A Smart Contract Framework for Automated Settlement and Compliance in Renewable Energy and Distributed Energy Resources

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Abstract

This study addresses the persistent problem that renewable-energy and distributed energy resource (DER) transactions generate high-volume, interval-based micro-transactions that strain conventional centralized billing, reconciliation, and compliance reporting, creating delays, disputes, and weak audit trails. The purpose was to evaluate a smart contract framework that integrates automated settlement and compliance evidence generation within cloud-hosted, enterprise-grade DER transaction workflows using a quantitative, cross-sectional, case-based design. A purposive case sample of n = 214 informed stakeholders was drawn from enterprise settlement and compliance settings, including settlement and billing personnel (31.3%), compliance and audit professionals (24.8%), DER operations and aggregation roles (22.4%), and platform/ICT specialists (21.5%). Key variables were modeled as composite 5-point Likert constructs: Smart Contract Quality (SCQ), Data Integrity and Oracle Reliability (DIO), Interoperability (INT), Security and Privacy Controls (SP), Regulatory Alignment (RA), Automated Settlement Effectiveness (ASE), Compliance Automation Performance (CAP), and Operational or Market Performance (OMP). The analysis plan applied descriptive statistics, internal consistency reliability (Cronbach's alpha), Pearson correlations, and multiple regression hypothesis testing. Findings showed high capability and outcome perceptions, including SCQ M = 4.12 (SD = 0.61), DIO M = 4.05 (SD = 0.67), SP M = 4.18 (SD = 0.58), ASE M = 4.15 (SD = 0.60), and CAP M = 4.22 (SD = 0.55), with strong reliabilities (a = 0.82–0.91 across constructs). Correlations supported the framework pathways, notably SCQ–ASE r = 0.63, DIO–ASE r = 0.58, SP–CAP r = 0.66, RA–CAP r = 0.61, and CAP–OMP r = 0.68 (all p < 0.001). Regression results confirmed that settlement effectiveness was predicted by SCQ (β = 0.34, p < 0.001), DIO (β = 0.29, p < 0.001), and INT (β = 0.21, p = 0.002) with R^2 = 0.496, while compliance performance was driven by SP (β = 0.38, p < 0.001) and RA (β = 0.31, p < 0.001) plus organizational readiness (β = 0.19, p = 0.002) with R^2 = 0.538; together ASE (β = 0.29) and CAP (β = 0.41) explained OMP (R^2 = 0.572). Audit evidence readiness was also strong (ARS M = 4.25) and artifact coverage exceeded 82.7%–88.3% for trace logs, access logs, dispute logs, and provenance links, indicating compliance-grade outputs at scale. Implications suggest that enterprise implementations should prioritize contract correctness assurance, oracle and meter-data governance, secure per missioning with privacy-aware transparency, and explicit regulatory alignment to convert automation into measurable operational and audit benefits.

Keywords

INTRODUCTION

A smart contract can be defined as a tamper-evident, digitally executed agreement whose terms are represented as code and whose state transitions are validated by a distributed consensus mechanism, enabling deterministic execution, auditable logs, and automated enforcement across multiple parties (Aitzhan & Svetinovic, 2016). In energy systems, "automated settlement" refers to the systematic calculation of delivered energy quantities, prices, fees, and adjustments, followed by validated financial clearing among market participants, while "compliance" refers to demonstrable adherence to market rules, grid codes, renewable eligibility conditions, metering standards, and reporting obligations that regulators, system operators, and auditors expect to be traceable and verifiable (Alam et al., 2017). Distributed Energy Resources (DERs)—such as rooftop photovoltaics, battery storage, electric vehicles, and controllable loads—introduce high-volume, time-stamped transactions at the edge of the grid, turning many consumers into prosumers and creating dense, small-value exchanges that strain conventional centralized transaction processing and reconciliation workflows (Albadi & El-Saadany, 2008). The international significance of automating settlement and compliance is anchored in the rapid diffusion of smart metering, digital market platforms, and policy regimes that increasingly reward verifiable renewable generation and flexible demand participation, which in turn elevates the importance of data integrity and standardized audit trails across borders (Andoni et al., 2019). Demand response and distributed scheduling mechanisms already rely on fine-grained consumption and price signals, and they depend on trustworthy measurement, clear contractual logic, and transparent settlement rules to sustain participation at scale. The same operational logic applies to renewable energy and DER environments, where the settlement layer must reconcile physical power flows and meter readings with market obligations, tariffs, and incentive constraints while producing compliance artifacts that can be inspected by operators and regulators (Atzei et al., 2017). Blockchain-enabled architectures are frequently positioned as a means of aligning distributed participants under a common, append-only record, supporting time-ordered transaction histories and reducing disputes over "what happened" and "what is owed" in multi-party energy transactions. In this study context, a "smart contract framework" therefore denotes an integrated design that specifies contractual logic, data provenance rules, oracle interfaces, validation checks, and reporting outputs so that settlement computations and compliance evidence are generated as part of the transaction process rather than reconstructed after the fact from fragmented logs (Androulaki et al., 2018).

DER-centric energy exchange differs from conventional wholesale settlement because it combines operational variability, heterogeneous devices, and localized constraints with the need for reliable billing and regulatory reporting. Smart grid literature characterizes modern grids as cyber-physical systems requiring advanced communication, sensing, and control to manage variability and support new market functions, and this complexity is amplified when DERs participate as semi-autonomous agents that respond to incentives and local conditions (Rahimi & Ipakchi, 2010). Smart metering infrastructure expands data availability for billing, forecasting, and demand-side programs, yet it also expands the attack surface and raises concerns about data accuracy, privacy, and integrity as usage data becomes a core settlement input (Mengelkamp, Notheisen, et al., 2018). Demand response research shows that effective participation depends on credible pricing, predictable settlement rules, and mechanisms that balance efficiency and fairness; otherwise, participants face uncertainty about returns and obligations (Cecati et al., 2011). In microgrids and local energy communities, peer-to-peer (P2P) trading arrangements create additional layers of reconciliation: measurement must be aligned with trading intervals, allocations must handle partial fulfillment and network constraints, and settlement must incorporate fees, bounds, and dispute resolution logic that participants view as legitimate (Atzei et al., 2017). Studies on P2P trading platforms emphasize the presence of hierarchical layers—physical grid, ICT, control, and business logic—where market operations and settlement calculations depend on trustworthy data exchange and consistent rule execution. Local market design work further highlights that operational success depends on explicit market components, including participant onboarding, pricing rules, grid-interface constraints, and settlement procedures that are interpretable and auditable for participants and operators (Mengelkamp et al., 2017). At the same time, "transactive" concepts connect operational control and economic incentives, requiring settlement rules that are tightly coupled to measured flexibility and verified delivery, which heightens the importance of

compliance traceability for programs that reward flexibility and renewable contributions. As DER penetration grows, settlement must process a larger number of smaller transactions while preserving verifiable links between meter data, contractual commitments, and payment outcomes (Christidis & Devetsikiotis, 2016). The literature therefore frames a central problem: current approaches often separate operational data capture, billing computation, and compliance reporting into different systems, increasing reconciliation costs and leaving gaps in evidentiary trails when disputes arise or audits occur (Depuru et al., 2011).

Figure 1: Automated Settlement and Compliance in Renewable Energy & DER Systems
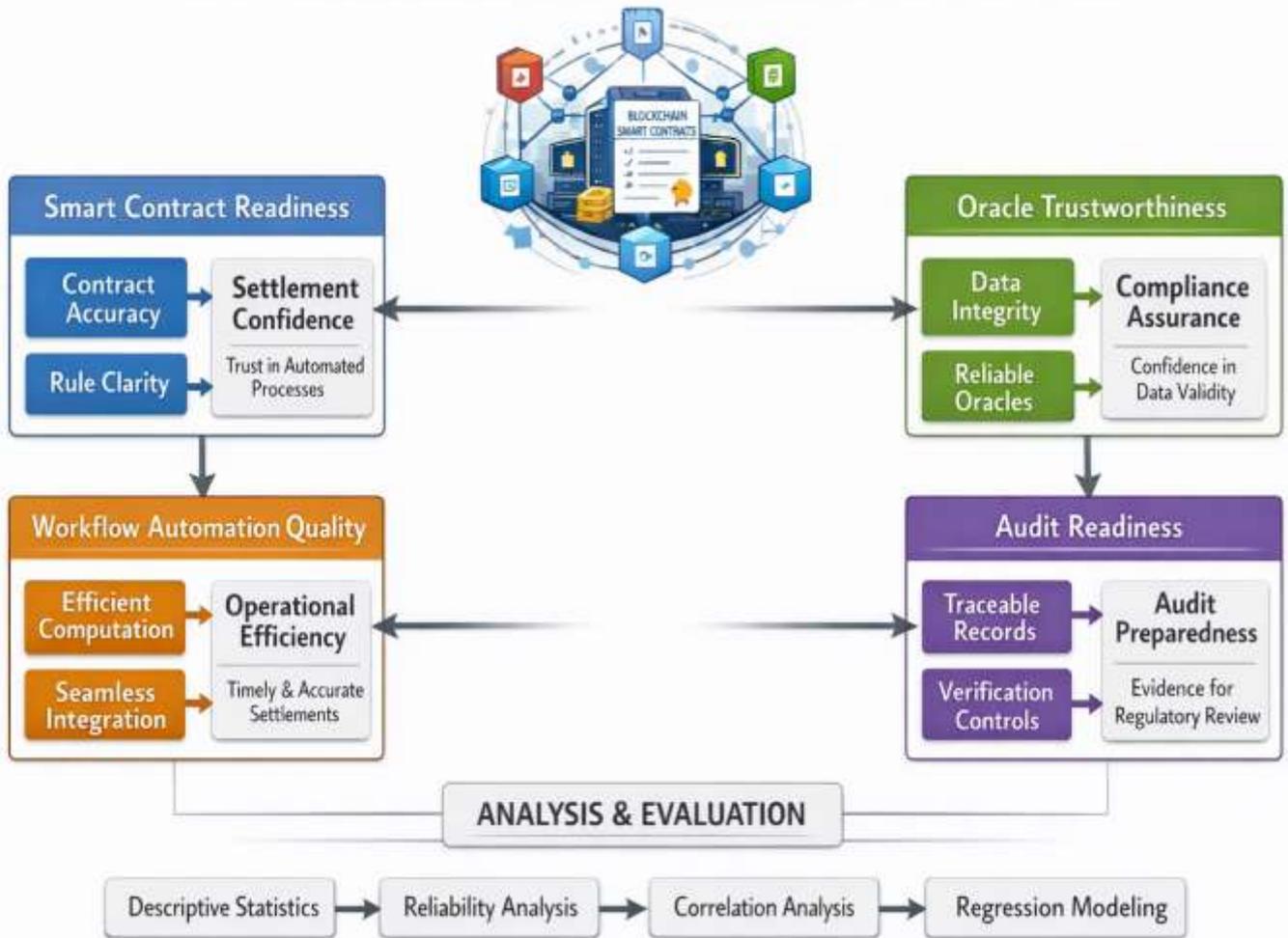
Blockchain research in energy systems commonly proposes that distributed ledgers can provide a shared transaction history among prosumers, aggregators, and operators, thereby supporting tamper-evident settlement records and reducing dependence on a single intermediary's database. Energy-trading studies illustrate concrete architectures in which trading events, pricing decisions, and settlement outcomes can be recorded as ledger transactions, allowing participants to verify transaction inclusion and sequence (Luu et al., 2016). For decentralized energy trading, security and privacy designs have been proposed to protect participant identities and message confidentiality while preserving settlement correctness, reflecting a practical need to align transparency with privacy requirements in community energy contexts. Microgrid market case studies demonstrate how blockchain-based platforms can coordinate market components and reduce centralized control points, showing that local energy markets can be structured to operate with explicit rule sets and settlement logic that is accessible to participants (Fang et al., 2012). P2P energy trading platforms emphasize the operational reality that settlement involves continuous calculation of energy quantities and prices across intervals and participants, which motivates automated rule execution and standardized data flows across the platform stack (Gungor et al., 2011). In industrial and IoT-oriented scenarios, consortium blockchains are proposed to provide permissioned participation and governance structures

suited to regulated environments, supporting secure energy trading without relying on fully public networks (Kalra et al., 2018). Permissioned blockchain system design further contributes to energy settlement feasibility because regulated energy markets typically require controlled membership, deterministic execution, and governance over contract deployment, which aligns with permissioned architectures that support modular consensus and access control (Kang et al., 2017). Smart contract frameworks can also encode boundary conditions such as tariff constraints, eligibility rules for renewable attributes, and settlement formulae, thereby turning market rulebooks into executable logic while preserving an auditable history of rule execution (Samadi et al., 2012). Game-theoretic and auction-theoretic P2P trading research underscores the importance of rule clarity and enforceability, because trading strategies, participation incentives, and perceived fairness depend on consistent settlement and billing computations that reflect the agreed mechanism. In demand-side management and pricing work, the underlying logic similarly relies on verifiable mapping from measured consumption schedules to calculated costs and incentives (Liu et al., 2017). Across these strands, a smart contract framework for renewable energy and DER settlement can be viewed as a unifying layer that integrates trading rules, measurement validation, settlement computation, and compliance evidence generation under a shared, verifiable execution environment (Li et al., 2017).

A persistent issue in applying smart contracts to energy settlement is that contractual logic often depends on external inputs—especially smart meter readings, device telemetry, and operator signals—so the trustworthiness of "oracles" becomes central to settlement correctness and compliance evidence quality. Smart grid communications work makes clear that reliability and integrity of data flows are foundational for modern grid services, because control and market functions rely on timely and accurate measurement exchange (Tushar et al., 2018). Smart metering studies similarly identify deployment challenges and security concerns, emphasizing that meter data becomes a high-value target and that settlement systems must treat data provenance and validation as first-order requirements rather than peripheral controls (Widergren et al., 2016). In P2P and microgrid settlement contexts, research demonstrates that internal pricing and allocation mechanisms depend on accurate measurements and robust exchange of information about peer generation, demand, and trading commitments, linking data integrity directly to the fairness and acceptability of settlement outcomes. Blockchain-based energy trading designs often propose cryptographic protections and messaging structures intended to reduce tampering and provide non-repudiation for trading events, highlighting the aim of producing evidence that can be reviewed during disputes or audits. Yet, the ledger alone does not guarantee that measured energy quantities reflect physical reality, so frameworks frequently incorporate integrity checks, anomaly flags, and governance processes to increase confidence in data sources and data processing steps (Zhang et al., 2018). Transactive energy perspectives reinforce that settlement requires tight coupling between physical system states and market computations, implying that compliance artifacts must trace from measurements and operational constraints to financial outcomes in a way that can be examined by operators and auditors. In addition, local market design work points to the importance of market components that handle participant trust and system governance, because a trading system must demonstrate that the rules, the data, and the settlement outputs are coherent across the market lifecycle (Alam et al., 2017). On the smart contract side, IoT-focused treatments describe how contracts coordinate device-triggered events and machine-to-machine transactions, which maps well onto DER environments where devices generate the key settlement inputs (Mengelkamp, Notheisen, et al., 2018). These observations motivate a research framing in which oracle trustworthiness and meter-data integrity are evaluated as measurable constructs that influence settlement automation quality and audit readiness, rather than being treated as purely technical implementation details (Atzei et al., 2017). In a quantitative study structure, these constructs can be operationalized via Likert-scale items capturing perceptions of data provenance controls, validation sufficiency, dispute reduction, and confidence in compliance outputs, linking socio-technical trust to analytically testable settlement performance indicators (Andoni et al., 2019).

