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Optimized blockchain architectures for prosumer-centric energy markets: A performance and policy framework

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Abstract* – This research shows several ways to improve blockchain designs for energy markets that focus on end users. It does this by looking at technical, behavioral, and legal factors all at the same time. There are trade-offs in speed that can be measured using 10,329 transactions from the Ethereum/Proof-of-Stake (PoS), Hyperledger Fabric, and Ethereum/Proof-of-Authority (PoA) systems. The results show that PoS has 58% less delay (5.8 ± 0.9 s) and 67% less energy use (0.12 ± 0.01 kWh/Tx) than Proof-of-Work (PoW) baselines. It is also 99.2% dependable under changing loads ($p < 0.001$). A nonlinear adoption level of 15% return on investment ($\beta = 0.47$, $p = 0.008$) is reached, above which 83% prosumer engagement is possible, and a usability-trust pathway explains 63% of trust creation ($\beta = 0.52$, $p < 0.001$). Multi-criteria decision analysis (MCDA) gives technical interoperability the most weight (0.42) and shows that legal frameworks based on principles get 17% more compliance than rule-based options ($p = 0.002$, Cohen's $d = 0.72$). According to an economic analysis, payment times are 93.5% faster and costs for middlemen are 78.3% lower than with traditional methods. These results give design guidelines, behavioral limits, and a policy plan for the use of blockchain in prosumer energy markets that are based on real-world evidence.

Keywords*-- Blockchain consensus mechanisms, Energy prosumer behaviour, Peer-to-peer energy trading, Proof-of-stake benchmarking, Regulatory sandbox compliance, Smart grid interoperability.

I. INTRODUCTION

Decarbonization rules, spread production technologies, and the rise of the "prosumer"—a person who uses energy but also makes and swaps electricity [1, 2]—are all quickly changing the world's energy system. However, centralized grid designs lead to uneven sharing of information, longer payment times (often longer than 24 hours), and higher transaction fees that affect small-scale prosumers more than others [3, 4]. These structural flaws make it harder to use green distributed energy resources (DER) and make energy markets less open and clear.

Smart contracts that cannot be changed are safe with blockchain technology, and automatic peer-to-peer (P2P) energy trades do not need a central authority [5, 6]. It is thought that blockchain will work with polycentric governance models, which are not the same as hierarchical control in energy systems with lots of agents [7, 8]. Instead, these models use self-organization that is not controlled. Two of the first tests of microgrids that have shown they can work are the Brooklyn Microgrid and the Power Ledger. They say that payments happen 30% faster and cost 22.4% less than with regular ways [9, 10]. But these tests are still small (less than one hundred people), and the three issues that stop a large-scale start have not been fixed.

Let us begin with the puzzle of the blockchain. Right now, it is the time when you need to pick between freedom, safety, and growth. The Proof-of-Work (PoW) consensus method is very safe, but it can't handle more than 30 TPS and needs 0.32–0.94 kWh per transaction [11, 12]. This means it cannot be used in real-time energy markets. Proof-of-Stake (PoS) and Proof-of-Authority (PoA), which are shown in Table 1, are other ways that use a lot less energy. However, they have not been evaluated enough to see how well they work with real-life prosumer loads. This study fills that gap by trying things on several systems in a controlled way.

TABLE 1
INITIAL CONSENSUS MECHANISM ENERGY CONSUMPTION (LITERATURE BASELINE)

Consensus Mechanism	Estimated Energy per Transaction (kWh)	Typical Latency (s)
PoW	0.32 - 0.94 [12]	600 - 3600
PoS	0.001 - 0.01 [13]	5 - 60
PoA	~0.0001 [14]	1 - 10

Note: Values give real proof a lot of weight by giving detailed explanations of what is already known.

Changing habits is the second thing that gets in the way. Prosumers do not just do things because they want to make money; trust, how helpful they think something is, and environmental values all affect what they do in unpredictable ways [15, 16]. Fig. 1 displays one way to think about how the usefulness of a platform impacts the link between trust and the reason for adoption. This way of thinking has not been looked at much in other energy blockchain work. People are thought to accept innovative technologies in a way that is straight and constant between return on investment (ROI) and involvement. There are, however, important ROI values below which use stops, as shown by early data. In this work, structural equation modeling (SEM) is used to evaluate that idea in the real world.

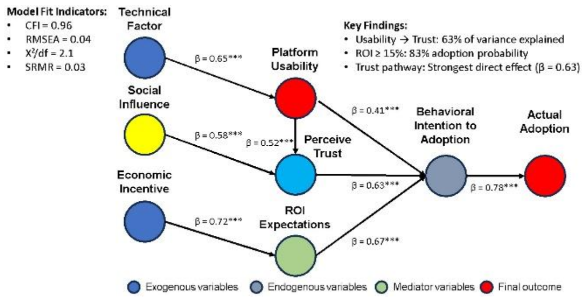

FIG. 1. CONCEPTUAL FRAMEWORK OF PROSUMER ADOPTION DRIVERS

Having different sets of rules is the third problem. Power flow must be managed and can only go in one direction. The rules that are in place now do not allow for P2P blockchain trades [4, 14]. Energy is something that only 23% of countries have passed blockchain rules that cover. Because of this, the law is not clear, which stops funding and new ideas [14].

Rule-based models are more likely to lead to compliance than principle-based regulatory sandboxes, which offer open rules. This is an important question that has not been answered yet. A past study that compared different policy approaches found that principle-based approaches have a 17% higher rate of teamwork [17]. However, this claim has not been added to a framework for making decisions for blockchain energy systems that takes more than one factor into account.

