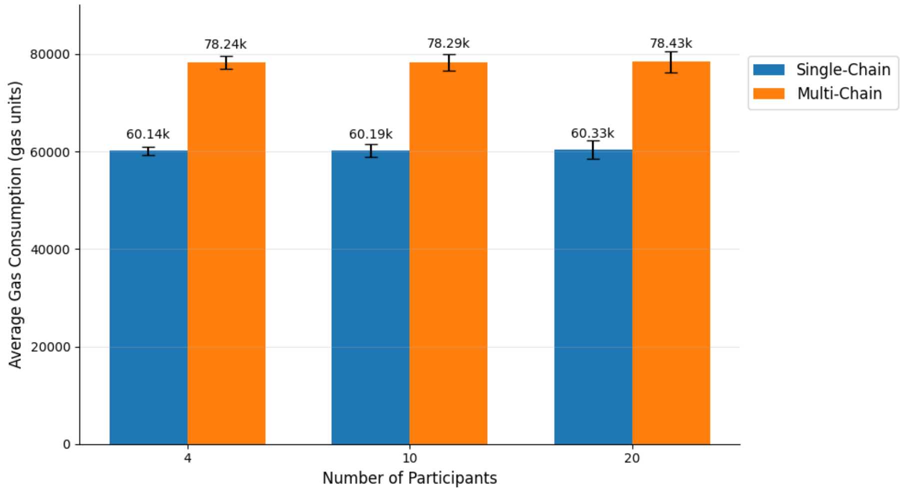



*Figure 18: Comparative average gas consumption between single-chain and multi-chain setup. Error bars denote one standard deviation.*

**Performance Variability:** Standard deviation metrics quantify this growing variability (*Table 3*). In single-chain setups, standard deviation increased by 122% (842 to 1,871 units) as users scaled from 4 to 20, while multi-chain deviations rose by 59% (1,340 to 2,129 units). This divergence suggests that cross-chain architectures inherently absorb more operational noise, likely due to:

1. *Relayer Dynamics:* Hermes' packet routing introduces non-deterministic delays.
2. *IBC Handshakes:* Cross-chain proof verification adds variable processing time.
3. *Middleware Overhead:* Metadata parsing/validation scales with transaction complexity.

While relative differences are high, absolute differences still seem rather small compared to the actual gas consumption.

*Table 3: Gas consumption metrics for on-chain and cross-chain transactions across participant scales*

| *Metric* | *4 Users Single* | *4 Users Multi* | *10 Users Single* | *10 Users Multi* | *20 Users Single* | *20 Users Multi* |
|---|---|---|---|---|---|---|
| *Avg Gas* | 60 142 | 78 238 | 60 192 | 78 293 | 60 326 | 78 429 |
| *Min Gas* | 59 929 | 77 906 | 59 936 | 77 902 | 59 959 | 77 964 |
| *Max Gas* | 73 449 | 105 058 | 73 449 | 105 058 | 73 449 | 105 070 |
| *Std Dev Gas* | 842 | 1 340 | 1 330 | 1 683 | 1 871 | 2 129 |

## 4.4. Analyzing Operational Cost Differences

To evaluate the operational cost disparities between single-chain and multi-chain architectures in the Cosmos ecosystem, it is essential to quantify the gas consumed during transactions in fiat terms (USD). This conversion depends on two variables: the *gas price* (denominated in native tokens) and the *token price* (USD value of the native token). This analysis focuses on two prominent Cosmos-based blockchains: *Cosmos Hub (*Native Token: *ATOM)* and *Osmosis (*Native Token: *OSMO)*.

In blockchain networks, gas prices represent the fee users pay to validators for processing transactions. These fees compensate validators for computational resources and incentivize network security. Gas prices are dynamic and influenced by network demand: during peak usage, validators prioritize transactions offering higher fees, accelerating block inclusion. Consequently, users may opt to pay elevated gas prices to ensure timely execution. Validators on Cosmos Hub and Osmosis enforce minimum gas price thresholds, which serve as baseline recommendations but can be adjusted upward depending on transactional urgency.

For this study, two gas price scenarios per network are examined (*Table 4*):

1. *Baseline scenario*: Adheres to the minimum recommended gas price.
2. *Elevated scenario*: Simulating congested network conditions.

Token prices (ATOM and OSMO) and gas price recommendations of each scenario are sourced from (Mintscan, 2025).