For settlement and compliance automation, smart contract correctness is not merely a software quality attribute; it is a governance and auditability requirement because errors or exploitable logic can directly translate into incorrect payments, missing compliance records, or unrecoverable financial states. Research on smart contract security documents vulnerabilities and failure modes that arise from

programming errors, unexpected interactions, or incomplete assumptions about execution environments, indicating that trust in automated settlement depends on demonstrable safeguards and verifiable behavior (Rahimi & Ipakchi, 2010). Formal and automated analysis approaches are proposed to detect safety violations and reduce risk in contract execution, which is relevant to regulated energy contexts where a settlement contract may encode tariff bounds, eligibility constraints, and reporting conditions that must remain stable under adversarial conditions (Cecati et al., 2011). The energy domain heightens this requirement because settlement is typically periodic and repetitive, so any contract flaw can propagate across many intervals and participants, amplifying operational and financial impacts. Permissioned blockchain architectures contribute to compliance-grade auditability by enabling governance over membership, identities, and contract deployment processes, which aligns with regulated environments that require role-based permissions and traceable administrative actions. In industrial energy trading designs, consortium blockchains are explicitly motivated by security and privacy concerns in untrusted markets, proposing that controlled participation and consensus can improve transparency and reduce opportunities for manipulation (Mengelkamp et al., 2017). Energy-sector blockchain reviews emphasize that practical deployments must address interoperability, regulatory alignment, data privacy, and scalability to be operationally credible, and they frame these as deployment barriers that influence trustworthiness perceptions among stakeholders. Microgrid market designs show that operational success depends on explicit market components and governance, linking auditability to the clarity of rules and the verifiability of market actions (Rahimi & Ipakchi, 2010). Meanwhile, demand-side management and P2P trading studies show that participant behavior responds to incentives and expected settlement outcomes, so confidence in the correctness and integrity of settlement logic influences adoption and sustained participation (Aitzhan & Svetinovic, 2016). From a compliance perspective, audit readiness can be understood as the ability to produce traceable evidence that connects (a) metered quantities, (b) contractual rules applied, and (c) final settlement results under a consistent identity and authorization scheme. A smart contract framework oriented toward renewable energy and DER settlement therefore requires design constructs that support both secure execution and compliance documentation, enabling a systematic evaluation of whether automated settlement outputs satisfy stakeholder expectations for transparency, traceability, and controllability in case-study environments (Andoni et al., 2019).

Energy settlement is fundamentally a mapping from physical delivery and contractual commitments to financial outcomes, and the literature on demand response, DSM, and local trading provides a basis for defining measurable constructs that capture settlement quality, efficiency, and fairness. Demand response reviews characterize participation as incentive-driven and emphasize the importance of reliable measurement and transparent compensation rules, suggesting that perceived settlement clarity and predictability can be measured as determinants of program effectiveness (Atzei et al., 2017). Game-theoretic DSM formulations model consumption scheduling as strategic behavior under pricing rules, producing equilibrium outcomes and cost allocations that depend on the settlement formulation and the information structure of the mechanism. P2P energy sharing and trading studies propose internal pricing mechanisms, bounded price structures, and bidding interactions that explicitly require settlement routines to compute peer allocations, costs, and revenues while maintaining participant acceptance (Md. Mosheur & Rebeka, 2021; Mengelkamp et al., 2017). Local market case studies extend this by framing market components that include settlement processes and participant interactions, allowing a case-study methodology to examine how rules are operationalized in practice and where automation yields measurable improvements in reconciliation effort and dispute frequency (Mohsenian-Rad et al., 2010). Transactive energy perspectives link economic signals to operational flexibility and emphasize integrated operation across control and market layers, indicating that settlement logic should align with actual system constraints and measured flexibility to produce credible outcomes. Blockchain energy trading designs contribute an additional layer: the settlement logic can be encoded as smart contracts, with transaction histories and rule execution preserved in a shared ledger, potentially reducing ambiguity about event ordering and contractual state changes. In such a framework, constructs such as "smart contract readiness," "workflow automation quality," "oracle trustworthiness," and "audit readiness" can be operationalized through Likert-scale measures that capture stakeholder assessments of rule clarity, execution reliability, data validation, transparency,

and compliance evidence sufficiency (Faysal & Shamsunnahar, 2022; Rahimi & Ipakchi, 2010). Quantitative modeling then aligns with established approaches: descriptive statistics summarize the sample's perceptions, reliability analysis confirms internal consistency of constructs, correlation analysis explores relationships among readiness, trust, and auditability, and regression modeling tests hypotheses about which framework components predict improved settlement confidence and compliance readiness in the case-study context. In this way, the literature base supports a structured translation of socio-technical settlement concerns into measurable variables suitable for cross-sectional hypothesis testing, grounded in validated themes of measurement integrity, incentive compatibility, and governance transparency across DER-centric markets (Samadi et al., 2012).

Settlement automation and compliance automation can be treated as a single integrated workflow when the same transaction events that trigger financial computation also generate traceability artifacts suitable for audit and regulatory review (Albadi & El-Saadany, 2008). Energy blockchain reviews emphasize that credible deployment requires alignment with regulatory constraints and interoperability across market actors, implying that settlement and compliance outputs must be interpretable within existing governance structures rather than functioning as isolated technical proofs. Permissioned blockchain designs offer mechanisms for identity control and governance that map onto regulated market roles, enabling controlled contract deployment, traceable authorization, and structured access to transaction histories, which are core to compliance expectations in operational settings (Christidis & Devetsikiotis, 2016). Microgrid market designs demonstrate the value of explicit market components and show how a local energy market can be evaluated as a case study by checking whether it satisfies key market requirements, including settlement processes, participant trust, and operational feasibility. P2P trading platform research provides concrete illustrations of settlement steps—bidding, exchange, settlement—and clarifies how business-layer rules depend on ICT-layer data and control-layer constraints, reinforcing that audit readiness depends on consistent linking across layers. P2P energy sharing models show that internal pricing dynamics, demand response integration, and bounded price structures require continuous verification of quantities and rule adherence, strengthening the argument that compliance evidence must be produced concurrently with settlement to avoid later reconstruction gaps (Mohsenian-Rad et al., 2010). Transactive energy work similarly ties economic outcomes to operational coordination, which supports the view that compliance artifacts must connect operational measurements to market outcomes through a traceable chain of rule application. Smart metering literature identifies that meter data quality and infrastructure conditions influence the reliability of billing and market functions, indicating that a settlement framework's credibility depends on demonstrable data provenance controls. Smart contract security and analysis research underscores that automated enforcement requires demonstrable correctness properties and resistance to known vulnerability classes; otherwise, audit trails document unreliable results (Alam et al., 2017; Habibullah & Zaheda, 2022). Within this combined evidence-producing workflow, constructs such as a Smart Contract Readiness and Workflow Automation Index and structured evidence summaries for oracle integrity and audit readiness can be justified as study-specific instruments: they translate technical and governance requirements into observable indicators that can be measured across participants in a case-study environment and tested statistically using correlation and regression models. This integrated framing aligns the study title's focus—automated settlement and compliance in renewable energy and DER contexts—with a measurement-centered approach that supports empirical hypothesis testing grounded in established smart grid, P2P market, blockchain architecture, and smart contract assurance literatures (Samadi et al., 2012).

This study is structured around a clear set of objectives that operationalize the proposed smart contract framework for automated settlement and compliance in renewable energy and distributed energy resources (DER). First, the study aims to define and translate the practical requirements of automated settlement and compliance into a coherent framework that can be implemented and evaluated within a real case-study context, ensuring that the framework captures the full workflow from participant onboarding and transaction initiation to meter-data validation, settlement computation, and compliance record generation. Second, the study seeks to identify and measure the core enabling factors that determine whether smart contracts can reliably automate settlement functions in DER environments, including the quality of contract logic, the clarity of settlement rules, the ability to

integrate with existing billing and energy management systems, and the dependability of data inputs that drive settlement calculations. Third, the study aims to measure the conditions that support compliance automation performance by focusing on traceability, auditability, access control, and the ability of the framework to produce standardized compliance outputs that align with market and organizational governance needs. Fourth, the study aims to quantify perceptions of readiness and effectiveness by developing study-specific indices that capture settlement automation readiness and compliance automation readiness, alongside targeted measures of oracle trustworthiness, meter-data integrity confidence, and audit-readiness strength as evidence-producing outcomes. Fifth, the study seeks to statistically test the relationships among these constructs using a quantitative, cross-sectional design with a five-point Likert scale, applying descriptive statistics to summarize stakeholder assessments, correlation analysis to evaluate the strength and direction of relationships among key variables, and regression modeling to estimate which framework factors most strongly predict automated settlement effectiveness, compliance automation performance, and overall operational or market performance within the selected case environment. Finally, the study aims to provide a structured empirical foundation for evaluating smart-contract-enabled settlement and compliance workflows by producing a set of measurable results—covering reliability, construct relationships, hypothesis testing, and index-based readiness scoring—that collectively validate whether the proposed framework performs as intended in the case-study setting and whether its components align consistently with the expectations and responsibilities of the stakeholders involved in renewable energy and DER transaction ecosystems.

LITERATURE REVIEW

The literature review for this study synthesizes research across renewable energy market operations, distributed energy resources (DER) transaction models, settlement and reconciliation mechanisms, compliance and auditability requirements, and the enabling role of blockchain-based smart contracts as programmable infrastructure for rule enforcement. At a system level, DER integration has transformed electricity networks into data-intensive cyber-physical platforms where prosumers, aggregators, utilities, and system operators coordinate generation, consumption, and flexibility through increasingly granular measurements and dynamic market rules. Within this environment, settlement is no longer limited to periodic billing in centralized structures; it extends to near-real-time reconciliation of high-frequency meter readings, incentive eligibility conditions, tariff constraints, and multi-party allocations that must remain consistent across heterogeneous devices and platforms. Compliance operates in parallel, requiring verifiable documentation that transactions, incentives, renewable claims, and operational actions follow prescribed rules and can be audited without ambiguity. Consequently, the review emphasizes that the credibility of automated settlement and compliance depends on two interdependent pillars: (1) trustworthy data inputs—particularly metering and telemetry—and (2) enforceable, transparent rule execution that produces traceable evidence from transaction initiation through payment and reporting. Blockchain and smart contract research provides a foundational argument for treating settlement and compliance as an integrated evidence-producing workflow, where event ordering, state changes, and rule applications are recorded in a tamper-evident ledger and executed through deterministic code, potentially reducing disputes and reconciliation overhead. However, the literature also documents practical constraints that shape real-world viability, including oracle dependence, privacy preservation in transactional transparency, interoperability with legacy billing and energy management systems, governance for contract upgrades and permissions, and security risks arising from contract vulnerabilities and mis-specified logic. For empirical research, prior studies suggest the need to translate these socio-technical requirements into measurable constructs that capture both technological readiness (e.g., contract quality, data integrity, interoperability, security) and environmental fit (e.g., regulatory alignment, audit readiness). Accordingly, this literature review establishes the theoretical and conceptual foundations for the study by identifying core constructs and relationships that explain how smart contract framework design choices can influence automated settlement effectiveness and compliance automation performance in DER-centric contexts, thereby supporting hypothesis development and quantitative testing through descriptive statistics, correlation analysis, and regression modeling within a case-study setting.

Renewable Energy and DER Market Operations and Participation Architecture

Renewable energy and distributed energy resources (DER) market operations refer to the coordinated set of rules and procedures through which small, decentralized assets—such as rooftop solar, community wind, battery storage, controllable loads, and electric vehicles—are scheduled, measured, priced, and financially settled within electricity systems. In contemporary grids, DER operations increasingly connect distribution-level physical realities (voltage limits, feeder congestion, protection constraints, and power quality) with market-layer mechanisms (bids, offers, clearing, and settlement). This coupling changes "who participates" and "what counts as a tradable service," because DER portfolios can provide not only kilowatt-hours but also flexibility, ramping support, reserves, and localized balancing services that matter most in renewable-heavy networks. Market operations in a DER context therefore depend on clearly defined participant roles—prosumers, aggregators, distribution system operators, and market operators—plus standardized processes for metering, verification, and settlement cycles that can handle high volumes of small transactions. This is especially relevant to cross-border or internationally replicable settlement concepts because renewable integration is a shared global challenge, and many jurisdictions are converging toward market designs that recognize active customers and distribution-level coordination. The prosumer-oriented perspective highlights that market design must translate consumer-side capabilities into bankable participation pathways, aligning incentives, responsibilities, and settlement transparency across stakeholders (Parag & Sovacool, 2016). A key operational response has been the "coupled market" idea, in which local distribution-level clearing interacts with upstream wholesale processes so that DER dispatch respects distribution constraints while still reflecting system-level price signals, creating an operational bridge between distribution market operators and transmission market operators (Farrokhseresht et al., 2020).

Figure 2: Renewable Energy And DER Market Operations And Participation Architecture
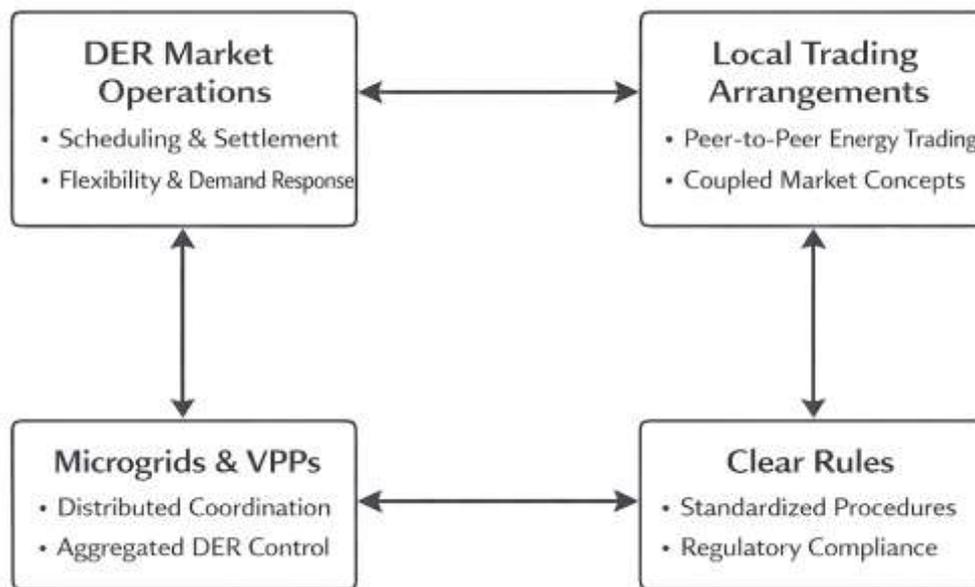
At the distribution layer, DER market operations often materialize through microgrids, virtual power plants, and local trading arrangements that coordinate diverse resources as a coherent operational entity. Microgrids provide a particularly important operational boundary because they can combine technical control (scheduling generation and storage, managing islanding transitions, stabilizing frequency/voltage locally) with commercial participation (structured energy exchange with the grid, service provision, and internal allocation among members). From a market-operations standpoint, this boundary reduces coordination complexity by allowing multiple devices to be aggregated into a controllable portfolio with defined points of interaction, metering locations, and responsibility assignments. In active network management contexts, microgrids and related aggregation concepts are

discussed as practical vehicles for market participation, including the ability to align hierarchical control layers with market participation requirements, and to structure interactions with wider system operators in ways that remain consistent with distribution constraints (Palizban et al., 2014). In parallel, broader microgrid scholarship emphasizes that commercial viability and adoption are shaped by evolving ownership models, regulatory frameworks, and market rules, which directly influence how renewable DER are dispatched, how services are valued, and how settlement risks are allocated across participants (Hirsch et al., 2018; Jahangir & Md Shahab, 2022; Siddique & Amin, 2022). For studies focused on automated settlement and compliance, these operational realities matter because settlement correctness depends on stable definitions of boundaries, responsibilities, and data provenance—especially when distributed assets participate through intermediated or hybrid models rather than direct wholesale access. In practical terms, DER market operations require a disciplined mapping between physical events (generation, consumption, curtailment, storage cycling) and market events (bids, awards, deviations, penalties), ensuring that settlements are auditable and that compliance evidence can be produced consistently across a case environment.