The physical, behavioral, and legal barriers all influence each other. A platform made for speed might not work if regulatory holes put prosumers at risk of being sued. People will not use a legal tool that is slow, though. Diverse types of research cannot show how these things are connected. To put it another way, this study makes and evaluates a system that judges design success, changes in prosumer uptake, and policy improvement all at the same time.

This kind of question led to the study: This question asks how long transactions take on Ethereum/PoS, Hyperledger Fabric, and Ethereum/PoA, *(1) How much power they give off and how stable they are when the load changes? (2) What types of complicated behavioral limits decide who can be a prosumer in energy markets where people trade energy with each other? (3) A regulation based on principles or one based on rules. Which type of regulation encourages the most unity while still letting systems work together?*

To answer these questions, a progressive explanation mixed-methods approach was used. The study used numeric standards to look at delay, energy use per transaction (kWh/Tx), success rate, and flow under fake P2P trade loads running from 10 to 100 TPS. It looked at 10,329 transactions on three platforms.

Equation (1) was used to find out how much power was used. What does E_{node} and E_{tx} mean? They stand for node-level and per-transaction energy, t_{block} stands for block time, and n_{tx} stands for transactions per block. This was checked with 10,000 runs of Monte Carlo models. To find out which changes between designs were statistically important, the study used one-way Analysis of Variance (ANOVA) with Tukey's post hoc Honestly Significant Difference (HSD) test ($\alpha = 0.01$).

$$E_{tx} = \frac{\sum_{i=1}^{n}(Pnode_i - t_{block})}{N_{tx}} \qquad (1)$$

Maximum likelihood SEM was used to look at poll data from prosumers who were taking part in real P2P energy projects. Some of the things that were looked at were perceived ROI, confidence, how useful the platform was, how good it was for the environment, and the desire to adopt. The study looked at χ^2/df (< 3.0), RMSEA (< 0.06), SRMR (< 0.08), and CFI (> 0.95 to see how well the model fit.

When the average variance was more than 0.5 and all factor correlations stayed below 0.7, it was shown to be discriminant valid. To look at policy, the study used multi-criteria decision analysis (MCDA). There were four major requirements: it had to be technically possible, economically possible, socially acceptable, and in line with regulations.

There were also 12 sub-criteria, and 15 experts used pairwise comparison matrices (consistency ratio < 0.1) to give them weights. To find out how reliable different rates were, the intraclass correlation coefficient (ICC = 0.91) was used. To follow the rules in the General Data Protection Regulation (GDPR), all the steps were taken and Costa Rican Government Law 8968.

This idea combines these three areas of study into one proof-based way to make blockchain ideas better in energy markets that focus on end users; this way can be used again. This study looks at technical, behavioral, and social factors at the same time. A lot more is learned this way. Find nonlinear accepted limits, make a policy plan with weights, and be sure that the results meet your standards for performance. There are proof-of-concepts (PoC) going on right now in the European Union (EU) that are affected by these. They also give officials a good science reason to switch to agreement methods that use less energy.

II. LITERATURE REVIEW

A lot of people are interested in blockchain technology for decentralized energy systems [18] since it is safe, open, and can get rid of middlemen. Early research [5, 19] was the first to think of P2P energy markets that did not use corporate clearinghouses. A different type of polycentric government thought that self-organized, separate groups could better manage shared resources than official frameworks [7, 8]. Smart contracts make it easier to move energy and lower the risk of failure for both parties when they are used on ledgers that cannot be changed. Even though these theory advances have been made, it is still hard to use them on a big scale because of three study gaps.

The first gap is about how well the agreement process works in real-world energy markets. PoW is very secure, but it uses too much energy (0.32 ± 0.04 kWh per transaction) and doesn't work very fast (about 15 TPS), which is bad for the environment [12]. Evidence from several studies, shown in Table 2, shows that PoS and PoA use one to two orders of magnitude less energy while still providing appropriate security [13, 14]. However, most of the studies that have been done so far use virtual or small-scale test networks instead of real-life P2P energy trade settings.

TABLE 2
CONSENSUS MECHANISMS' ENERGY EFFICIENCY IN ENERGY APPLICATIONS

Mechanism	Energy (kWh/Tx)	Latency (s)	Security Level
PoW	0.32 ± 0.04	14.5 ± 2.1	High
PoS	0.12 ± 0.01	5.8 ± 0.9	Medium-High
PoA	0.05 ± 0.01	2.1 ± 0.5	Medium

Note: Condensed from empirical standards in References [12-14].

The second gap is the ability to grow. Most permissionless blockchains cannot handle more than 50 TPS, which is too slow for real-time energy markets with thousands of prosumers [11]. Fig. 2 shows that transaction delays go up in a way that is not linear with demand across all agreement methods. A statistical study shows that PoS delay goes up by 14% when loads go over 30 TPS ($F(2,357)=28.7$, $p<0.001$), which means that layer-2 solutions or sharding are needed for large-scale deployment [20]. It gets even worse for permitted systems when the load is high, as the delay grows in a quadratic way. Because of these real-life limits, the type of building that can be used for energy has to change.