*Table 4: Gas price and token value for Cosmos Hub and Osmosis blockchains*

| Chain | Scenario | Gas Price | Token Value |
|---|---|---|---|
| Cosmos Hub | Baseline | 0.005 uatom/gas | $4.15/ATOM |
| Cosmos Hub | Elevated | 0.025 uatom/gas | $4.15/ATOM |
| Osmosis | Baseline | 0.025 uosmo/gas | $0.22/OSMO |
| Osmosis | Elevated | 0.040 uosmo/gas | $0.22/OSMO |

Notes:

- µATOM = micro-ATOM (1 ATOM = 1,000,000 µATOM)
- µOSMO = micro-OSMO (1 OSMO = 1,000,000 µOSMO)

**Cost Calculation Methodology:** For each architecture (single-chain/multi-chain), average gas consumption was derived ((1), (2)) from the previous simulation results (*Table 3*):

- Single-Chain: $Avg\,Gas = \frac{60{,}142 + 60{,}192 + 60{,}326}{3} = 60{,}220$ (1)
- Multi-Chain: $Avg\,Gas = \frac{78{,}238 + 78{,}293 + 78{,}430}{3} = 78{,}320$ (2)

Transaction costs in USD are calculated by multiplying average gas consumption by the gas price (token units) and the token's USD value, like in equation (3):

$$Cost(USD) = \frac{Gas\,Used(gas) * Gas\,Price\left(\frac{\mu Token}{gas}\right)}{1{,}000{,}000\left(\frac{\mu Token}{Token}\right)} * Value(USD) \quad (3)$$

The computed costs for both architectures (single-chain vs. multi-chain) considering each network, and its scenarios are summarized in *Table 5:*

*Table 5: Transaction cost results, single-chain vs. multi-chain setup*

| Chain | Scenario | Single-Chain Cost | Multi-Chain Cost |
|---|---|---|---|
| Cosmos Hub | Baseline | $0.00125 | $0.00163 |
| Cosmos Hub | Elevated | $0.00625 | $0.00813 |
| Osmosis | Baseline | $0.000331 | $0.000431 |
| Osmosis | Elevated | $0.000529 | $0.000689 |

The results of *Table 5* show that multi-chain transactions are consistently more expensive than single-chain operations, with baseline costs rising from $0.00125 to $0.00163 (30%↑) on Cosmos Hub and $0.000331 to $0.000431 (30%↑) on Osmosis. For elevated gas prices Cosmos Hub multi-chain costs reach $0.00813 ($0.000689 (30%↑). Despite these increases, absolute costs remain extremely low, with even the highest multi-chain transaction costing less than $0.01.

## 4.5. Contextualizing Transaction Costs with Energy Prices

To evaluate the economic impact of on-chain and cross-chain transactions, fees will be benchmarked against real-world energy prices. As energy price Portugal's June 2024 average household electricity price excluding taxes of 0.1823 €/kWh (countryeconomy.com, 2025) which equals 0.21 USD/kWh (Date: 19.04.2025) will be considered. Now assuming a energy purchase of 10 kWh the cost-to-value ratio of each transaction type within our two example networks and its two scenarios will be compared. The cost-to-value ratio will be calculated as follows:

$$cost\ value\ ratio = \frac{Transaction\ Cost}{Energy\ Amount * Energy\ Price} * 100 \quad (4)$$

The computed cost-value-ratios (4) for both architectures (single-chain vs. multi-chain) considering each network, and its scenarios are summarized in *Table 6:*

*Table 6: Cost-value-ratio results, single-chain vs. multi-chain setup*

| Chain | Scenario | Energy Amount * Energy Price | Single-Chain cost-value-ratio | Multi-Chain cost-value-ratio |
|---|---|---|---|---|
| Cosmos Hub | Baseline | $2.10 | 0.059 % | 0.078 % |
| Cosmos Hub | Elevated | $2.10 | 0.298 % | 0.387 % |
| Osmosis | Baseline | $2.10 | 0.016 % | 0.021 % |
| Osmosis | Elevated | $2.10 | 0.025 % | 0.033 % |

The results confirm those of previous analysis. The Multi-Chain cost-value-ratios are slightly higher than Single Chain cost-value-ratios, due to their higher costs. Despite these increases, all cost-value-ratios remain rather small in absolute values. The highest cost-value-ratio appear for the Cosmos Hub elevated scenario with a ratio of 0.387 % of total transaction cost.