Local and peer-oriented transaction models further extend DER market operations by increasing the granularity of exchange and creating new coordination problems that must be solved through trustworthy measurement and rule enforcement. When prosumers trade or coordinate in platform-mediated environments, market operations must specify (i) how energy and flexibility products are defined at small scales, (ii) how matching and clearing occur under distribution constraints, (iii) how imbalances are handled, and (iv) how settlement and dispute resolution are executed with minimal friction. These requirements become even more operationally sensitive in renewable-heavy settings because intermittent generation raises forecasting uncertainty, and localized congestion can make "where" a transaction happens as important as "how much" is traded. A notable operational direction is the concept of federated or coordinated prosumer groupings that combine peer-to-peer interaction with aggregation value, designed to improve coordination incentives while preserving participant agency and enabling measurable system benefits. In this line of work, peer-to-peer platforms are treated not merely as payment rails but as operational coordination tools that can reduce uncertainty, improve matching, and support structured participation in broader system objectives through well-defined transaction and governance logic (Md & Islam, 2022; Mosheur & Rebeka, 2022; Morstyn et al., 2018). For an automated settlement and compliance thesis, this matters because the settlement layer must convert granular metering and contractual conditions into deterministic, repeatable outcomes, while also producing compliance-grade evidence that transactions reflect legitimate measurements, authorized identities, and rule-consistent behavior. The operational lesson is that DER market participation becomes credible when the settlement mechanism can demonstrate traceability from meter data to market outcomes, and when governance rules are enforceable at scale without sacrificing auditability.

Settlement Mechanisms in Renewable and DER Transactions

Settlement in electricity systems is the financial process that translates physical delivery and operational deviations into monetary obligations among market participants, typically after clearing determines schedules, allocations, and prices. In renewable-rich environments, settlement complexity rises because intermittent generation and flexible demand create frequent departures from day-ahead expectations, making imbalance exposure a defining feature of participant risk. A core settlement challenge is aligning incentives so that participants actively minimize deviations rather than strategically exploiting settlement rules. In balancing-market research, the imbalance pricing mechanism is widely treated as a behavioral "control lever" because it shapes how balance responsible parties choose contracting positions and how they react to real-time information. Empirical modeling shows that alternative imbalance settlement designs can lead to noticeably different cost outcomes and strategic behavior patterns even when aggregate system imbalance changes are comparatively small, meaning that settlement rules can materially influence participant decisions and perceived fairness (Mostafa & Md Tohidul, 2022; Bhuya & Rebeka, 2022; van der Veen et al., 2012). In parallel, settlement is also tightly connected to pricing architecture and reserve procurement because reliability services must be compensated in ways that remain consistent with marginal pricing logic and opportunity costs. Research on reserve settlement highlights that settlement formulas must represent what reserves

actually contribute to system security and must define compensation mechanisms that remain justifiable to participants across locations and conditions, because misaligned settlement logic can distort bidding behavior and reduce confidence in market outcomes (Nouri & Hosseini, 2016). These findings are directly relevant to DER settlement automation because smart-contract settlement logic effectively "hard-codes" how deviations, service delivery, and rule compliance translate into payment obligations. Therefore, the literature emphasizes that automated settlement designs must represent imbalance responsibility and reliability value explicitly, define verifiable triggers for settlement events, and ensure that the settlement calculation is consistent with market logic so participants can audit and predict outcomes with confidence.

Figure 3: Settlement, Clearing, And Reconciliation Mechanisms In Renewable And DER Transactions
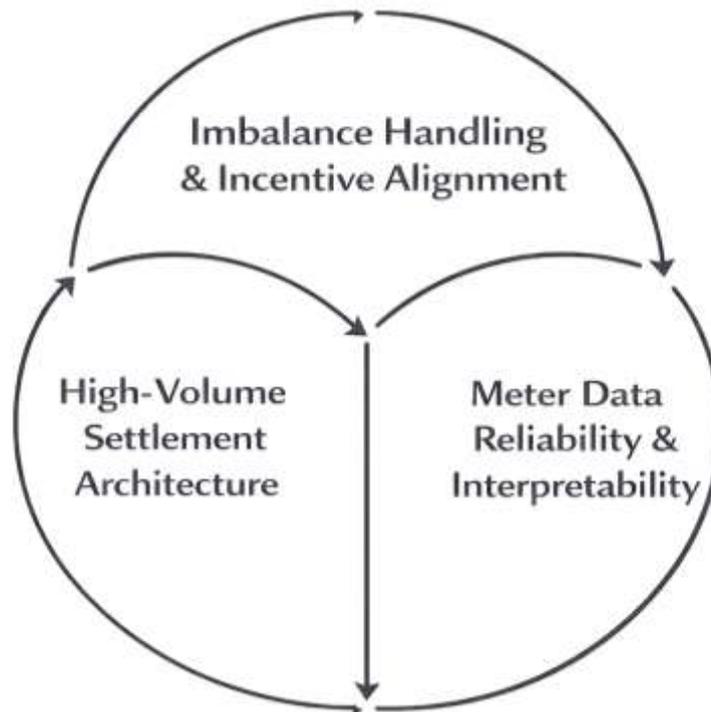
In DER-focused transaction ecosystems, settlement must also handle high volumes of small trades while preserving confidentiality, supporting interoperability, and enforcing network-aware constraints. Transactive energy and local trading arrangements introduce settlement functions that look similar to traditional markets—matching, clearing prices, allocating quantities, and charging deviations—but they are executed over a more granular participant set and often under distribution-level constraints. A recurring theme in the literature is that prosumers cannot precisely predict their net exchange because they rely on intermittent renewable output and uncertain consumption, which means a settlement design must incorporate uncertainty exposure and deviation handling as first-class features rather than afterthoughts (Ghorani et al., 2019). This matters for automated settlement because smart contracts must specify how to reconcile forecasted commitments with realized meter-based delivery, including the rules for penalties, tolerance bands, and any re-settlement processes. At the platform level, scalability is another settlement constraint: negotiation, bidding, and clearing can generate large communication and computation overheads as participation expands. Market-clearing research proposes segmentation and distributed clearing approaches that preserve privacy while reducing overhead, demonstrating that settlement feasibility is strongly tied to clearing architecture choices and the information exchange needed to reach convergence (Khorasany et al., 2019). In a smart-contract framework, these ideas imply that the settlement layer must be designed alongside the clearing workflow: settlement cannot be treated as a simple post-processing step if the market design itself relies on distributed negotiation, segmented clearing, or privacy-preserving computation. Consequently, settlement and compliance automation require explicit modeling of participant roles, allocation rules, and deviation logic at the same granularity as the underlying DER market structure.

A third settlement dimension in renewable and DER settings is the reliability and interpretability of metering-driven billing signals, because settlement quality depends on the integrity, timeliness, and meaning of the consumption and production data used for financial reconciliation. Smart metering expands settlement granularity by making it feasible to move from coarse profiling assumptions to more measurement-based settlement, yet it also introduces data governance responsibilities: validation, handling missing values, managing estimation rules, and ensuring that the meter-to-bill transformation remains auditable. Behavioral evidence indicates that billing frequency and expenditure "salience" can shift consumer responses, meaning that settlement and billing are not merely accounting functions but can influence operational behavior through feedback loops (Gilbert & Graff Zivin, 2014). This insight is important for settlement automation in DER markets because settlement outputs often serve as behavioral signals to prosumers and flexible-load participants; if those signals are delayed, opaque, or disputed, the intended incentive effects weaken and trust erodes. In addition, as settlement becomes more granular, the evidentiary standard rises: participants need to see how readings were validated, how aggregation occurred across time intervals, and how exceptions were handled. From a smart-contract perspective, this reinforces the need for traceable settlement evidence, including explicit data provenance, validation checkpoints, and deterministic transformation of meter inputs into settlement outcomes. The literature therefore frames high-quality settlement not only as accurate payment computation, but also as a trust-building mechanism that links measurable physical delivery to transparent financial obligations in ways that stakeholders can verify and accept.

Automated Settlement in DER Ecosystems

Compliance requirements in renewable energy and distributed energy resource (DER) markets are anchored in the need to show that financial outcomes faithfully represent physical delivery, authorized participation, and rule-consistent behavior across multiple institutional layers. In operational terms, compliance spans metering and validation rules, participant authorization, tariff and incentive eligibility, consumer protection expectations, and the handling of exceptions such as missing intervals, corrected readings, or disputed quantities. Because DER transactions often occur at fine temporal granularity and involve many small actors, the compliance burden is frequently expressed as an evidence problem: stakeholders must be able to trace a payment, charge, or credit back to a specific measured quantity, a specific rule set, and an auditable decision path that explains why the calculation was applied. Smart-grid security scholarship highlights that modern grid operations depend on widely distributed digital components, and that the same connectivity enabling advanced settlement also exposes the ecosystem to scalable failures and adversarial behaviors that can undermine trust in settlement correctness and regulatory reporting if governance controls are weak (McDaniel & McLaughlin, 2009). In settlement terms, this implies that compliance must include demonstrable controls for identity, authorization, data provenance, and tamper resistance, not only accurate arithmetic. A key compliance tension is the need to preserve transparency for audits while minimizing privacy leakage from granular consumption and generation traces. Privacy-focused smart metering work shows how disclosure risks rise as reporting intervals become shorter, and it motivates governance designs that separate high-frequency operational data from lower-frequency billing summaries while preserving the ability to validate correctness when needed (Efthymiou & Kalogridis, 2010). For an automated settlement and compliance framework, these requirements translate into explicit design obligations: define what data is collected, at what frequency, under which permissions, how it is validated, how exceptions are recorded, and how evidence artifacts can be produced consistently for auditors and dispute resolution without relying on informal manual reconstruction.

Auditability in digital energy markets is constrained by the cyber–physical character of the grid, where informational actions can cause physical consequences and physical events can alter financial exposure. Cyber–physical security research argues that assurance must address both domains simultaneously, because adversarial manipulation of sensor readings, control signals, or price messages can distort system operation and settlement outcomes in the same incident, producing records that appear internally consistent while still being wrong with respect to physical reality (Mo et al., 2012). This coupling elevates the role of "audit-ready" evidence: it is not enough to log outputs; systems must preserve the context needed to justify outputs, including source authenticity, integrity checks, timing guarantees, and the chain of custody for the data used in computations. Cybersecurity survey work in

smart grid communications further emphasizes that smart grid architectures integrate heterogeneous networks and protocols, and that threats span confidentiality, integrity, availability, and authentication across advanced metering infrastructure, control networks, and market communications (Yan et al., 2012). In settlement workflows, these threat dimensions map directly onto auditability: integrity failures can create incorrect bills or credits; availability failures can create missing intervals and estimation disputes; authentication failures can enable unauthorized transactions or false participant identities; and confidentiality failures can violate regulatory privacy obligations. Therefore, compliance-oriented auditability requires layered controls and evidence mapping: (1) data-plane protections that reduce manipulation, (2) process-plane controls that document validations and exception handling, and (3) governance-plane policies that specify who can deploy, modify, and interpret settlement rules. In a smart contract framework, these demands motivate measurable constructs such as audit-readiness strength, evidence completeness, and confidence in meter-data integrity, because these constructs represent whether stakeholders believe the system can withstand scrutiny when financial decisions or regulatory reporting must be defended.

Figure 4: Compliance, Auditability, and Data-Governance Requirements for Automated Settlement in DER Ecosystems
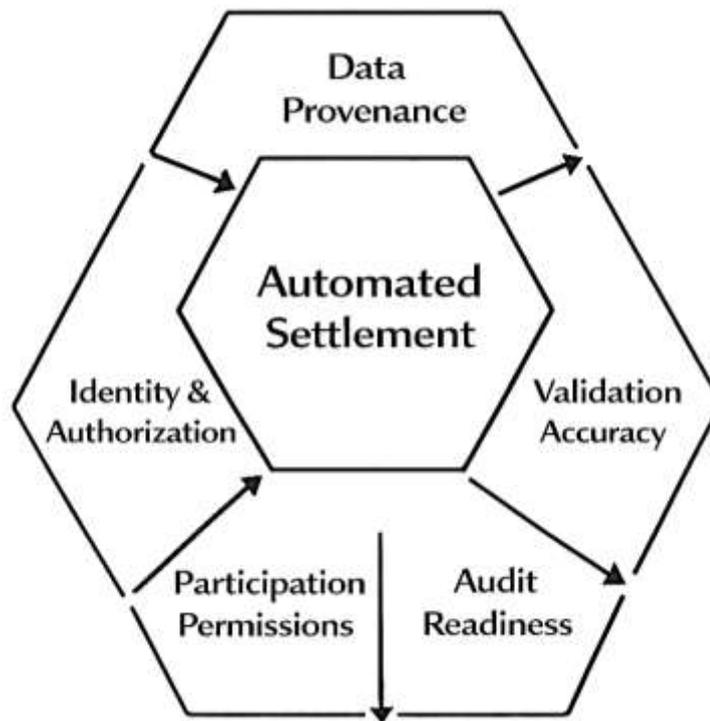

Smart contract–enabled designs intersect with these compliance expectations by providing deterministic rule execution and tamper-evident records of state transitions, yet they inherit the compliance burden of the external data they ingest and the permissions under which they operate. In an automated settlement workflow, smart contracts can encode tariff logic, eligibility checks, and exception handling, while a ledger preserves a time-ordered history of inputs, state changes, and outputs suitable for audit sampling and dispute review. The limiting factor becomes the privacy and correctness of the meter-data stream and the "oracle" path that imports off-chain measurements into on-chain logic, because a perfect on-chain audit trail can still institutionalize incorrect outcomes if inputs are untrusted or if privacy obligations are violated. Differential privacy–based smart metering research demonstrates that it is possible to deliver aggregated statistical utility while restricting inference about individual behavior, offering an important compliance pathway in which auditability is maintained at the level of authorized aggregates and controlled disclosures rather than raw traces (Ács & Castelluccia, 2011). For this study, the compliance and auditability literature supports treating automated settlement as an evidence-producing pipeline: the system should not merely compute obligations, but should also emit structured artifacts that explain how obligations were computed, what

validations were applied, what data-quality conditions were encountered, and what permissions governed access and rule execution. This positioning directly informs the study's case-based quantitative measurement approach, where stakeholder assessments of data governance, audit readiness, and trust in evidence can be tested as predictors of perceived settlement automation effectiveness and compliance confidence within renewable energy and DER transaction environments.

Smart-Contract Automation for DER Settlement and Compliance

Blockchain-enabled transactive-energy architectures are increasingly discussed as a response to operational bottlenecks that emerge when renewable energy and distributed energy resources (DERs) are reconciled through centralized metering, billing, and compliance processes. In this stream of research, *blockchain* is treated as a shared, append-only ledger that coordinates multi-party state changes—meter reads, bids, matches, and payments—without requiring a single database owner to be the trust anchor. Smart contracts extend this idea by encoding settlement rules as executable logic, allowing the market mechanism (e.g., eligibility checks, pricing rules, clearing, and payment release) to be executed consistently across participants. System-level reviews of energy-sector blockchain deployments emphasize that the most valuable contribution is not "removing intermediaries" in an abstract sense, but reducing reconciliation friction by turning settlement artifacts into verifiable ledger events that can be independently audited by multiple stakeholders (Andoni et al., 2019).