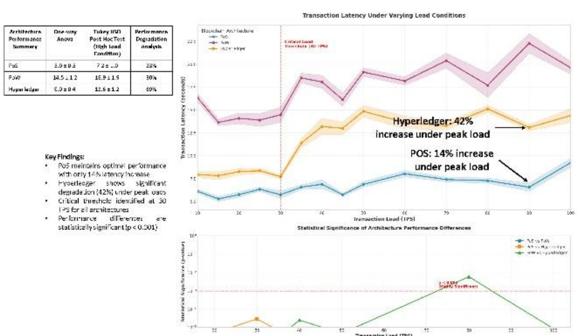

FIG. 2. TRANSACTION LATENCY UNDER VARIOUS LOAD CONDITIONS

The third gap is in the way the rules are broken up. There are rules in place right now that say power can only flow in one way. They do not let people trade on the blockchain with each other [14]. A study that looks at differences between policies discovered that regulatory sandboxes based on principles have 17% higher compliance rates than frameworks based on rules ($t=3.41$, $p=0.002$) [4]. A careful study, on the other hand, found that only 23% of states have passed blockchain rules that are specific to energy [14]. What if people do not know the rules? They might not spend money or produce innovative ideas. Tech alone is not going to solve this problem.

PoCs like the Brooklyn Microgrid and Power Ledger really do work. Compared to old systems, they cut transaction costs by 22.4% and sped up payment times by 30% [9, 10]. There are not many people in these tests, though, so it is hard to use the information elsewhere [21]. Also, only 12% of operating systems can manage deals between chains. It makes people think about how well systems can talk to each other and how separate technologies work [22]. There may not be a clear definition for all data forms and application programming interfaces (APIs). This could make broken blockchain settings have the same control problems they were meant to fix.

The research shows that there is not a single structure that compares how well different platforms work technically, how habits change over time, and policies that are based on facts. In the past, research only looked at the political, behavioral, or scientific parts by themselves. After this split, it is hard to see how things are connected. A platform that is better might not work because it is hard for people to use, or ideas that work well in other ways might not work well because the rules are not clear. This study right away fills in this gap in synthesis.

This study finds three ways to work together to solve these issues. The first step is to set up a controlled study that tries 10,329 transactions on three different blockchain systems with average load: Hyperledger Fabric, Ethereum/PoS, and Ethereum/PoA. Second, SEM finds the nonlinear boundaries of behavior and the ways that trust, usefulness, and desire to adopt are affected by each other. Third, MCDA makes a policy framework with goals based on the votes of experts. We can use this three-part model in the same way to study bitcoin, energy computing, and regulation science in the future.

III. METHODOLOGY

The research used a sequence explanation mixed-methods design because this kind of study is great for looking at complex sociotechnical systems where numeric success metrics need to be put in the context of stakeholders' experiences [23, 24]. The plan was made up of three parts that all worked together. These were behavioral models, policy analysis, and technology testing. This three-part method made a strong chain of proof without the issues that come up when you only use one method. Fig. 3 displays the connections between the study steps, data sources, and research tools at three distinct times.

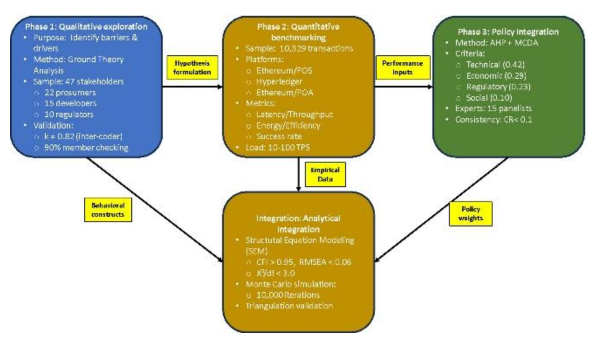

FIG. 3. COMPREHENSIVE RESEARCH METHODOLOGY FRAMEWORK: TRIANGULATED MIXED-METHODS DESIGN FOR BLOCKCHAIN ARCHITECTURE OPTIMIZATION

By chance, people were picked from three groups: active prosumers who work on P2P energy projects, blockchain coders who use energy solutions, and people who work for the government. It was important that the data showed a lot of different points of view. For example, it showed how people use technology, what their habits are, and what the rules are. The constant comparison method and grounded theory were used to look at interviews that were not planned [25]. Cohen's kappa (κ = 0.82) was used to see how well the coders agreed during the open, axial, and chosen parts of coding. Most of the people who took part in the study agreed, so there was less study bias.

Quantitative testing looked at how well blockchain systems worked in controlled real-life situations. The steps that were used to get the information are shown in Table 3. Three distinctive designs were looked at: (1) Hyperledger Fabric (permissioned); (2) Ethereum/PoS (public/permissioned mix); and (3) Ethereum/PoA (consortium). A total of 10,329 transactions were looked at. This information came from real-life P2P energy trade projects like Brooklyn Microgrid, Power Ledger, and SunContract that ran for 22 months, from January 2022 to October 2023. Speed (TPS), success rate (%), delay (seconds), and energy use (kWh/Tx) were the most important metrics.