The consistent 100% transaction success rate validates the underlying blockchain technology as ready for real-world application in peer-to-peer energy trading. This should encourage regulators to prioritize developing supportive legal and regulatory frameworks that enable decentralized energy markets, rather than focusing on the technology's core viability.
From a practical perspective, while multi-chain transactions incur a slight increase in gas consumption, their absolute costs remain negligible (under $0.01), suggesting that this overhead isn't an economic barrier for adoption. This means the choice between single-chain and multi-chain systems for energy trading should be driven by the need for broader market connectivity and scalability across diverse energy ecosystems, not by marginal transaction fee differences. The focus for implementers should shift towards integrating these systems with existing grid infrastructure, enhancing user experience, and navigating the remaining regulatory hurdles to unlock the full potential of decentralized energy markets.

# 5. Conclusion

This study explored how blockchain interoperability can support peer-to-peer energy trading between connected microgrids, comparing the performance of single-chain and multi-chain setups within the Cosmos ecosystem. The experiments confirmed that both on-chain (single-chain) and cross-chain (multi-chain) transactions can enable asset and data transfers, but with notable differences in efficiency. Cross-chain transactions consumed approximately 24% more gas than on-chain transactions. However, when converted to real-world costs, this difference remained minimal: the most expensive cross-chain transaction totaled \$0.00813, compared to \$0.00163 for a comparable on-chain transaction, based on Cosmos Hub's gas pricing and token valuation.

These findings highlight a critical trade-off: while cross-chain architectures introduce modest cost overheads, they unlock decentralized flexibility by enabling interactions across independent microgrid networks. The study also provides a practical framework for evaluating blockchain performance in energy applications, helping stakeholders balance scalability, cost, and interoperability needs.

Several limitations must be acknowledged. The simulations relied on simplified test networks, which lacked real-world security measures, scalability features, and governance structures. Additionally, synthetic energy data was used instead of empirical datasets from operational microgrids, and the analysis was restricted to Cosmos-based chains. These constraints limit the generalizability of the results to more complex, heterogeneous blockchain ecosystems.

Despite these challenges, the work underscores the promise of blockchain interoperability in building resilient energy systems. Future efforts should address scalability bottlenecks, integrate real-world energy data, and expand testing to diverse blockchain platforms (e.g., Ethereum, Hyperledger). By bridging these gaps, decentralized solutions could transform energy markets, enabling secure, transparent, and efficient peer-to-peer trading while supporting global sustainability goals.

# 6. Limitations and Future Work

This study demonstrates the feasibility of employing multiple Cosmos-based blockchains for asset and data exchange in peer-to-peer energy trading across interconnected microgrids. However, several limitations inherent to the experimental setup warrant acknowledgment, alongside opportunities for future research.

The blockchains deployed in this work were intentionally simplified to prioritize functionality over robustness. All simulations utilized test networks lacking production-grade security, scalability, or governance mechanisms. Furthermore, the chains were deployed on a single physical machine with a single validator per chain, omitting the distributed infrastructure and validator diversity inherent to real-world blockchain ecosystems. Transaction execution was also limited to sequential processing, which does not reflect the parallel transaction handling required for high-throughput energy trading scenarios. To enhance practical relevance, subsequent studies should incorporate multi-node deployments, validator decentralization, and concurrent transaction testing under realistic load conditions.

Another constraint lies in the synthetic energy data used for transaction simulations. While this approach enabled controlled experimentation, future work should integrate empirical datasets from operational microgrids to validate performance under dynamic, real-world conditions. Such data could account for temporal energy fluctuations, grid congestion, and demand-response behaviors, strengthening the ecological validity of findings.

The scope of interoperability analysis was restricted to Cosmos-based chains using the Hermes relayer. While this provided a controlled environment for cross-chain experimentation, practical energy systems may involve heterogeneous blockchain ecosystems (e.g., Ethereum, Hyperledger Fabric, or Polkadot). Future research should assess interoperability across diverse architectures, consensus mechanisms, and token standards, as well as compare alternative relayers (e.g., IBC-compatible implementations) and cross-chain protocols (e.g., bridges, sidechains).

Lastly, the rapid evolution of blockchain frameworks necessitates continuous reassessment. Tools and protocols used in this study may become outdated as interoperability standards mature. Ongoing research that follows the progress of new technologies, like modular blockchains or privacy-protecting zero-knowledge proofs for moving information between different blockchains, could provide useful and up-to-date information for when these technologies might be widely used in the industry.

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