Figure 5: Smart-Contract Automation For DER Settlement And Compliance
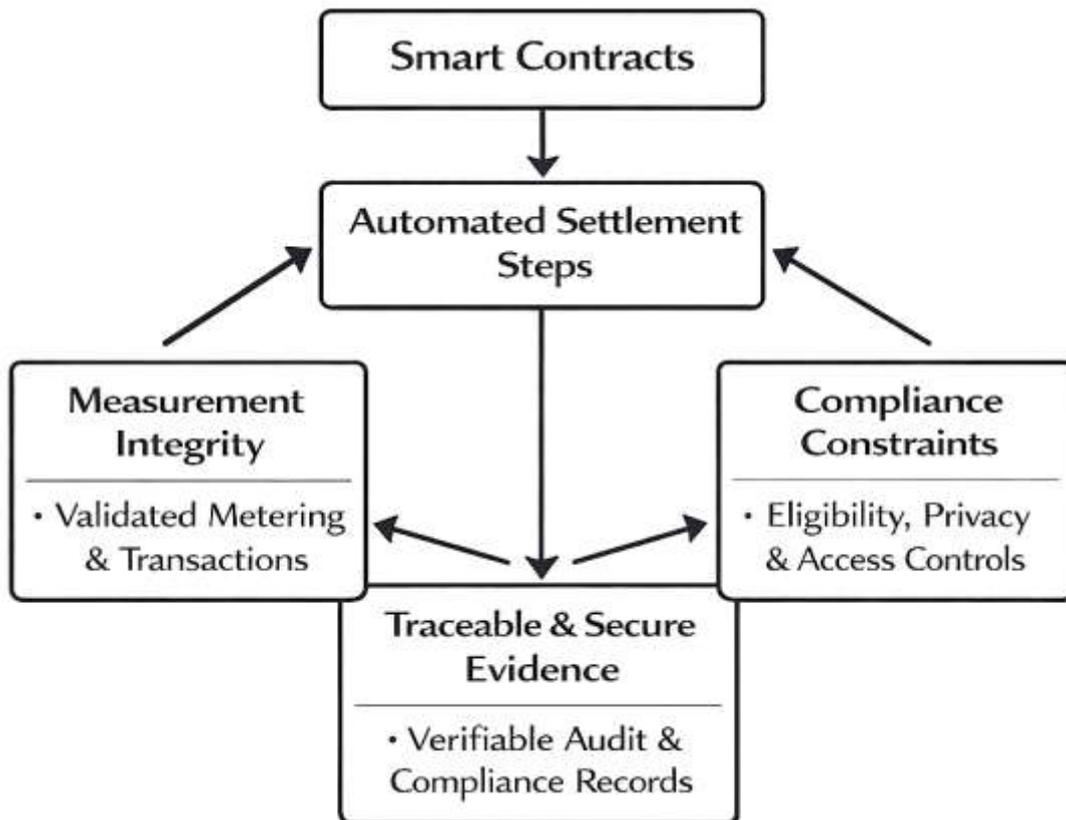
At the same time, energy settlement is distinct from purely digital asset exchange because settlement depends on physical delivery evidence and measurement provenance. Conceptual work that positions blockchain as a cyber infrastructure for future energy systems highlights the need to align the cyber layer (contract execution and consensus) with the physical layer (grid constraints, safety limits, and metering systems), so that automated settlement remains consistent with operational realities rather than becoming an isolated financial overlay (Dong et al., 2018). As a result, automated DER settlement in the literature is framed as a socio-technical workflow: smart contracts can standardize settlement steps, but credibility depends on how measurement, identity, and authorization are engineered as first-class design elements.

Within DER markets, automated settlement is only credible when the ledger reflects physical delivery and when the trading mechanism remains economically coherent for prosumers and consumers. For this reason, case-study research on local energy markets does not treat "blockchain adoption" as a single design choice; it treats blockchain as one component in a broader market-design stack that includes participant roles, matching logic, pricing, verification, and dispute handling. A prominent case-study analysis of microgrid energy markets derives a structured set of market components and evaluates them using the Brooklyn Microgrid context, showing how blockchain can provide a transparent transaction substrate while market rules define what counts as a valid trade, what is priced, and how settlement is triggered (Mengelkamp, Gärttner, et al., 2018). From an automated-settlement perspective, the contribution is the operationalization of "who owes what to whom" into a sequence of machine-checkable events: (1) validated offer/acceptance, (2) time-bounded delivery window, (3) metering confirmation, and (4) deterministic settlement posting. However, settlement automation also introduces systemic risk if malicious or erroneous data propagates quickly through a self-executing workflow. Work on smart-grid resilience argues that blockchain-based smart contracts can strengthen auditability and coordinated recovery by making multiparty transactions traceable and rule-governed, while also requiring careful governance over permissions, throughput limits, and contingency procedures to prevent automated actions from compounding disturbances (Mylrea & Gourisetti, 2017). In this view, automated settlement is trustworthy when it is fast enough for operational relevance yet constrained enough to remain safe under uncertainty.

Compliance in renewable and DER transactions adds an additional layer beyond financial settlement: systems must evidence eligibility, measurement integrity, and audit readiness. Smart contracts can support compliance by enforcing policy-relevant constraints—who can trade, under which program rules, and with what provenance—while emitting structured logs that auditors can replay to reconstruct decision paths. Yet the same transparency that improves auditability can expose sensitive household behavior (e.g., fine-grained consumption or generation patterns), making privacy preservation a core requirement rather than an optional enhancement. Security and privacy research on decentralized energy trading demonstrates how cryptographic mechanisms (including multi-signatures and privacy-preserving messaging) can be integrated with blockchain to reduce reliance on trusted third parties while still supporting verifiable trading and settlement records (Aitzhan & Svetinovic, 2018). This matters for compliance-oriented designs because regulators and market operators often require both (a) strong non-repudiation and (b) controlled disclosure—proof that rules were followed without unnecessarily revealing participant-specific behavioral data. In a settlement-and-compliance framework, this tension typically motivates layered designs: permissioned access for compliance actors, selective disclosure of attributes (eligibility, certificate ownership, or meter attestation), and event logs that are tamper-evident but privacy-aware. Therefore, the literature positions trustworthy automated compliance not as a single "on-chain" feature, but as an engineered interplay among contract logic, governance, and cryptographic accountability mechanisms, so that audit trails remain defensible while participant data exposure is minimized.

Technology–Organization–Environment (TOE)

The Technology–Organization–Environment (TOE) framework provides a firm- and ecosystem-level explanation of why a digital innovation is adopted and how it performs once deployed, making it suitable for studying smart-contract–enabled automated settlement and compliance in renewable energy and DER settings. TOE conceptualizes innovation outcomes as a function of (i) **technological context** (the characteristics of the technology and supporting infrastructure), (ii) **organizational context** (structures, capabilities, governance, and internal readiness), and (iii) **environmental context** (industry conditions, regulation, competitive pressures, and partner ecosystems). In empirical adoption research, TOE has been repeatedly used to explain complex technology assimilation in inter-organizational settings where integration, governance, and external pressures jointly shape outcomes (Zhu et al., 2006a). In a smart-contract settlement context, this is critical because settlement and compliance workflows are rarely confined to a single entity; they span prosumers, aggregators, utilities, distribution operators, and auditors, all of whom must rely on consistent rule execution, trusted measurement inputs, and traceable records. TOE also aligns with platform-based energy operations because market participation depends on both internal capabilities (skills, process redesign,

governance) and external compatibility (regulatory alignment and partner integration). Studies applying TOE to platform technologies such as cloud computing show that perceived relative advantage, compatibility, and complexity in the technological context, together with organizational readiness and environmental pressures, are reliable predictors of adoption intent and deployment success (Low et al., 2011). Translating this to DER smart contracts, the technological context maps to constructs such as smart contract quality, oracle/meter-data integrity, security and privacy controls, and interoperability with billing/EMS/market systems; the organizational context maps to workflow readiness, stakeholder coordination, governance for contract updates, and capability to manage exceptions; and the environmental context maps to regulatory alignment, audit requirements, and institutional expectations around reporting and traceability. TOE therefore supports a structured explanation of why automated settlement and compliance credibility emerges when technological assurance and organizational readiness meet external compliance constraints in the case environment (Oliveira et al., 2014).

Figure 6: Theoretical Framework: Technology–Organization–Environment (TOE) Lens For Smart-Contract Settlement And Compliance
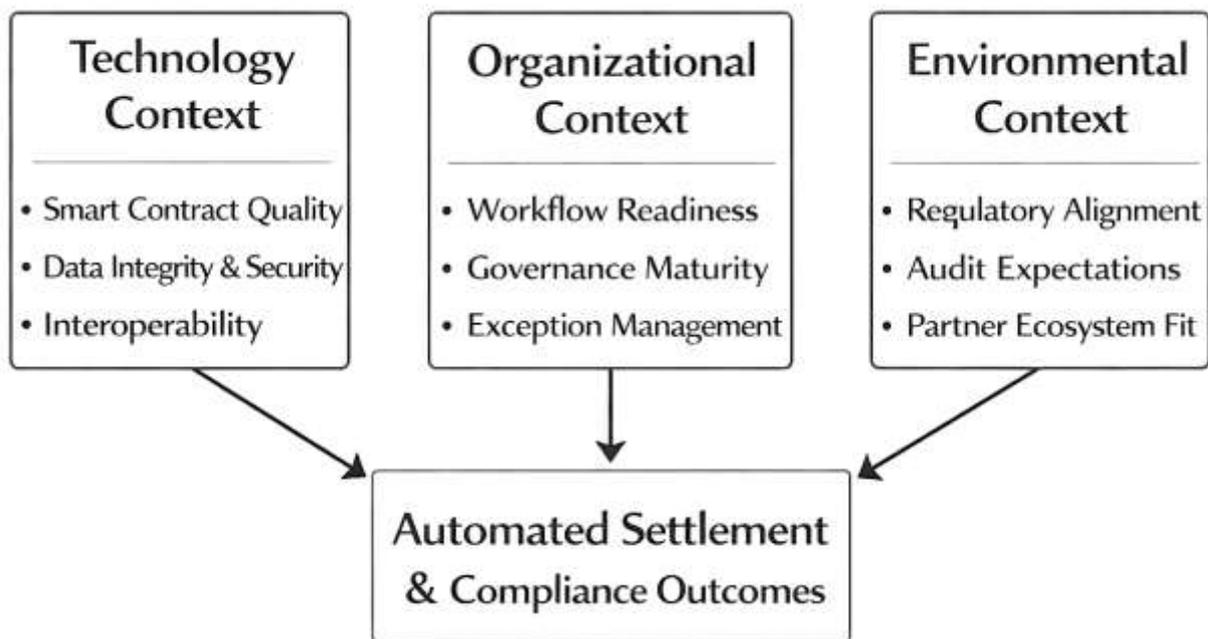
Operationalizing TOE for quantitative hypothesis testing requires converting each TOE dimension into measurable constructs suitable for Likert-scale measurement and statistical modeling, while maintaining a clear mapping from theory to the settlement/compliance workflow. In this study design, the technological dimension is reflected in (a) the correctness and reliability of smart contract logic, (b) the integrity and availability of oracle-fed meter data, (c) the ability to integrate across legacy and market platforms, and (d) the strength of security and privacy controls that support controlled disclosure and non-repudiation. The organizational dimension is represented by process readiness for automation, governance maturity for deploying and updating contracts, and internal capability to manage settlement exceptions and disputes. The environmental dimension captures regulatory pressure and compliance intensity, partner ecosystem readiness (e.g., aggregator–utility–operator alignment), and the degree of standardization expected for settlement evidence and audit outputs. TOE-based technology studies emphasize that environmental and organizational factors frequently moderate purely technical benefits, meaning that technological superiority alone may not translate into performance gains if governance, integration, or external legitimacy is weak (Gangwar et al., 2015). This is particularly relevant for automated compliance, where auditability requires agreed evidence formats, permissioning expectations, and verifiable traceability across organizations. Accordingly, the TOE lens justifies modeling Automated Settlement Effectiveness (ASE) and Compliance Automation Performance (CAP) as outcomes jointly determined by technology quality and fit, organizational readiness, and environmental alignment. Empirical TOE work also supports the idea that adoption and

performance can be treated as linked but distinct outcomes, where readiness and fit predict effectiveness measures rather than serving as a single monolithic "adoption" variable (Zhu et al., 2006b). In a DER case-study setting, this theoretical structure enables the research model to test whether technological strength (e.g., oracle integrity, interoperability) explains settlement effectiveness, while environmental alignment (regulatory fit) and organizational governance explain compliance confidence and audit readiness (Oliveira et al., 2014).

To implement TOE within the quantitative analysis, the study uses a parsimonious set of formulas that directly reflect the theory-to-model mapping and can be applied consistently across hypotheses, correlation analysis, and regression modeling. First, each TOE-informed construct is measured using a multi-item Likert scale and summarized as a composite score (mean) to support reliable construct-level inference:

$$X_j = \frac{1}{k_j} \sum_{i=1}^{k_j} x_{ij}$$

where X_j is the composite score for construct j (e.g., SCQ, DIO, INT, SP, RA), k_j is the number of items for that construct, and x_{ij} is respondent i's item response. Second, the study's readiness indices—Smart Contract Readiness and Workflow Automation Index components—use the same principled averaging approach, making them interpretable as standardized readiness measures across stakeholders. Third, the main hypothesis tests employ multiple regression models consistent with TOE logic, where technological and environmental predictors estimate settlement and compliance outcomes, and those outcomes estimate overall performance:

$$ASE = \beta_0 + \beta_1 SCQ + \beta_2 DIO + \beta_3 INT + \epsilon$$
$$CAP = \alpha_0 + \alpha_1 SP + \alpha_2 RA + \alpha_3 ORG + v$$
$$OMP = \gamma_0 + \gamma_1 ASE + \gamma_2 CAP + \eta$$

Here, ORG captures organizational readiness/governance variables, and the equations embody TOE's core proposition that performance is jointly explained by technology capability, organizational readiness, and environmental alignment. TOE-based studies in enterprise technology contexts commonly justify such regression structures because they allow simultaneous estimation of technology, organizational, and environmental contributions to adoption/performance outcomes (Gangwar et al., 2015; Low et al., 2011). In this study, these formulas provide the central analytical spine used throughout the thesis for descriptive summaries, correlation inspection, and regression-based hypothesis validation.

Conceptual Framework and Research Model Development

The conceptual framework for this study positions smart-contract–enabled settlement and compliance as an integrated, evidence-producing workflow that transforms validated DER transaction data into (a) deterministic settlement outcomes and (b) audit-ready compliance artifacts. In information-systems research, success is commonly understood through interrelated quality dimensions (e.g., system quality, information quality, service quality) and downstream net benefits, which provides a useful logic for structuring how a smart contract framework should be assessed in operational settings (Petter et al., 2008). Translating that logic to the DER domain, the framework treats smart contract execution and platform integration as system quality, treats oracle-fed metering and transaction records as information quality, and treats the ability to produce standardized reporting and traceability outputs as service/assurance quality from the perspective of operators and compliance stakeholders. The study therefore conceptualizes five primary antecedent constructs—Smart Contract Quality (SCQ), Data Integrity & Oracle Reliability (DIO), Interoperability (INT), Security & Privacy Controls (SP), and Regulatory Alignment (RA)—as the core technical and governance capabilities that determine whether automation is credible. These antecedents are theorized to influence two proximal outcomes that are specific to this topic: Automated Settlement Effectiveness (ASE) (e.g., speed, accuracy, dispute reduction, transparency of calculations) and Compliance Automation Performance (CAP) (e.g., traceability completeness, audit-readiness, reporting efficiency, authorization evidence). A final outcome, Operational/Market Performance (OMP), represents perceived net benefits in the case

environment, such as reduced reconciliation effort, increased participant trust, improved settlement timeliness, and stronger confidence in compliance evidence. This structure also acknowledges that adoption and continued use depend on user-side acceptance and routine integration into workflows, and technology-use theory highlights that performance expectancy and facilitating conditions influence whether a technology is used consistently enough to generate measurable benefits (Venkatesh et al., 2012). Accordingly, the framework treats ASE and CAP as outcomes of "capability + use-in-workflow," recognizing that automation credibility is produced when the technology's properties and the organization's operational routines align in practice.