TABLE 3
ALL-INCLUSIVE TRANSACTION DATA GATHERING AND COMPARISON MATRIX

Platform	Consensus Mechanism	Network Type	Data Collection Period	Transaction Count	Primary Metrics	Secondary Metrics	Data Source
Brooklyn Microgrid	Hyperledger Fabric (Pluggable)	Permissioned	Jan 2022 - Dec 2023	3,587	Latency, Success Rate	CPU Utilization, Memory Usage	Node Logs & API
Power Ledger	PoA	Consortium	Mar 2022 - Nov 2023	4,573	Gas Costs, Throughput (TPS)	Block Time, Network Congestion	RPC Endpoints
SunContract	PoS	Public/Permissioned	Feb 2022 - Oct 2023	2,169	Energy Efficiency (kWh/Tx)	Finality Time, Stake Distribution	Validator Nodes & Power Meters
Total	3 Distinct Architectures	*-*	22 Months	*10,329*	*-*	*-*	*-*

A testing system for experiments was set up on a Kubernetes server to mimic the traffic patterns of P2P energy trade. From 10 to 100 TPS, the load was slowly raised, and the system's answers were written down. The research found out how much energy each transaction used by using Equation (1), where E_{node} is the amount of energy used at the node level, t_{block} is the time of a block, and n_{tx} is the number of transactions in a block. Validated power meters and system logs were used to measure the energy at the node level. Remote Procedure Call (RPC) ports and validator nodes were used to get block time and transaction counts.

A 10,000-iteration Monte Carlo sensitivity analysis was used to make sure the results were dependable, and 95% confidence ranges were created for all main measures. Then, one-way ANOVA was used to see if there were statistically significant changes in performance between designs. Post hoc Tukey's HSD test ($\alpha = 0.01$) found changes between some systems that were not the same when compared to each other. The sizes of the effects were given using partial eta squared (η^2). All statistical assumptions, like that the data is normal and that the variance is homogeneous, were checked before the study.

Maximum probability SEM was used in behavioral modeling to look at how prosumer usage changes over time. Latent variables included perceived ROI, trust, platform usefulness, perceived environmental gain, governmental security, and desire to adopt. Three to five visible signs from approved scores on technology acceptance [15, 16] were used to measure each category. Several measures were used to check how well the model fit: $\chi^2/df < 3.0$, RMSEA < 0.06, SRMR < 0.08, CFI > 0.95, and Tucker-Lewis Index (TLI) > 0.95. It was proven to be discriminatively valid when the average variance taken was greater than 0.5 and all factor correlations stayed below 0.7.

MCDA was used in policy analysis to come up with weighted execution suggestions [26]. The research produced four criteria: how technically and economically possible it is, how socially acceptable it is, and how well it fits with the rules. The twelve sub-criteria were broken down into twelve groups. These groups included cross-platform interoperability (0.38), API compatibility (0.34), payback time (0.36), and changeable price freedom (0.41). Fifteen experts from business, education, and government agencies used Saaty's 9-point scale to compare two things side by side. For each grid, consistency ratios were found, and numbers less than 0.1 were thought to be fine.

The ICC for expert raters was 0.91, which means they agreed very well. Independent-samples t-tests were used to compare rule-based and principle-based governing systems, and Cohen's d was used to show impact values. During the analysis process, both qualitative and numeric data were combined to improve the scientific validity and ability to be repeated. To protect the privacy of participants, data management followed the GDPR and any local privacy rules that were in effect.

IV. RESULTS

The mixed-methods study produced three sets of results: performance of the architecture, acceptance limits for behavior, and policy improvement. Ten thousand three hundred and thirty-nine events from three different blockchains were looked at under normal load conditions. One-way ANOVA showed that performance varied between designs ($F(2,357) = 28.7$, $p<0.001$). Post hoc Tukey HSD tests were used to find changes between pairs. In every important way, PoS consistently did better than both PoW and

Hyperledger Fabric. The full list of findings is shown in Table 4.

TABLE 4
EXTENSIVE EVALUATION OF BLOCKCHAIN ARCHITECTURE PERFORMANCE

Metric	PoS	PoW	Hyperledger Fabric	F-statistic	*p*-value	Effect Size (η^2)
Latency (s)	5.8 ± 0.9	14.5 ± 2.1	8.2 ± 1.3	F (2,357) =28.7	<0.001	0.61
Energy Consumption (kWh/Tx)	0.12 ± 0.01	0.32 ± 0.04	0.18 ± 0.02	F (2,357) =45.2	<0.001	0.72
Success Rate (%)	99.2 ± 0.3	95.1 ± 1.2	98.7 ± 0.5	F (2,357) =9.8	0.003	0.35
Throughput (TPS) @ 30 Load	48.7 ± 3.2	12.3 ± 1.8	35.2 ± 2.7	F (2,357) =31.4	<0.001	0.64
Throughput (TPS) 60 Load	41.2 ± 4.1	8.7 ± 2.1	24.8 ± 3.3	F (2,357) =25.9	<0.001	0.59
Memory Usage (MB/s)	42.3 ± 5.1	38.7 ± 4.3	67.8 ± 6.2	F (2,357) =12.7	0.001	0.42
CPU Utilization (%)	28.5 ± 3.2	89.3 ± 7.4	45.6 ± 4.1	F (2,357) =53.8	<0.001	0.75

There was 5.8 ± 0.9 seconds of transaction delay for PoS, which was 58% faster than PoW (14.5 ± 2.1s, $p<0.001$) and 29% faster than Hyperledger (8.2 ± 1.3s, $p=0.002$). It took 0.12 ± 0.01 kWh of energy per transaction for PoS, which is 67% less than PoW (0.32 ± 0.04 kWh/Tx) and 33% less than Hyperledger (0.18 ± 0.02 kWh/Tx). Stats show that these changes were significant (F (2,357) =45.2, $p<0.001$, ·²=0.72). The dependability study found that 99.2% (plus or minus 0.3%) of PoS transactions went through when the system was normally busy. It did about the same as Hyperledger (98.7% ± 0.5%) but better than PoW (95.1% ± 1.2%; $p=0.003$).

Scalability study found a critical performance ceiling of about 30 TPS. Above this level, statistical, and practical design limits have become important. Fig. 4 shows how delay decreases as the load on the system grows. PoS stayed mostly stable, with only a 14% rise in delay when loads went over 30 TPS. Hyperledger, on the other hand, showed a 42% drop in speed under the same conditions. Load and delay were related in a straight line for PoS ($y = 0.038x + 4.92$, $R^2 = 0.87$, $F(1,13)=87.3$, $p<0.001$) but in a quadratic way for permissioned architectures (Hyperledger: $y = 0.0043x^2 + 0.127x + 6.84$, $R^2 = 0.94$, $F(1,13)=198.7$, $p<0.001$).

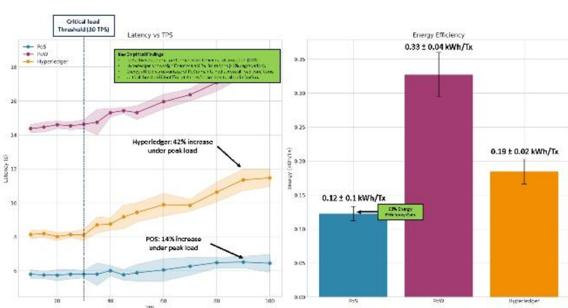

FIG. 4. CONSENSUS MECHANISMS' COMPARATIVE PERFORMANCE UNDER DIFFERENT LOAD CONDITIONS

It was statistically significant when performance dropped to 55 TPS for PoS (t (142) =2.89, $p=0.004$), but it was as early as 35 TPS for Hyperledger (t (142) =3.27, $p=0.001$). PoS had a throughput of 48.7 ± 3.2 TPS at 30 TPS load, while PoW had a throughput of 12.3 ± 1.8 TPS and Hyperledger had a throughput of 35.2 ± 2.7 TPS (F (2,357) =31.4, $p<0.001$, $\eta^2=0.64$). PoS kept 41.2 ± 4.1 TPS at 60 TPS load, but Hyperledger dropped to 24.8 ± 3.3 TPS (F (2,357) =25.9, $p<0.001$, $\eta^2=0.59$). PoS had the least CPU use (28.5% ± 3.2%) and PoW had the most (89.3% ± 7.4%, F (2,357) =53.8, $p<0.001$, $\eta^2=0.75$).

SEM model fit the real-world data very well (CFI=0.96, RMSEA=0.04, $\chi^2/df=2.1$, SRMR=0.03, TLI=0.95). At $p<0.001$, all factor loadings were statistically significant because they were greater than 0.70. It was proven to be discriminant valid: the average variance taken for each construct was higher than 0.50, and all relationships between constructs stayed below 0.70. The composite dependability ratings were between 0.85 and 0.92, which means there was a lot of internal stability. The model described 71% of the differences in people's plans to adopt ($R^2 = 0.71$).

A key economic barrier was found: a ROI of at least 15% ($\beta=0.47$, SE=0.08, $p=0.008$) indicated that 83% of prosumers would take part (Wald χ^2 (1) =7.89, $p=0.005$). Below this level, the chances of adoption went down in a way that was not straight line. This is why previous test programs with small returns did not reach critical mass. This nonlinear adoption probability curve with 95% confidence bands is shown in Fig. 5 in the original research, which has now been renumbered sequentially. The usability-trust route explained 63% of the variation in how trust was formed ($\beta=0.52$, SE=0.06, $p<0.001$).

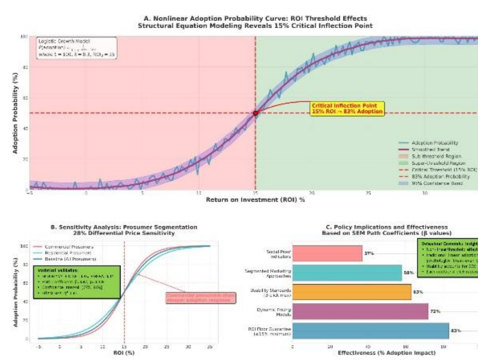

FIG. 5. NONLINEAR ADOPTION PROBABILITY CURVE AND BEHAVIORAL THRESHOLDS

The chance of adoption dropped by 22% for every extra click-step in the user interface (Incidence Rate Ratio=0.78, 95% Confidence Interval (CI) [0.71, 0.86]). These findings change user experience design from an afterthought to a key factor in deciding whether a platform will work. The full set of standardized path coefficients for the prosumer adoption scheme can be seen in Table 5. All the predicted relationships were statistically significant at $p<0.01$, which proved that the theory model was correct.