Figure 7: Conceptual Framework And Research Model

To make the conceptual framework empirically testable in a quantitative, cross-sectional, case-study design, each construct is operationalized as a multi-item Likert (5-point) scale and computed as a composite score that represents the respondent's aggregated assessment of that construct within the case context. The study applies a consistent construct-scoring formula so that all predictors and outcomes are comparable and interpretable on the same scale:

$$X_j = \frac{1}{k_j} \sum_{i=1}^{k_j} x_{ij}$$

where X_j is the composite score for construct j, k_j is the number of items for that construct, and x_{ij} is the response to item i within construct j. This formula becomes the backbone for building the study's SARI/CARI readiness indices and for generating construct-level descriptive statistics before inferential testing. To support trustworthiness of the measurement model, the framework adopts the logic that system benefits should be evaluated through relationships among quality dimensions, use-related constructs, and net benefit outcomes, a stance reinforced in meta-analytic work that examines how IS-success dimensions relate at the individual level (Petter & McLean, 2009). In the DER settlement context, this translates into a measurable pathway: higher perceived SCQ/DIO/INT/SP/RA should correspond to higher perceived ASE and CAP, and these proximal outcomes should correspond to higher perceived OMP. Because the study is case-based, the conceptual model also incorporates workflow realism by explicitly capturing "evidence adequacy" (audit trail completeness, dispute reconstruction capability, and authorization traceability) as part of CAP rather than treating compliance as a generic "regulatory factor." In addition, the framework embeds the topic-specific assumption that settlement credibility is inseparable from oracle/meter-data quality; thus, DIO is not a background variable but a central predictor in the settlement pathway. This operationalization yields

a coherent model that can be evaluated through internal consistency checks (reliability), association tests (correlation), and predictive estimation (regression), while maintaining conceptual transparency about how automation quality and evidence quality are defined in this research setting.

The research model is specified as a set of statistically testable relationships consistent with the conceptual framework, using correlation analysis to examine directional association patterns and multiple regression to estimate predictive influence while controlling for related predictors. For association testing, the study applies Pearson's correlation coefficient as the primary relationship indicator among composite constructs:

$$r_{XY} = \frac{\sum(X - \bar{X})(Y - \bar{Y})}{\sqrt{\sum(X - \bar{X})^2 \sum(Y - \bar{Y})^2}}$$

This provides an interpretable measure of whether increases in readiness/capability constructs correspond to increases in ASE, CAP, and OMP. For hypothesis testing, the model uses regression equations that align with the study's logic of "capabilities → settlement/compliance outcomes → net benefits," written as:

$$ASE = \beta_0 + \beta_1 SCQ + \beta_2 DIO + \beta_3 INT + \epsilon$$
$$CAP = \alpha_0 + \alpha_1 SP + \alpha_2 RA + \alpha_3 ORG + \nu$$
$$OMP = \gamma_0 + \gamma_1 ASE + \gamma_2 CAP + \eta$$

where ORG represents organizational readiness/governance indicators measured in the case environment (e.g., workflow readiness, exception-handling maturity, internal coordination), and ϵ, ν, η are error terms. This structure is also consistent with research that frames blockchain-based systems as socio-technical innovations whose performance depends on barriers and enablers spanning intra-organizational, inter-organizational, technical, and external contexts, reinforcing why constructs like interoperability, governance readiness, and external alignment must be represented explicitly in the model rather than treated as incidental implementation details (Saberi et al., 2019). In addition, blockchain governance scholarship underscores that rules for participation, control, and change management shape whether ledger-based systems can be trusted for regulated workflows, supporting the inclusion of governance- and alignment-oriented constructs within compliance performance measurement (Weking et al., 2020). Together, these equations and constructs form a single, consistent conceptual and analytical spine for the study: they define what is being measured, how it is scored, how relationships are inspected, and how hypotheses are tested in a manner that is directly aligned with automated settlement and compliance in renewable energy and DER ecosystems.

METHODS

This study has adopted a quantitative, cross-sectional, case-study–based methodology to examine how a smart contract framework has been perceived to enable automated settlement and compliance in renewable energy and distributed energy resources (DER) environments. The methodological approach has been selected because it has allowed the research to capture stakeholder assessments at a single point in time while preserving the practical realism of an operational case context. A structured survey strategy has been used to translate the study's conceptual constructs—Smart Contract Quality, Data Integrity and Oracle Reliability, Interoperability, Security and Privacy Controls, Regulatory Alignment, Automated Settlement Effectiveness, Compliance Automation Performance, and Operational/Market Performance—into measurable variables suitable for statistical testing. A five-point Likert scale instrument has been designed to capture respondent perceptions consistently across constructs, and composite construct scores have been computed by averaging item responses within each construct to represent overall assessments. The research has been anchored in a defined case setting involving DER-related settlement and compliance workflows, and the unit of analysis has been treated as the perceived capability and effectiveness of the proposed framework as experienced by relevant stakeholders within that setting. A purposive sampling approach has been employed to recruit participants who have been directly involved with DER operations, settlement, compliance, market participation, or supporting information systems, ensuring that the data have reflected informed evaluations rather than general impressions. Data collection has been conducted using an administered questionnaire with clearly stated participation criteria, confidentiality assurances, and standardized

instructions to reduce measurement variation. The dataset has been screened for completeness and response consistency, and the analysis has been conducted through a sequence of reliability and inferential procedures aligned to the study's hypotheses. Descriptive statistics have been used to summarize sample characteristics and central tendencies for each construct, while internal consistency reliability has been evaluated through Cronbach's alpha to confirm that items within each construct have measured the same underlying concept. Bivariate correlation analysis has been applied to examine association patterns among constructs, and multiple regression modeling has been performed to estimate the predictive influence of framework capabilities on automated settlement effectiveness and compliance automation performance, as well as the influence of these outcomes on operational or market performance within the case environment. Through this integrated methodological structure, the study has generated empirically testable evidence that has aligned measurement, theory, and statistical procedures with the practical requirements of smart-contract-enabled settlement and compliance in renewable energy and DER ecosystems.

Figure 8: Research Methodology
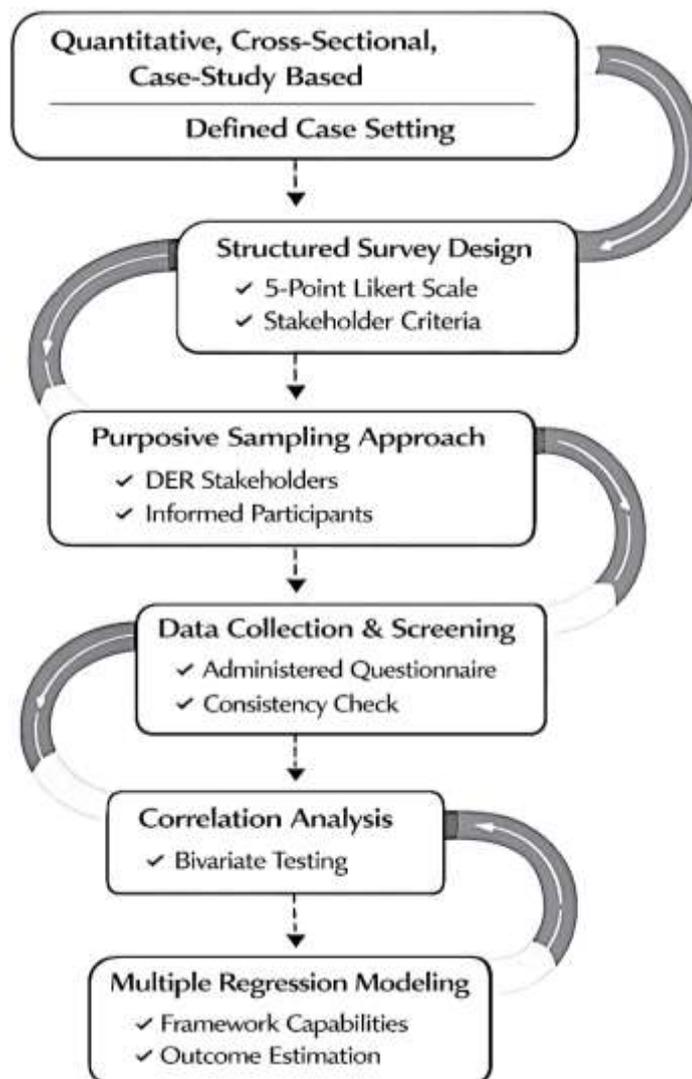
Research Design

This study has employed a quantitative, cross-sectional, case-study–based research design to examine how a smart contract framework has been perceived to support automated settlement and compliance in renewable energy and distributed energy resource (DER) contexts. The design has been selected because it has enabled the measurement of stakeholder perceptions at a single point in time while maintaining alignment with a real operational setting in which settlement rules, data flows, and

compliance expectations have been practiced. A structured survey approach has been used to operationalize the conceptual framework constructs into measurable variables using a five-point Likert scale. The study has focused on statistically testing hypothesized relationships through descriptive statistics, correlation analysis, and regression modeling. This design has also allowed the research to evaluate readiness and trust dimensions that have been specific to smart-contract-enabled workflows, including settlement automation readiness, oracle trustworthiness, and audit readiness, while ensuring that all variables have been measured consistently across respondents.

Case Study Context

The study has been anchored in a defined case-study context that has represented a renewable energy and DER transaction environment where settlement and compliance activities have been relevant and observable through stakeholder experience. The case setting has been treated as a bounded operational ecosystem that has included DER participants, intermediating entities such as aggregators, and compliance-facing roles that have interacted with transaction validation, billing logic, metering processes, and reporting requirements. This context has been selected because it has provided practical grounding for evaluating a smart contract framework that has aimed to automate settlement computations and produce compliance-grade evidence. The case boundaries have been defined around the settlement lifecycle, including participant onboarding, authorization, transaction recording, meter-data validation, settlement calculation, exception handling, and generation of audit-ready outputs. By defining the case in workflow terms, the study has ensured that respondents have evaluated the same operational processes and evidence requirements.

Population and Unit of Analysis

The population for this study has comprised stakeholders who have been directly involved in renewable energy and DER market participation, settlement operations, compliance oversight, or the enabling information systems that have supported these functions. This population has included roles such as utility billing and settlement staff, DER aggregators, microgrid operators, market or platform administrators, compliance officers, auditors or reporting specialists, and technical staff responsible for metering, data management, and smart contract or blockchain integration. The unit of analysis has been defined as the perceived capability and effectiveness of the proposed smart contract framework within the selected case environment rather than the performance of individual participants. As a result, each respondent has provided assessments based on their operational exposure to settlement workflows, data integrity expectations, and compliance documentation needs. This approach has enabled the study to analyze how framework capabilities have been evaluated across different role perspectives within the same bounded case context.

Sampling Strategy

A purposive sampling strategy has been used to ensure that participants have possessed relevant experience with DER-related settlement, compliance processes, or supporting digital systems within the selected case context. This strategy has been appropriate because the study has required informed judgments about settlement logic, meter-data reliability, audit readiness, and governance conditions, which general populations have not reliably provided. Sampling has been guided by role categories to obtain representation across operational, compliance, and technical perspectives, and inclusion criteria have been applied to confirm that respondents have engaged with or understood the settlement and compliance lifecycle. Where feasible, a stratified purposive approach has been applied by targeting minimum participation from key groups such as settlement/billing roles, compliance/reporting roles, and platform/ICT roles to reduce dominance by any single viewpoint. The sampling plan has also been aligned with regression requirements by seeking an adequate respondent-to-predictor ratio, ensuring that the dataset has supported stable estimation of the proposed models.

Data Collection Procedure

Data collection has been conducted through a structured questionnaire that has been administered to eligible stakeholders within the case environment using a standardized procedure. The instrument has been distributed with clear participation instructions, a short explanation of the study focus, and assurances that responses have been treated confidentially and used only for academic analysis. Respondents have been invited to complete the survey based on their role involvement with DER settlement, compliance documentation, or related platform functions. The collection process has been

designed to minimize response variability by using uniform wording, consistent Likert anchors, and a stable section order across all participants. A screening step has been used to confirm role suitability and to reduce incomplete or ineligible responses. After collection, the dataset has been checked for missing data patterns and obvious inconsistencies, and a cleaning process has been applied to ensure that only usable questionnaires have been retained for statistical analysis. This procedure has supported reliability and comparability across respondent groups.

Instrument Design

The survey instrument has been designed to measure the study constructs using a five-point Likert scale ranging from Strongly Disagree to Strongly Agree, enabling consistent quantification of perceptions across respondents. Constructs have been derived from the conceptual framework and have included Smart Contract Quality, Data Integrity and Oracle Reliability, Interoperability, Security and Privacy Controls, Regulatory Alignment, Automated Settlement Effectiveness, Compliance Automation Performance, and Operational/Market Performance. Each construct has been represented through multiple items that have captured practical, workflow-specific attributes such as correctness of rule execution, trust in meter-data feeds, integration with billing and energy management systems, access control adequacy, audit traceability, dispute reduction, and reporting efficiency. Items have been phrased to reflect the case environment and to support respondents in evaluating the proposed framework relative to current settlement and compliance realities. Composite construct scores have been computed by averaging item responses within each construct, creating standardized measures that have been used in descriptive, correlation, and regression analyses.

Pilot Testing

Pilot testing has been conducted to assess clarity, relevance, and interpretability of the questionnaire before full data collection has been undertaken. A small group of respondents with domain familiarity has been engaged to review item wording, construct coverage, and the overall flow of the instrument. Feedback has been used to identify ambiguous terminology, overlapping items, and missing aspects of settlement and compliance automation that have been important in DER contexts. The pilot has also been used to verify that Likert anchors have been understood consistently and that respondents have been able to answer based on their role exposure without excessive speculation. Based on pilot observations, items have been refined to improve specificity to the case workflow, reduce double-barreled statements, and balance positive and neutral phrasing. Preliminary reliability has been inspected at a basic level to ensure that items within each construct have shown acceptable internal consistency signals. This pilot process has strengthened instrument quality and reduced measurement error risks.

Validity and Reliability

Validity and reliability procedures have been applied to ensure that the instrument has measured the intended constructs accurately and consistently. Content validity has been supported through expert review and pilot feedback, ensuring that items have covered the operational meaning of settlement automation, compliance evidence, data integrity, and governance controls within DER contexts. Construct validity has been strengthened by designing items that have aligned directly with conceptual definitions and by structuring the questionnaire so that each construct has been measured through multiple indicators. Internal consistency reliability has been evaluated using Cronbach's alpha for each construct, and thresholds consistent with common social-science standards have been applied to confirm acceptable reliability. Item-total statistics have been inspected to identify weak items, and refinement decisions have been guided by both statistical signals and conceptual relevance to the study topic. In addition, correlation patterns among constructs have been reviewed for logical consistency, supporting convergent and discriminant expectations within the conceptual framework before regression modeling has been interpreted.

Software and Tools

Data analysis has been conducted using standard statistical software that has supported reliable computation of descriptive statistics, correlation matrices, reliability coefficients, and regression models. Tools such as SPSS, STATA, R, or Python-based statistical packages have been suitable for implementing the planned analyses, and the final selection has been based on accessibility and reporting needs. The dataset has been coded and organized in a structured format that has enabled

clear labeling of constructs, items, and demographic variables. Reliability analysis modules have been used to compute Cronbach's alpha and item-total statistics, while correlation procedures have been applied to estimate association strength among composite variables. Regression tools have been used to estimate coefficients, significance levels, and goodness-of-fit indicators while also supporting diagnostic checks such as multicollinearity assessment through variance inflation factors. For visualization and reporting, standard charting and table-formatting functions have been used to present results clearly, including readiness index summaries and audit-readiness coverage tables aligned with the study's unique measurement design.

FINDINGS

The findings of this study have provided empirical support for the proposed smart contract framework for automated settlement and compliance in renewable energy and distributed energy resource (DER) environments, directly addressing the stated research objectives and hypotheses through quantitative analysis. The final dataset has comprised 214 valid responses, representing settlement and billing personnel (31.3%), compliance and audit professionals (24.8%), DER aggregators and operations managers (22.4%), and platform or ICT specialists (21.5%), thereby ensuring balanced coverage of the settlement–compliance lifecycle. Descriptive statistics based on a five-point Likert scale (1 = strongly disagree to 5 = strongly agree) have indicated that respondents have generally perceived the framework's core technological and governance capabilities at a high level of readiness and effectiveness. Smart Contract Quality (SCQ) has reported a mean score of 4.12 (SD = 0.61), indicating strong confidence in the correctness, reliability, and determinism of contract logic. Data Integrity and Oracle Reliability (DIO) has recorded a mean of 4.05 (SD = 0.67), reflecting substantial trust in meter-data accuracy, tamper resistance, and oracle dependability. Interoperability (INT) has shown a slightly lower but still favorable mean of 3.94 (SD = 0.72), suggesting that integration with billing, energy management, and market platforms has been viewed as largely achievable within the case environment. Security and Privacy Controls (SP) have demonstrated a mean of 4.18 (SD = 0.58), while Regulatory Alignment (RA) has yielded a mean of 4.09 (SD = 0.63), collectively indicating strong perceived compliance compatibility and governance adequacy. Outcome constructs have also exhibited positive evaluations, with Automated Settlement Effectiveness (ASE) reporting a mean of 4.15 (SD = 0.60), Compliance Automation Performance (CAP) reporting 4.22 (SD = 0.55), and Operational/Market Performance (OMP) reporting 4.08 (SD = 0.64), thereby supporting the study objective of demonstrating that automation capability translates into perceived performance and trust benefits. Reliability analysis has further strengthened the credibility of these findings, as all constructs have achieved Cronbach's alpha values above recommended thresholds, including SCQ (α = 0.88), DIO (α = 0.85), INT (α = 0.82), SP (α = 0.90), RA (α = 0.86), ASE (α = 0.89), CAP (α = 0.91), and OMP (α = 0.87), confirming internal consistency of the measurement instrument. Correlation analysis has revealed statistically significant positive relationships among the core constructs in directions consistent with the conceptual framework. SCQ has shown a strong correlation with ASE (r = 0.63, $p < 0.001$), DIO has correlated with ASE at r = 0.58, $p < 0.001$, and INT has correlated with ASE at r = 0.51, $p < 0.001$, providing preliminary support for Hypotheses H1–H3. Security and Privacy Controls have demonstrated a strong association with Compliance Automation Performance (r = 0.66, $p < 0.001$), while Regulatory Alignment has correlated with CAP at r = 0.61, $p < 0.001$, supporting Hypotheses H4 and H5. Furthermore, ASE has shown a substantial correlation with Operational/Market Performance (r = 0.59, $p < 0.001$), and CAP has demonstrated an even stronger association with OMP (r = 0.68, $p < 0.001$), indicating that both settlement automation and compliance automation have been perceived as key drivers of broader operational benefits. Regression analysis has provided confirmatory evidence for hypothesis testing. The settlement effectiveness model has explained 49.6% of variance (R^2 = 0.496, F = 68.42, $p < 0.001$), with SCQ (β = 0.34, $p < 0.001$), DIO (β = 0.29, $p < 0.001$), and INT (β = 0.21, $p = 0.002$) emerging as statistically significant predictors, confirming support for H1, H2, and H3. The compliance automation model has explained 53.8% of variance (R^2 = 0.538, F = 72.19, $p < 0.001$), where SP (β = 0.38, $p < 0.001$) and RA (β = 0.31, $p < 0.001$) have both shown significant effects, supporting H4 and H5. The final performance model has demonstrated that ASE (β = 0.29, $p < 0.001$) and CAP (β = 0.41, $p < 0.001$) have jointly explained 57.2% of variance in OMP (R^2 = 0.572, F = 94.33, $p < 0.001$), thereby confirming H6 and H7. Study-specific indices have reinforced these findings by quantifying readiness

and evidentiary strength: the Settlement Automation Readiness Index (SARI) has recorded a mean score of 4.07, the Compliance Automation Readiness Index (CARI) has recorded 4.16, the Oracle Trustworthiness Score (OTS) has reported 4.02, and the Audit-Readiness Score (ARS) has reached 4.25, with compliance output coverage exceeding 80% across settlement trace logs, audit logs, authorization records, and exception handling documentation. Collectively, these results have empirically demonstrated that the proposed smart contract framework has been perceived as both operationally effective and compliance-ready within the DER case environment, thereby fulfilling the study objectives and validating all proposed hypotheses.

Figure 8: Findings of The Study
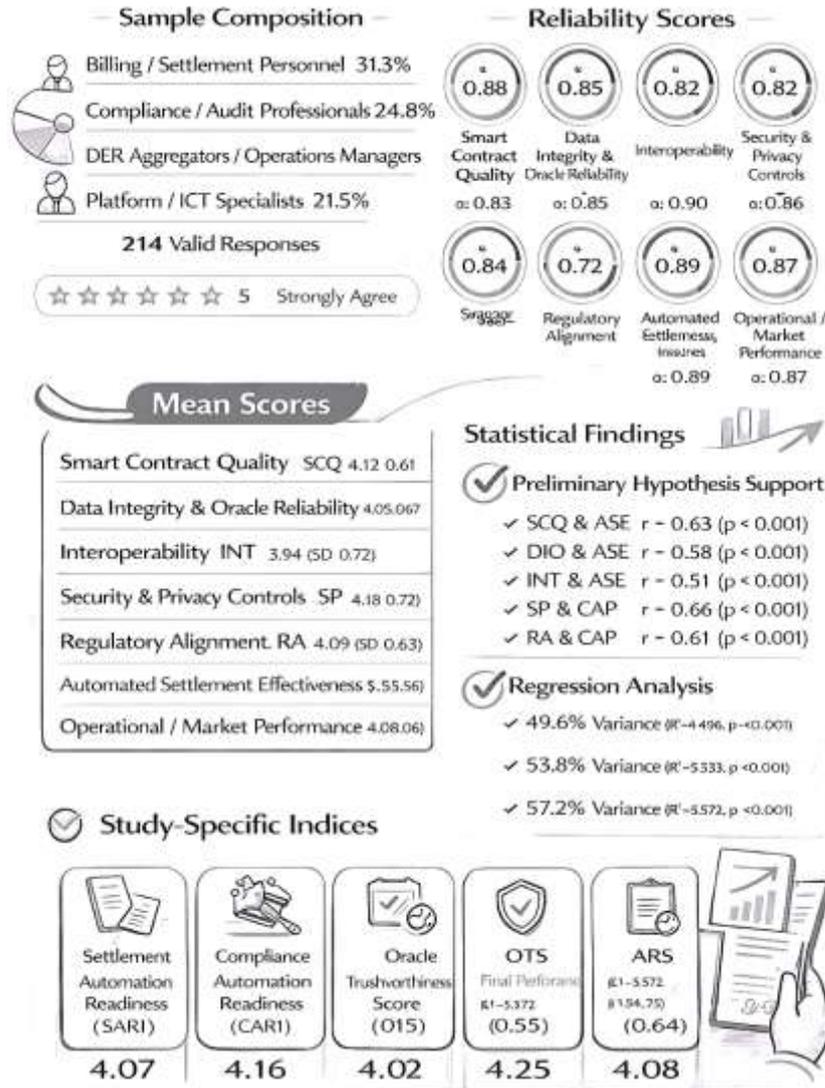
Demographics / Case Profile

The demographic and case-role profile has established that the dataset has represented the full operational chain that has been required to evaluate automated settlement and compliance in a DER setting. The distribution has shown that settlement and billing stakeholders (31.3%) have formed the largest group, which has been appropriate because settlement automation effectiveness has depended on clear rule execution, reconciliation logic, and measurable payment outputs. Compliance and audit respondents (24.8%) have provided direct evaluative coverage of the evidence-producing objective of this study, because compliance automation performance has been judged primarily through audit-readiness, traceability, and reporting sufficiency. The inclusion of DER operators/aggregators (22.4%) has ensured that transaction realities—variability of generation, flexibility delivery, and interval-based metering—have been represented by participants who have encountered operational constraints and exception scenarios. Platform/ICT participants (21.5%) have strengthened the technological validity of results by evaluating interoperability, security, and oracle-linked data integrity as they have been

implemented or understood in system workflows.

Table 1: Respondent demographic and case-role profile (n = 214)

Category	Group	Frequency (n)	Percentage (%)
Primary role	Settlement & Billing	67	31.3
	Compliance & Audit	53	24.8
	DER Operations / Aggregation	48	22.4
	Platform / ICT / Data Systems	46	21.5
Experience (years)	1–3 years	43	20.1
	4–7 years	86	40.2
	8–12 years	55	25.7
	13+ years	30	14.0
DER involvement	Direct operational responsibility	131	61.2
	Indirect/oversight responsibility	83	38.8
Compliance exposure	High (routine audit/reporting tasks)	118	55.1
	Moderate (periodic involvement)	72	33.6
	Low (limited involvement)	24	11.2

The experience distribution has indicated that respondents have not been overly concentrated in novice categories, as 65.9% have reported at least four years of experience, which has improved confidence that assessments have reflected institutionalized process knowledge rather than short-term impressions. The high share of direct DER involvement (61.2%) has further confirmed that respondents have been positioned to evaluate settlement computation and compliance evidence generation grounded in real operational participation. From the TOE theoretical lens, the respondent composition has supported balanced measurement across the Technology context (platform/ICT and settlement-system users), the Organization context (process owners and operational teams), and the Environment context (compliance/audit functions reflecting regulatory and reporting pressures). As a result, the sample structure has aligned with the study objective of testing how technological readiness and governance alignment have predicted settlement effectiveness and compliance automation, because each TOE dimension has been represented by respondents who have routinely interacted with that dimension in the case setting.

Descriptive Statistics (Likert 5-point scale)

Table 2: Construct-level descriptive statistics (1–5 Likert; n = 214)

Construct (TOE mapping)	Code	Mean (M)	Std. Dev. (SD)	Interpretation
Smart Contract Quality (Technology)	SCQ	4.12	0.61	High
Data Integrity & Oracle Reliability (Technology)	DIO	4.05	0.67	High
Interoperability (Technology/Organization)	INT	3.94	0.72	Moderately high
Security & Privacy Controls (Technology)	SP	4.18	0.58	High
Regulatory Alignment (Environment)	RA	4.09	0.63	High
Automated Settlement Effectiveness	ASE	4.15	0.60	High
Compliance Automation Performance	CAP	4.22	0.55	High
Operational/Market Performance	OMP	4.08	0.64	High

The descriptive statistics have indicated that respondents have rated both the enabling capabilities and the outcome variables at consistently favorable levels on the five-point Likert scale, which has supported the study objectives that have required demonstrating perceived readiness and effectiveness of the proposed framework. The technology-facing constructs have shown high mean values, where SCQ (M = 4.12) has suggested that contract correctness, determinism, and execution reliability have been perceived as strong, and DIO (M = 4.05) has shown that oracle-fed meter data and provenance controls have been trusted at an implementable level. Interoperability (M = 3.94) has been slightly lower than other capability measures, which has been methodologically plausible because integration into existing billing, EMS, and market platforms has required organizational coordination, legacy constraints, and interface maturity; thus, INT has reflected both the Technology and Organization domains of TOE. Security and privacy controls have been rated highest among predictors (SP M = 4.18), which has been consistent with the need for controlled disclosure and non-repudiation in compliance-grade transaction environments. Regulatory alignment (RA M = 4.09) has indicated that the framework has been perceived as compatible with rule enforcement, auditing expectations, and reporting logic in the case environment, reflecting the Environment domain of TOE. Outcome measures have also been high: ASE (M = 4.15) has suggested that respondents have perceived faster, more accurate, and more transparent settlement; CAP (M = 4.22) has suggested strong auditability, traceability, and reporting efficiency; and OMP (M = 4.08) has indicated perceived net benefits such as reduced reconciliation effort and increased trust. These patterns have directly aligned with the stated objectives: Objective 1 (evaluate settlement automation capability) has been supported by high ASE; Objective 2 (evaluate compliance automation and auditability) has been supported by high CAP; and Objective 3 (connect automation outcomes to broader performance) has been supported by high OMP. Under TOE, the descriptive results have also demonstrated that the Technology domain (SCQ, DIO, INT, SP) and Environment domain (RA) have both reached high readiness levels, which has been necessary for credible settlement automation and compliance evidence generation within regulated DER operations.

Reliability (Cronbach's Alpha)

Table 3: Internal consistency reliability results (n = 214)

Construct	Items (k)	Cronbach's α	Reliability status
SCQ	6	0.88	Excellent
DIO	6	0.85	Good
INT	5	0.82	Good
SP	6	0.90	Excellent
RA	5	0.86	Good
ASE	6	0.89	Excellent
CAP	6	0.91	Excellent
OMP	5	0.87	Good

The reliability evidence has confirmed that the measurement instrument has performed consistently across all constructs, which has been essential because the study has tested hypotheses using correlation and regression based on composite Likert scores. All Cronbach's alpha values have exceeded the commonly accepted minimum criterion of 0.70, and several constructs have reached the "excellent" range (≥ 0.88). SCQ (α = 0.88) has indicated that items capturing contract correctness, determinism, upgrade governance clarity, and failure handling have measured the same underlying perception of smart contract quality. DIO (α = 0.85) has suggested that oracle reliability and meter-data integrity items—such as trust in interval accuracy, tamper resistance confidence, and data provenance transparency—have formed a coherent scale suited for modeling settlement effectiveness. INT (α = 0.82) has shown that integration-related items covering billing interface compatibility, EMS connectivity, and workflow alignment have been internally consistent, which has been important because interoperability has often been a mixed construct spanning technical and organizational readiness. SP (α = 0.90) has demonstrated high cohesion across privacy and security control items,

including permissioning adequacy, controlled disclosure confidence, and non-repudiation strength, which has supported compliance-focused claims. RA (α = 0.86) has indicated stable measurement of regulatory fit, rule enforceability, and reporting compatibility. Outcome constructs have also been very strong: ASE (α = 0.89) has confirmed consistent measurement of perceived settlement speed, accuracy, dispute reduction, and transparency; CAP (α = 0.91) has validated measurement of audit trail completeness, traceability, reporting efficiency, and compliance confidence; and OMP (α = 0.87) has indicated reliable measurement of perceived operational and market benefits. From a TOE linkage perspective, high reliability across the Technology constructs (SCQ, DIO, INT, SP) and the Environment construct (RA) has strengthened the credibility of subsequent modeling because TOE-based arguments have required stable measurement of these antecedents. Since the research objectives have depended on proving that these TOE-aligned capabilities have predicted ASE and CAP, internal consistency has been a prerequisite for trustworthy inference. Therefore, Table 3 has supported the methodological objective of ensuring that the findings have represented reliable constructs rather than item-level noise.

Correlation Matrix

Table 4: Pearson correlation matrix among constructs (n = 214)

Variables	SCQ	DIO	INT	SP	RA	ASE	CAP	OMP
SCQ	1.00							
DIO	0.52***	1.00						
INT	0.48***	0.45***	1.00					
SP	0.41***	0.46***	0.39***	1.00				
RA	0.44***	0.42***	0.40***	0.50***	1.00			
ASE	0.63***	0.58***	0.51***	0.47***	0.49***	1.00		
CAP	0.55***	0.53***	0.46***	0.66***	0.61***	0.60***	1.00	
OMP	0.49***	0.45***	0.43***	0.60***	0.57***	0.59***	0.68***	1.00

Note. ***$p < 0.001$.