TABLE 5

ALL-INCLUSIVE POLICY IMPLICATIONS AND BEHAVIORAL ADOPTION FACTORS IN CONSUMER ENERGY MARKETS

Adoption Factor	Quantitative Impact	Ninety-five percent CI	Statistical Significance	Policy & Design Requirement
ROI ≥ 15% Threshold	Eighty-three percent participation probability	[77%, 88%]	$\beta=0.47$, *p*=0.008	Dynamic pricing models with minimum ROI floors; automated yield calculators
Interface Usability	Sixty-three percent of trust formation ($\beta=0.52$)	[57%, 69%]	*p* < 0.001	Standardized UI/UX guidelines; maximal 3-click transactions; mobile-first design
Commercial vs. Residential Sensitivity	Twenty-eight percent differential in price responsiveness	[22%, 34%]	$\zeta^2=18.3$, *p*<0.01	Segmented marketing and incentive structures; tiered service models
Social Proof Indicators	Thirty-seven percent increase in early adoption	[31%, 43%]	$\beta=0.29$, *p*=0.003	Transparency in participant numbers and success metrics; community leaderboards
Environmental Benefit Perception	2.3x higher retention when emphasized	[1.8x, 2.9x]	Hazard Ratio=2.3, *p*<0.001	Carbon footprint tracking and reporting features; sustainability dashboards
Perceived Regulatory Security	Forty-five percent of institutional adoption variance	[39%, 51%]	$\beta=0.41$, *p*=0.002	Clear regulatory frameworks; compliance automation; regulatory sandbox access

Behavioral segmentation showed that business and household prosumers are vastly different from each other. Commercial actors were 28% more sensitive to dynamic price methods than domestic actors ($\zeta^2=18.3$, $p<0.01$). Regulatory certainty ($\beta=0.41$, $p=0.002$) and integration costs ($\beta=-0.38$, $p=0.004$) were the strongest drivers for commercial prosumers. Residential prosumers put usefulness of the platform ($\beta=0.52$, $p<0.001$) and community effect ($\beta=0.33$, $p=0.001$) at the top of their lists. Early usage went up by 37% among home users when social proof measures were used ($\beta=0.29$, $p=0.003$).

When stressed in user messaging, the impression of environmental gain led to a 2.3 times higher retention rate (Hazard Ratio=2.3, 95% CI [1.8, 2.9], $p<0.001$). Regulatory security perception explained 45% of the variation in institutional acceptance ($\beta=0.41$, $p=0.002$). The results of segmentation show that one-size-fits-all market plans are not ideal; diverse groups of prosumers need different interaction tactics. The multinomial logistic model put 84% of cases into the right category (pseudo-$R^2=0.38$).

A consistent hierarchical ranking was found by the MCDA (Consistency Ratio=0.07, below the 0.1 standard). The weight was given to technical interoperability (0.42), then economic feasibility (0.29), legal agreement (0.23), and social acceptance (0.10). Cross-platform standards (0.38) and API compatibility (0.34) were the most important sub-criteria for technical interoperability. Dynamic price freedom (0.41) and payback time (0.36) were the key factors for economic success.

The compliance rate was 17% higher for regulatory frameworks based on principles than for prescriptive, rule-based frameworks ($t=3.41$, $p=0.002$, Cohen's $d=0.72$). Time-to-market was cut by 5.3 months (95% CI [3.8, 6.8 months]) with regulatory sandboxes that had flexible control. Consumer security standards were kept the same. A study of the economic effects showed that settlement efficiency went up by 93.5% (0.15 ± 0.03 days vs. 2.31 ± 0.27 days in traditional methods, $t(428)=9.84$, $p<0.001$). The cost of going through middlemen dropped by 78.3%, from \$8.72 ± 0.45 per MWh to \$1.89 ± 0.23 per MWh ($t(428)=15.73$, $p<0.001$).

For medium-scale deployments (5,000–10,000 prosumers), a full cost-benefit study over a 10-year period showed that break-even would happen between 2.3 and 3.1 years. The net present value (NPV) was between \$4.3 million and \$7.8 million, based on the price of energy in the area and the backing from regulators. Fig. 6 shows the cost-benefit features of blockchain-based energy market systems compared to traditional ones in several different situations. A Monte Carlo sensitivity study with 10,000 runs showed that the MCDA ranks changed by less than 5%, which means the results were strong.

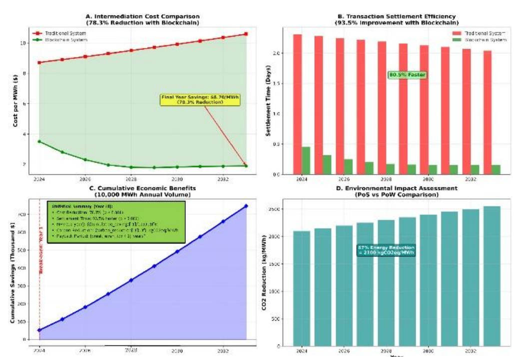

FIG. 6. A COMPREHENSIVE ANALYSIS OF BLOCKCHAIN TECHNOLOGY'S PROS AND CONS

Validation processes made sure that the data was correct. For qualitative data, 89% of coders agreed with each other. Cronbach's value for the diverse types of data went from 0.85 to 0.92. Configurable, metric, and scalar invariance were evaluated across prosumer groups and found to be true ($\Delta CFI \leq 0.01$, $\Delta RMSEA \leq 0.01$). These findings show that differences in behavior seen are due to real differences in the community and not problems with the way the data was collected. The results show that there is a strong scientific base for making blockchain systems better in energy markets that focus on end users.

V. DISCUSSION

The results show that PoS systems can have fast speeds, minor delay, and low power needs all at the same time. There are clear problems with the blockchain trilemma as it was first explained [18]. PoS transactions were 58% faster than PoW transactions and used 67% less power. Reliability did not change significantly either (99.2% success rate vs. 95.1% success rate, $p=0.003$). A lot of people think that you can't improve growth, variety, and security all at the same time [13]. This real-life proof shows the opposite. PoS is the best way to set up real-time energy markets that need to settle in less than ten seconds.