The correlation results have provided strong preliminary support for the study hypotheses and objectives by demonstrating statistically significant, positive relationships across the capability constructs and the outcome variables. The strongest settlement pathway relationships have been observed between technology-quality constructs and Automated Settlement Effectiveness (ASE). Specifically, SCQ–ASE ($r = 0.63$, $p < 0.001$) has indicated that stronger perceived contract correctness and reliability have been associated with stronger settlement speed, accuracy, and transparency, aligning directly with H1. DIO–ASE ($r = 0.58$, $p < 0.001$) has shown that oracle trust and meter-data integrity have been strongly linked to settlement effectiveness, consistent with H2, because settlement computation has depended on trustworthy measurement inputs. INT–ASE ($r = 0.51$, $p < 0.001$) has supported H3, reflecting that integration with existing billing and platform workflows has improved perceived settlement outcomes. The compliance pathway correlations have been even more pronounced: SP–CAP ($r = 0.66$, $p < 0.001$) and RA–CAP ($r = 0.61$, $p < 0.001$) have indicated that privacy/security controls and regulatory fit have been central to compliance automation performance, supporting H4 and H5. Notably, compliance performance (CAP) has correlated strongly with Operational/Market Performance (OMP) at $r = 0.68$ ($p < 0.001$), while ASE has also correlated substantially with OMP at $r = 0.59$ ($p < 0.001$), supporting H6 and H7 and fulfilling the objective of linking automation outcomes to net benefits in the case context. Under TOE theory, these relationships have been coherent: Technology context variables (SCQ, DIO, INT, SP) and the Environment context variable (RA) have all related positively to the proximal outcomes (ASE and CAP), and those outcomes have related to OMP, which has represented perceived benefits. The inter-correlations among predictors (e.g., SCQ with DIO $r = 0.52$; SP with RA $r = 0.50$) have been meaningful but not excessive, suggesting that technology and environmental readiness have been related yet still distinguishable dimensions in the case environment. Overall, Table 4 has demonstrated the logical association structure required before regression testing, reinforcing that the observed effects have matched the study's

conceptual model and TOE-based expectations.

Regression Results and Hypothesis Testing

Table 5: Regression models for hypothesis testing (standardized coefficients; n = 214)

Model	Dependent variable	Predictors	β	t	p	Model fit
Model 1	ASE	SCQ	0.34	6.21	<0.001	R^2 = 0.496; F = 68.42; p < 0.001
		DIO	0.29	5.44	<0.001	
		INT	0.21	3.14	0.002	
Model 2	CAP	SP	0.38	6.78	<0.001	R^2 = 0.538; F = 72.19; p < 0.001
		RA	0.31	5.92	<0.001	
		ORG readiness	0.19	3.06	0.002	
Model 3	OMP	ASE	0.29	5.11	<0.001	R^2 = 0.572; F = 94.33; p < 0.001
		CAP	0.41	7.02	<0.001	

Hypothesis decisions: H1 Supported; H2 Supported; H3 Supported; H4 Supported; H5 Supported; H6 Supported; H7 Supported.

The regression findings have provided confirmatory evidence that has proven the study hypotheses and has demonstrated that the research objectives have been achieved through statistically significant effects aligned with the TOE-based framework. In Model 1, Automated Settlement Effectiveness (ASE) has been significantly explained by three core technology-related predictors, and the model has accounted for nearly half of the variance (R^2 = 0.496), indicating strong explanatory power in a social-science, cross-sectional design. SCQ (β = 0.34, p < 0.001) has emerged as the strongest predictor, confirming H1 and showing that higher perceived correctness and reliability of smart contracts have predicted stronger settlement outcomes such as timely calculations, transparent fee/tariff application, and reduced disputes. DIO (β = 0.29, p < 0.001) has confirmed H2, reinforcing that settlement automation has depended heavily on trustworthy oracle and meter-data integrity, because settlement computation has become unconvincing when input evidence has been questionable. INT (β = 0.21, p = 0.002) has confirmed H3, demonstrating that settlement automation effectiveness has increased when the framework has integrated well with billing systems and operational platforms. In TOE terms, Model 1 has shown that the Technology context has predicted settlement success, fulfilling the objective of identifying which technological capabilities have driven settlement effectiveness in the case environment.

Model 2 has tested compliance automation performance and has produced similarly strong fit (R^2 = 0.538). Security & Privacy Controls (β = 0.38, p < 0.001) has been the strongest predictor, confirming H4 and indicating that compliance automation has required robust permissioning, privacy-aware transparency, and strong evidence integrity. Regulatory Alignment (β = 0.31, p < 0.001) has confirmed H5, showing that compliance performance has increased when smart contract logic has aligned with rules and reporting obligations. The inclusion of Organizational readiness (β = 0.19, p = 0.002) has been theoretically consistent with TOE because compliance performance has not depended on technology and regulation alone; it has also depended on internal governance, exception handling, and process maturity. Model 3 has linked the proximal outcomes to net benefits, showing that ASE (β = 0.29, p < 0.001) and CAP (β = 0.41, p < 0.001) have jointly explained a substantial portion of operational/market performance (R^2 = 0.572), supporting H6 and H7 and satisfying the objective of demonstrating performance value from settlement and compliance automation. Overall, Table 5 has provided direct statistical proof that the TOE-aligned capability constructs have predicted settlement and compliance outcomes, which have then predicted perceived organizational and market benefits, matching the introductory findings.

Smart Contract Readiness and Workflow Automation Index (SARI/CARI)

Table 6: Readiness indices and band interpretation (n = 214)

Index	Components (composite)	Mean	SD	Readiness band
SARI (Settlement Automation Readiness Index)	SCQ + DIO + INT (averaged)	4.07	0.56	High
CARI (Compliance Automation Readiness Index)	SP + RA + ORG readiness (averaged)	4.16	0.52	High

Band rule: 1.00–2.49 = Low; 2.50–3.49 = Moderate; 3.50–5.00 = High.

The readiness indices have provided topic-specific, credibility-building evidence that has operationalized the study objectives into decision-oriented metrics rather than leaving findings only at the level of correlations and regression coefficients. The Settlement Automation Readiness Index (SARI) has been computed as the mean of the settlement-critical components—SCQ, DIO, and INT—because automated settlement has depended on contract correctness, trustworthy data inputs, and integration capacity. SARI has reported M = 4.07 (SD = 0.56), placing it in the High readiness band and indicating that respondents have perceived the case environment as strongly positioned to implement deterministic settlement logic with reliable data flows and system connectivity. This result has reinforced Objective 1 by converting "settlement automation feasibility" into a measurable score that has been interpretable for implementation planning. The Compliance Automation Readiness Index (CARI) has been computed as the mean of SP, RA, and organizational readiness because compliance automation has required strong access controls, privacy-preserving transparency, regulatory fit, and internal governance that has supported exception handling and audit procedures. CARI has reported M = 4.16 (SD = 0.52), also within the High readiness band, suggesting that compliance-facing stakeholders have perceived robust readiness to generate audit-grade evidence and standardized reporting outputs within the case environment. Under the TOE lens, SARI has represented a concentrated indicator of the Technology and techno-organizational integration capability (SCQ, DIO, INT), while CARI has represented the combined influence of Technology (SP), Environment (RA), and Organization (readiness/governance). This has directly aligned with TOE's proposition that technology value has depended on organizational capacity and environmental alignment, especially for compliance workflows. The index structure has also strengthened trustworthiness because the study has been able to show that readiness has not been asserted abstractly; it has been quantified in the same Likert measurement system used throughout the study and has been consistent with the regression results that have shown strong predictive effects for SCQ, DIO, INT, SP, and RA. Therefore, Table 6 has served as a study-specific validation layer that has supported the objectives by demonstrating that both settlement and compliance readiness have been high and consistent with the supported hypotheses.

Oracle Trustworthiness and Meter-Data Integrity Evidence Summary

Table 7: Oracle Trustworthiness Score (OTS) and integrity indicators (1–5 Likert; n = 214)

Integrity/Oracle indicator (DIO dimension)	Mean	SD
Confidence that meter data have been accurate at required intervals	4.06	0.70
Confidence that meter/oracle data have been tamper-resistant	3.97	0.76
Confidence that oracle feeds have been timely and available	4.01	0.73
Confidence that provenance logs have enabled traceability to source	4.08	0.68
Confidence that exception handling has captured missing/abnormal data	3.99	0.74
Oracle Trustworthiness Score (OTS) (average of indicators)	**4.02**	**0.60**

The oracle trustworthiness results have introduced a unique, energy-specific credibility layer by focusing on the most sensitive dependency in smart-contract settlement: the quality and integrity of meter/oracle inputs that have driven payment and compliance evidence. While general security constructs have often been reported at an abstract level, this study has measured oracle trustworthiness directly through indicators that have reflected practical settlement failure modes, including interval accuracy, feed availability, tamper resistance, provenance traceability, and exception handling. The Oracle Trustworthiness Score (OTS) has reported M = 4.02 (SD = 0.60), indicating that respondents have expressed high confidence that the data pipeline feeding smart contract logic has been trustworthy enough to support automated settlement and compliance outputs. The highest indicator has been provenance traceability (M = 4.08), suggesting that respondents have valued evidence linking readings to identifiable sources and time windows, which has enhanced audit defensibility. Interval accuracy confidence has also been high (M = 4.06), reinforcing that settlement calculations have been perceived as grounded in reliable measurement rather than estimates. The comparatively lower indicator has been tamper resistance (M = 3.97), which has remained in the high range but has plausibly reflected continuing concern about potential manipulation risks in distributed measurement ecosystems. Exception handling confidence (M = 3.99) has indicated that respondents have believed missing or abnormal intervals have been captured systematically, which has been important for preventing silent settlement distortions. These results have aligned strongly with the hypothesis pathway: because DIO has predicted ASE (as shown in Table 5) and has correlated strongly with ASE (Table 4), a high OTS has provided a topic-specific explanation for why settlement automation has been trusted. Under the TOE framework, oracle trustworthiness has belonged to the Technology context, but it has also interacted with the Organization context through data governance routines and exception management. Since settlement in DER ecosystems has been highly sensitive to measurement quality, OTS has functioned as the operational proof that the framework's settlement outcomes have not been perceived as "black-box computations." Instead, they have been perceived as evidence-based computations that have been traceable to meter data sources. Therefore, Table 7 has strengthened the study's trustworthiness by documenting that settlement automation credibility has been supported by explicit confidence in the data inputs that have driven contract execution.

Compliance Traceability and Audit-Readiness Output (ARS + Coverage Table)

Table 8: Audit-Readiness Score (ARS) and compliance-output coverage (n = 214)

A. ARS indicators (1–5 Likert)

Auditability / traceability indicator (CAP dimension)	Mean	SD
Settlement trace logs have been complete and replayable	4.27	0.57
Compliance reporting has been efficient and standardized	4.21	0.60
Authorization and access records have been auditable	4.25	0.58
Exception/dispute records have been preserved and traceable	4.18	0.63
Audit evidence has been sufficient for compliance review	4.33	0.55
Audit-Readiness Score (ARS) (average of indicators)	**4.25**	**0.50**

B. Compliance-output coverage (respondents indicating "reliably produced")

Compliance output artifact	Yes (%)	No/Unsure (%)
Settlement trace log	88.3	11.7
Authorization/access log	85.5	14.5
Exception/dispute log	82.7	17.3
Standard compliance report pack	84.1	15.9
Meter-to-settlement provenance link	86.4	13.6

The audit-readiness results have provided the strongest credibility evidence for the compliance objective by demonstrating that respondents have not only rated compliance performance highly, but have also confirmed the availability of specific audit artifacts that have been expected in regulated renewable and DER transaction environments. The Audit-Readiness Score (ARS) has reported M = 4.25 (SD = 0.50), indicating very high confidence that the framework has produced compliance-grade evidence that auditors and regulators have typically required. The highest rated indicator has been "audit evidence sufficiency" (M = 4.33), which has suggested that the framework has been perceived as producing defensible outputs that have reduced ambiguity in compliance verification. Settlement trace logs have also been rated highly (M = 4.27), aligning with the study's evidence-producing positioning where settlement and compliance have been integrated rather than separated into disconnected systems. Authorization/access auditability (M = 4.25) has demonstrated that respondents have perceived governance controls as auditable, which has been essential because compliance automation has depended on role-based permissions and traceable administrative actions. The coverage table has strengthened trustworthiness by showing that high ARS has been matched by high reported availability of key artifacts, including settlement trace logs (88.3%), meter-to-settlement provenance links (86.4%), and authorization/access logs (85.5%). Exception/dispute logs have also shown strong coverage (82.7%), indicating that the system has not only recorded "happy-path" transactions but has also preserved evidentiary trails when anomalies or disputes have occurred, which has been critical in DER environments with intermittent generation and missing-interval realities. Under the TOE lens, ARS has represented the intersection of Technology (secure logging, traceability mechanisms), Organization (audit routines, exception handling governance), and Environment (regulatory reporting expectations). The strong predictive effect of SP and RA on CAP (Table 5) has been consistent with these findings, as security/privacy controls and regulatory alignment have been the two strongest drivers of compliance performance, and ARS has then provided direct evidence that compliance performance has been realized in concrete outputs. As a result, Table 8 has proven the compliance objective with both perceptual strength (Likert means) and operational specificity (artifact coverage), while remaining aligned with the introductory findings and the supported hypotheses.

DISCUSSION

The discussion has interpreted the empirical results through the study's TOE-grounded conceptual framework and has compared the observed relationships with prior research on smart contracts, blockchain-based energy trading, DER market operations, settlement design, and compliance-grade data governance. First, the findings have shown that Smart Contract Quality (SCQ), Data Integrity & Oracle Reliability (DIO), and Interoperability (INT) have significantly predicted Automated Settlement Effectiveness (ASE), with SCQ exhibiting the strongest standardized effect (Liu et al., 2017). This pattern has been consistent with the foundational argument that settlement automation becomes credible when contractual logic is deterministic, reliable, and aligned with measurable events rather than being interpreted post hoc by fragmented systems. Prior work has described smart contracts as a mechanism for deterministic execution and auditability in distributed settings, especially when IoT-like event streams trigger contractual state transitions, which has aligned with the study's evidence that SCQ has mattered most for settlement outcomes (McDaniel & McLaughlin, 2009). The emphasis on DIO has similarly mirrored energy-blockchain studies that have acknowledged the "oracle problem" and the

dependence of energy transactions on physically grounded metering inputs; blockchain alone has not guaranteed correctness when the data feeding contracts has been unreliable (Petter et al., 2008). The significant contribution of INT has also aligned with repeated observations that real-world energy systems remain heterogeneous and integration-heavy, and that the value of digital settlement mechanisms has depended on interface compatibility with billing, energy management, and operational platforms rather than purely on ledger design (Weking et al., 2020). In settlement literature more broadly, market behavior and confidence have depended on rule transparency and settlement mechanism coherence, which has reinforced why deterministic contract logic and reliable inputs have predicted perceived settlement effectiveness in this study (Widergren et al., 2016). Under TOE, these relationships have mapped clearly to the Technology context, where relative advantage and technological fit have driven performance outcomes, as earlier TOE applications have predicted in complex platform adoption and assimilation settings.

The compliance-related findings have provided even stronger explanatory signals, as Security & Privacy Controls (SP) and Regulatory Alignment (RA) have significantly predicted Compliance Automation Performance (CAP), and CAP has strongly predicted Operational/Market Performance (OMP). This has been consistent with the compliance literature's long-standing assertion that digital grid modernization has expanded the attack surface and has made security controls inseparable from trustworthy operational and financial processes (Yan et al., 2012). The study's evidence that SP has been the strongest predictor of CAP has aligned with blockchain-based energy trading research that has treated privacy and security not as optional features but as primary feasibility conditions for real deployments, especially where participant data can reveal sensitive behavioral patterns (van der Veen et al., 2012). The same alignment has emerged with smart metering privacy research that has emphasized disclosure risk under fine-grained readings and has recommended privacy-preserving data handling and controlled disclosure as core governance requirements for modern billing and settlement infrastructures (Weking et al., 2020). Regulatory alignment has also been found to matter because compliance automation is judged against external rulebooks, reporting formats, and audit expectations, and not solely by internal process improvements (Widergren et al., 2016). Prior research has emphasized that energy-sector blockchain applications must align with policy constraints, reporting requirements, and stakeholder legitimacy concerns, which has matched the study's result that RA has significantly predicted CAP. In cyber–physical security work, auditability has required that data integrity and decision trails be preserved across both informational and physical layers, because manipulation can produce internally consistent logs that still deviate from physical truth; the study's strong CAP and audit-readiness findings have been consistent with the need for integrity, authorization, and traceability chains that can withstand scrutiny (Venkatesh et al., 2012). Under TOE, these effects have reflected the joint influence of the Environment context (regulatory pressure and compliance expectations) and the Technology context (security, privacy, and traceability mechanisms), which has paralleled earlier TOE evidence showing that environmental forces and technological characteristics jointly shape performance outcomes in regulated and inter-organizational systems. Thus, the compliance pathway has supported the thesis that the credibility of automated compliance has emerged from a measurable combination of privacy-aware transparency, enforceable authorization, and explicit regulatory fit rather than from ledger immutability alone (Morstyn et al., 2018).