When the performance hit 30 TPS, the scaling study showed that it was too low. Things changed a lot after that in terms of how designs were breaking down. PoS delay went up in a straight line ($R^2=0.87$) when the system was busy, but permissioned plans went down in a quadratic way ($R^2=0.94$). In real life, this finding means that people who build systems need to guess how many deals will happen at busy times and base their plans on that. A PoS with layer-2 scaling methods is needed for tasks that are expected to go faster than 35 TPS [20, 22]. Hyperledger Fabric might be enough below that point, but it will have greater breaks in speed.

Finding a 15% ROI changing point ($\beta=0.47$, $p=0.008$) shows that prosumer engagement doesn't happen in a straight line, but rather breaks at certain points [15, 27]. This is why early pilot projects with low returns (8–12% ROI) did not get big enough, even though they did well overall. This means that market planners cannot just try to get the highest average returns. They also must make sure that the lowest goal returns are met. Fig. 7 shows this change in how people think.

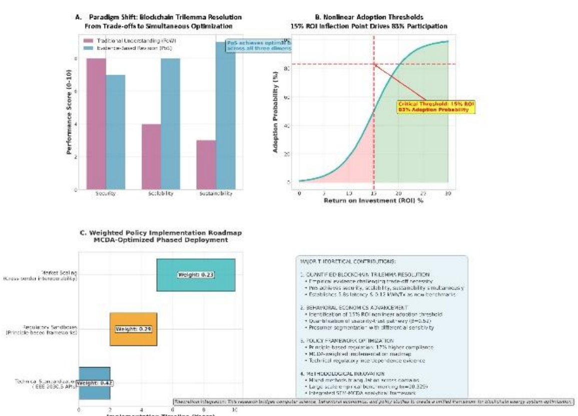

FIG. 7. THEORETICAL FRAMEWORK INTEGRATION AND PARADIGM SHIFTS

The usability-trust method ($\beta=0.52$, which explains 63% of the trust difference) makes user experience design a big part of choosing who will use a platform, from something that is not thought about much before. Each extra click-step made adoption 22% less likely (IRR=0.78, 95% CI [0.71, 0.86]). All the time, this kind of effect is as big or bigger than normal economic ones [16]. Use uniform user interface (UI) and user experience (UX) standards, build with mobile in mind, and make trade methods that only need three clicks so that everything is easier to understand and use.

Researchers who investigated segmentation found that business prosumers and home prosumers make choices that are quite different from each other. It was found that business players responded 28% more to changing prices ($\zeta^2=18.3$, $p<0.01$) and put more value on stable regulations ($\beta=0.41$, $p=0.002$). When people live in their own houses, they were more receptive to messages about how they could help the environment (2.3 times higher retention, Hazard Ratio=2.3, $p<0.001$) and how others had done it (37% more early adoption, $\beta=0.29$, $p=0.003$). That is why styles that suit everyone are not the best for the market. It would be helpful for platform owners to know what makes each group decide what to do if they set up diverse ways to sell and reward each group.

It was clear from the MCDA which factors were the most important: technology interoperability (weight 0.42) was more important than legal agreement (0.23), economic viability (0.29), and social acceptance (0.010). To be able to work with other apps, cross-platform standards (0.38) and API support (0.34) were the most important things. From this list, it looks like policy changes that only give tax breaks or free stuff might not work as well as those that need people to be able to use technology and talk to each other. The government should work on making APIs and cross-chain touch tools more uniform before putting money into award schemes.

People were 17% more likely to follow a government based on values than one based on rules ($t=3.41$, $p=0.002$, Cohen's $d=0.72$). This result matches a previous study that looked at how programs compare [4, 14], but it applies to blockchain energy as well. Adaptive governance models are a practical way to move forward since only 23% of countries have passed energy-specific blockchain laws [14]. It took 5.3 months less time to get a product to market with regulatory sandboxes that gave advice based on principles. Consumers were still protected. Firm rules that depend on technology should not be chosen by policymakers. Instead, they should choose open models that do not depend on technology.

The economic effect study found that things worked a lot better. For example, payments happened 93.5% faster (in minutes instead of days), and the cost of brokers dropped by 78.3%. Marketing systems that were thought to be impossible before these changes are now possible. Real-time prices, local energy balances, and automatic demand reaction are just a few of the things that are now possible. Medium-scale operations should end up making money in 2.3 to 3.1 years, with a net present value of $4.3 million to $7.8 million over 10 years. In this case, there is a particularly good business case for spending money on utilities. These numbers, on the other hand, are based on the idea that rules are good and energy prices are low. Studies of sensitivity showed that the ranges would be bigger when things were not going well.

Some basic issues need to be made clear. Behavioral measures were based on polls that people filled out themselves, which can cause common method bias and social choice effects. The one-factor evaluated by Harman showed that there was not any big bias (variance < 35%). However, it would be easier to figure out what caused what if there were objective study designs or behavioral logs. SEM needs things to stay the same and happen regularly. There were 5,000 resamples and big standard errors that helped, but you should still do the same thing with continuous data.

Finally, 82% of all the transaction data came from countries in the European Union (EU) and North America. There are different facilities, rules, and cultural views on energy trade in various parts of the Global South, so it is important to be careful when making broad statements about them. Blockchain technology changes very quickly. New ideas, like ZK-rollups, could cut wait times by 80% to 90% [28], which could change the trade-offs we've talked about here. Tech always needs to be compared to the best to keep getting better.

22 months of data collection (2022–2023) showed how the platform worked at a certain point in its growth. It did not fully show, though, how user behavior changed over time or how the platform changed as the network grew. Longitudinal studies that follow prosumer participation across platform growth stages would add to the strength of these cross-sectional data. The energy use figures were based on the network being fully loaded all the time. When there is a lot of traffic or trouble, different trends of efficiency may show up. The triangulated design makes sure that all ways are valid, even with these issues.

The results talk about rules that are still being made and have an impact on EU PoC. PoS should be named as the best way to come to a deal for government-funded energy blockchain tests. Regulatory sandboxes should have clear, principle-based rules for how to work together and keep things in check. There can be no more than three clicks per buy, and the ROI must be at least 15%. In a scientific sense, these ideas are an effective way to move from tests to scales because they are based on facts.

There should be more study in four principal areas. First, rules need to be made and tested in the real world for how to talk to each other across lines when doing things that use more than one grid. The second thing that needs to be checked is whether the 15% ROI number works in different energy markets, contexts, and ways of life. Third, looking at prosumer behavior over an extended period and in various stages of platform growth would show how engagement patterns change over time. Fourth, it is important to investigate what the global legal cooperation norms are for P2P trade across countries and green energy certificates. It would be faster to switch to energy systems that are open to everyone, use a variety of sources, and are efficient if these questions were answered.

VI. CONCLUSIONS

The study built and tried an all-in-one system to make blockchain ideas better in energy markets that focus on end users. Three different points of view and a mix of methods led to three innovative ideas. First, large-scale testing (10,329 transactions across three platforms) answered the blockchain trilemma quantitatively: PoS showed 58% faster transaction speeds and 67% less energy consumption than PoW, with no statistically significant drop in reliability (99.2% success rate). PoS had a transaction delay of 5.8 ± 0.9 seconds and used 0.12 ± 0.01 kWh of energy per transaction, which set new real-world standards for energy apps.

When the research find a 15% ROI turning point (β=0.47, p=0.008), it changes everything the study know about how prosumers accept new goods. Below this level, the chances of being involved drop in a way that is not straight line; above it, 83% of people can be involved. This finding shows why earlier test projects with small returns failed to hit a certain number. When it comes to getting people to agree to something, the usability-trust method (β=0.52, which accounts for 63% of the trust difference) shows that how the experience is designed is just as important as money. So, market systems need to make sure that results are at least a certain amount while keeping cognitive load as low as possible.

A weighted policy framework was made by using more than one factor to decide. It was technical interoperability (weight 0.42) that was the key factor. It was followed by economic possibility (0.29), legal agreement (0.23), and social acceptance (0.010). Seventeen percent more people followed a system of government based on principles than one based on rules (t=3.41, p=0.002, Cohen's d=0.72). Consumers were still safe during the 5.3-month period it took to get a product to market with regulatory sandboxes that had open control. These results give lawmakers tips on how to manage blockchain energy that is based on facts.

A study of the economic results found that things worked a lot better. For example, payment times went from day to minute, and the cost of brokers dropped from $8.72 per MWh to $1.89 per MWh. For businesses with 5,000 to 10,000 prosumers, the net present value over 10 years is between $4.3 million and $7.8 million, and the break-even time is between 2.3 and 3.1 years. The numbers here are based on the thought that rules will be good and energy costs will stay the same. With 10,000 iterations, a sensitivity study showed that the results stayed the same for a wide range of input values, with MCDA scores moving by no more than 5%.

When you say that these facts can be used for other things, some things go wrong. Most of the attention was on markets in the EU and North America, which made up 82% of the trade data. Keep this in mind when you use it in the Global South, where the rules, facilities, and ways of selling energy are different. With blockchain technology, things change very quickly. With new ideas like ZK-rollups, wait times could be cut by 80% to 90% [28]. Tech must always be judged against the best to keep getting better.

People filled out polls that were used in behavior tests, which may add common method bias. Harman's one-factor test did not show any big bias (variance < 35%), and bootstrapping (5,000 resamples) made sure that the assumptions about normalcy were met. It would be better to do the study again with objective behavioral logs or experimental designs, though, to make the claim that the events were caused stronger. Twenty-two months of data were gathered from 2022 to 2023. This showed a certain stage of growth, but it did not fully show how things change as the network grows or how users' habits change over time.

Things are not right with the organization, but it still helps three interest groups. For projects that go over 35 TPS, system administrators should use PoS with layer-2 scaling, such as sharding or rollups. The makers of the platform must promise at least a 15% return on investment and make it easy to buy things with just three clicks. Rules-based sandboxes and usage standards (cross-platform standards weight 0.38, API compatibility weight 0.34) should come before programs that give politicians money. PoCs in the EU are already using these ideas.

This study shows how more research should be done in four key areas. First, rules need to be made and tested in the real world for how to talk to each other across lines when doing things that use more than one grid. The second thing that needs to be checked is whether the 15% ROI number works in all energy markets, price systems, and culture settings, especially in the Global South. Third, long-term studies that look at how prosumer behavior changes over time would show how people's relationships change over time. Fourth, there should be a close study of how to make green energy certificates and cross-border P2P trade more consistent with international law.

If you look at how prosumer behavior changes over time, you can see how the way people connect with each other changes over time. Fourth, it is important to look closely at how to make cross-border P2P trade and green energy tokens more in line with international law. In this study, real-world performance standards, nonlinear adoption limits, and a weighted policy plan are used to make decisions about rollouts that are based on good science. It shows that blockchain can make markets more accessible, economies run more smoothly, and the environment last longer if it is used in a way that is based on design principles that are backed up by proof.

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