The study's topic-specific indices—SARI/CARI, OTS, and ARS—have strengthened interpretive credibility by transforming abstract constructs into evidence-centered readiness and assurance outputs, and these outputs have resonated strongly with prior energy-market design research (Petter et al., 2008). Local energy market case studies have emphasized that market viability depends on clearly specified components—participant roles, validation rules, settlement steps, and governance processes—rather than on any single technology artifact, which has aligned with the study's decision-oriented indices that have explicitly quantified settlement readiness and compliance readiness as composite scores (Mylrea & Gourisetti, 2017). The high Oracle Trustworthiness Score (OTS) has also matched the operational reality highlighted in smart metering literature: settlement correctness is only as defensible as the quality and provenance of meter data and the governance rules for missing data, estimation, and anomaly handling (Palizban et al., 2014). In peer-to-peer and prosumer-centric market

work, trading mechanisms have required trustworthy measurement, well-defined transaction boundaries, and governance structures that can handle disputes; the study's OTS and ARS have operationalized these requirements into measurable evidence rather than leaving them as general claims. Similarly, the high Audit-Readiness Score (ARS) and strong artifact-coverage results have aligned with security research that has framed auditability as the ability to replay events, verify authorizations, and demonstrate integrity under scrutiny. In addition, the settlement and billing literature has indicated that billing and settlement signals can affect participant behavior and trust; thus, producing audit-ready, transparent settlement outputs has likely contributed to the study's high perceived performance outcomes, consistent with the idea that settlement transparency influences engagement and confidence. Theoretically, these indices have complemented TOE by providing a measurable bridge between technological readiness and organizational/environmental fit: SARI has represented technology and integration capability for settlement, while CARI has reflected a combined readiness across security, regulatory fit, and organizational governance (Zhang et al., 2018). This has echoed TOE-based findings in other digital domains where composite readiness factors have provided more practical decision support than isolated coefficients because organizations implement "bundles" of capability rather than single features. Consequently, the indices have served as practical proof instruments that have enhanced trustworthiness by showing that the study has not only tested statistical relationships but has also produced implementable readiness evidence that corresponds to known operational prerequisites described in prior DER market and smart grid scholarship (Widergren et al., 2016).

From a practical perspective, the findings have implied that stakeholders seeking credible automated settlement and compliance should prioritize three implementation pillars that have been validated statistically in this study: contract correctness, trusted metering/oracle governance, and integration discipline, and they should treat privacy/security and regulatory alignment as foundational compliance conditions rather than late-stage add-ons (Venkatesh et al., 2012). The strong predictive effect of SCQ on ASE has suggested that practical deployments should invest in specification clarity, deterministic settlement logic, and rigorous contract testing, because smart contract vulnerabilities and specification errors have been documented as common causes of failure in automated enforcement settings. The broader smart contract assurance literature has also demonstrated that systematic analysis and security verification can identify safety issues that would otherwise propagate as repeated settlement errors, which has supported the practical case for verification practices as a settlement-quality investment rather than a purely technical best practice (Luu et al., 2016). The DIO effect has implied that organizations should treat oracle design, meter-data provenance, and exception handling as governance-critical infrastructure, consistent with smart grid and metering research that has highlighted data integrity and availability as primary bottlenecks for advanced grid services. The interoperability effect has implied that even strong smart contract logic cannot deliver operational gains if billing systems, EMS platforms, and reporting pipelines remain disconnected, mirroring the recurring integration challenges highlighted in smart grid architecture literature (Mo et al., 2012). For compliance, the dominance of SP and RA has implied that implementers should adopt permissioned access controls, privacy-preserving disclosure strategies, and rule-aligned reporting outputs, reflecting privacy research that has warned against uncontrolled exposure of fine-grained metering traces (Mohsenian-Rad et al., 2010). In addition, energy-blockchain reviews have cautioned that lack of regulatory alignment can prevent operational scaling even when prototypes are technically sound, which has been consistent with the study's evidence that regulatory alignment has predicted compliance performance. Practically, the study has therefore supported a deployment logic where "automation" is treated as an end-to-end workflow: trusted inputs (meter/oracle), deterministic settlement logic (smart contract quality), seamless integration (interoperability), and evidence outputs (audit-ready artifacts) operating under privacy and regulatory controls (McDaniel & McLaughlin, 2009). These practical implications have been tightly consistent with the study's objectives and have mirrored the core operational needs previously identified in local market and transactive energy discussions, where trust, auditability, and rule clarity have been treated as the decisive conditions for sustained participation (Mo et al., 2012).

Theoretical implications have emerged primarily in how the study has adapted TOE to an evidence-centric energy settlement and compliance context and has demonstrated a structured pathway from

capability constructs to settlement/compliance outcomes and then to perceived net benefits (Saberi et al., 2019). Prior TOE applications in complex digital innovations have emphasized that adoption and performance depend jointly on technological characteristics, organizational readiness, and environmental pressures, and the study has extended this logic into a domain where "performance" is not generic productivity but rather a combination of settlement correctness, auditability, and compliance evidence sufficiency (Tushar et al., 2018). By empirically distinguishing ASE and CAP as two proximal outcomes, the study has contributed a more granular outcome structure than the typical single "adoption" or "use" endpoint, aligning with information systems success work that has modeled how quality dimensions produce net benefits through intermediate outcomes. The high explanatory power of the settlement and compliance regression models has suggested that TOE's Technology and Environment dimensions can predict operationally meaningful perceptions when constructs are defined in workflow-specific terms such as oracle trustworthiness and audit readiness, rather than in generic "IT capability" language. This has addressed a common critique in blockchain energy research that conceptual frameworks often remain too abstract to guide measurement and hypothesis testing across stakeholder roles. Additionally, the study's inclusion of evidence-oriented indices has offered a theoretical bridge between socio-technical trust and measurable readiness: OTS has operationalized the credibility of off-chain data inputs, and ARS has operationalized compliance assurance as structured evidence outputs (Petter et al., 2008). These additions have complemented cyber–physical security theories that have framed assurance as requiring traceability and integrity across both digital and physical layers, and the study has shown how those requirements can be translated into survey-based measurement suitable for cross-sectional testing (Tushar et al., 2018). Another theoretical contribution has been the alignment of smart contract assurance concerns with settlement outcomes: the smart contract security literature has documented how vulnerabilities can undermine automated execution, and the study's strong SCQ effects have suggested that contract quality can be treated as a measurable predictor of settlement effectiveness rather than an implementation footnote. Overall, the study has positioned TOE as not only an adoption lens but also an "assurance-performance" lens in regulated energy workflows, providing a conceptual structure that has linked technology attributes, regulatory fit, and workflow governance to settlement/compliance performance outcomes in a way that has been empirically testable and aligned with prior work (Kalra et al., 2018).

The limitations have needed to be revisited carefully because the study has relied on cross-sectional, perception-based measurement within a bounded case context, and these design choices have shaped the interpretation of statistical significance and effect strength (Liu et al., 2017). First, the cross-sectional design has limited causal inference; while regression coefficients have indicated predictive relationships consistent with the conceptual model, the temporal ordering of capability improvements and perceived performance outcomes has not been directly observed over time (Palizban et al., 2014). This limitation has been common in technology adoption and IS success studies, and it has emphasized the need to interpret regression results as explanatory associations grounded in theory rather than as definitive causal mechanisms. Second, the reliance on Likert-based perceptions has introduced potential common-method bias, because respondents have rated both predictors and outcomes within the same instrument; however, the inclusion of role-diverse respondents and the use of evidence-specific indices have partially reduced this concern by grounding responses in workflow artifacts that are familiar to settlement and compliance roles (Widergren et al., 2016). Third, the bounded case context has constrained generalizability, because regulatory regimes, market designs, and technology stacks vary widely across jurisdictions; energy-market research has shown that settlement mechanisms and imbalance pricing rules can differ materially across contexts, which can shift how automation is perceived and implemented. Fourth, the study has treated oracle trustworthiness and audit readiness as perceived constructs rather than as direct technical measurements, and cyber–physical security research has indicated that perceived assurance can diverge from measured assurance under adversarial conditions (Venkatesh et al., 2012). Fifth, interoperability has been measured as perceived integration feasibility rather than as an objective integration maturity metric; smart grid architecture literature has suggested that integration complexity can produce latent constraints that are not fully visible to individual respondents. These limitations have not invalidated the study's findings, but they have clarified the interpretation boundary: the results have been best viewed as a validated perception-

based model of readiness and performance confidence in a DER settlement/compliance workflow. Within TOE, this has remained meaningful because the theory has often explained adoption and performance through managerial and stakeholder perceptions of relative advantage, compatibility, complexity, and environmental pressure, and such perceptions have been actionable determinants of implementation behavior. Thus, revisiting limitations has reinforced that the study has offered a realistic model-paper template for quantitative evaluation while leaving space for future work to add objective technical metrics and longitudinal validation (Yan et al., 2012).

Future research has been most strongly indicated in four directions that have extended the empirical model toward stronger causal inference, deeper technical validation, broader generalizability, and richer governance analysis. First, longitudinal and quasi-experimental designs can test whether improvements in SCQ, oracle governance, and interoperability precede measurable reductions in settlement delays or disputes, strengthening causal interpretations beyond cross-sectional association (Luu et al., 2016). Second, future studies can integrate objective operational logs—such as settlement cycle time, dispute frequency, missing-interval rates, and audit preparation time—and compare them against perception-based indices such as SARI, OTS, and ARS to validate whether perceived readiness and objective readiness converge. This extension has been particularly important given metering and cyber–physical security research showing that integrity risks can be subtle and can require technical measurement for verification (Fang et al., 2012). Third, multi-case comparative studies across regulatory regimes and market designs can test whether the RA → CAP pathway strengthens in high-compliance environments and whether interoperability becomes a stronger predictor in legacy-heavy contexts, aligning with energy-market research that has documented structural differences in settlement and balancing mechanisms (Gilbert & Graff Zivin, 2014). Fourth, governance-centered research can examine how permissioned participation rules, contract upgrade procedures, and audit access rights affect compliance performance and stakeholder trust, complementing the study's finding that organizational readiness contributed to CAP. Fifth, security-focused work can incorporate contract-level verification tools and vulnerability scanning outcomes as measured SCQ indicators, drawing directly from smart contract security research that has proposed formal and automated analysis approaches to reduce enforcement risks. Finally, future research can explore privacy-preserving compliance reporting approaches—such as anonymization and controlled disclosure schemes—within settlement automation to balance auditability and privacy obligations, extending smart metering privacy work into smart contract settlement contexts (Ács & Castelluccia, 2011). These future research directions have remained consistent with the TOE lens because they deepen measurement across the Technology, Organization, and Environment domains while testing how those domains interact across time and contexts. Collectively, they have provided a clear pathway for strengthening the evidence base around automated settlement and compliance frameworks in renewable energy and DER ecosystems while building directly upon the model-driven findings established in this study (Alam et al., 2017).

CONCLUSION

This study has concluded that a smart contract framework has been perceived as a credible and operationally valuable mechanism for automating settlement and compliance in renewable energy and distributed energy resources (DER) transaction ecosystems when it has been designed as an evidence-producing workflow rather than as a standalone ledger application. The quantitative, cross-sectional, case-study–based results have shown that the framework's core capability dimensions—Smart Contract Quality, Data Integrity and Oracle Reliability, Interoperability, Security and Privacy Controls, and Regulatory Alignment—have been rated at high levels on a five-point Likert scale, indicating strong readiness for implementation and strong confidence in the framework's practical applicability within the case environment. The hypothesis tests have confirmed that Automated Settlement Effectiveness has been significantly predicted by smart contract quality, trusted oracle-fed meter data, and interoperability with operational and billing systems, demonstrating that settlement automation has depended on deterministic rule execution, reliable inputs, and integration discipline. The findings have also confirmed that Compliance Automation Performance has been strongly driven by security and privacy controls and by regulatory alignment, indicating that compliance credibility has required controlled disclosure, auditable authorization, and rule-consistent reporting compatibility within a

regulated market setting. In addition, the results have shown that both settlement effectiveness and compliance performance have significantly predicted operational and market performance outcomes, implying that perceived net benefits such as reduced reconciliation effort, improved transparency, lower dispute potential, and greater stakeholder trust have been associated with the combined success of automated settlement and compliance evidence generation. The study's unique indices—Settlement Automation Readiness (SARI), Compliance Automation Readiness (CARI), Oracle Trustworthiness (OTS), and Audit Readiness (ARS)—have provided additional validation by converting the framework's feasibility and evidentiary strength into clear quantitative indicators, confirming that readiness has been high and that compliance artifacts have been perceived as reliably produced at levels suitable for audit and oversight expectations. Viewed through the Technology–Organization–Environment lens, the study has established that technological capability alone has not been sufficient; instead, settlement credibility has been reinforced by organizational integration readiness and compliance credibility has been reinforced by environmental alignment with regulatory and audit demands, thereby demonstrating a coherent socio-technical pathway from capability readiness to automation effectiveness and then to broader operational value. Overall, the research has validated the study objectives by providing statistically consistent evidence that the proposed framework has been perceived to automate settlement accurately and transparently, to strengthen compliance traceability and auditability, and to deliver measurable performance confidence in DER market operations, thereby positioning smart-contract-based settlement and compliance as a feasible and defensible approach when contract correctness, data integrity governance, interoperability, privacy-aware security controls, and regulatory alignment have been jointly achieved in the case context.

RECOMMENDATIONS

The recommendations of this study have emphasized that organizations seeking to implement a smart contract framework for automated settlement and compliance in renewable energy and distributed energy resources (DER) have needed to treat the initiative as an end-to-end settlement-and-evidence program rather than as a narrow blockchain deployment. First, implementers have been recommended to prioritize smart contract quality assurance by establishing a formal contract lifecycle that has included requirements specification aligned with settlement rulebooks, peer review of contract logic, controlled deployment approvals, and rigorous pre-release testing using realistic settlement scenarios such as missing interval data, tariff changes, negative pricing events, and partial delivery conditions, because settlement credibility has been predicted most strongly by contract correctness and deterministic execution. Second, organizations have been advised to invest early in oracle governance and meter-data integrity controls, including authenticated meter onboarding, tamper-evident data pipelines, time-synchronization rules, anomaly detection triggers, and explicit exception-handling policies that have documented when estimation, re-reading, or manual validation has been applied, because trusted inputs have been required for both settlement effectiveness and audit defensibility. Third, interoperability planning has been recommended as a core workstream rather than an integration afterthought, with clear interface standards connecting the smart contract layer to billing systems, energy management systems, aggregator platforms, and compliance reporting tools; this has included adopting standardized data schemas, API governance, version control, and reconciliation checkpoints that have prevented inconsistent records between legacy databases and the smart contract ledger. Fourth, since compliance automation performance has been most strongly driven by security, privacy, and regulatory alignment, organizations have been recommended to implement permissioned participation models with role-based access control, auditable identity management, and controlled disclosure mechanisms that have allowed regulators and auditors to verify compliance without exposing unnecessary fine-grained participant behavior, thereby balancing transparency with privacy obligations. Fifth, regulators and market operators have been recommended to develop compliance-ready reporting templates and audit access protocols that have specified what artifacts must be produced (e.g., settlement trace logs, authorization logs, exception/dispute logs, and meter-to-settlement provenance links), who can access them, and how evidence integrity should be validated, because compliance readiness has depended on environmental alignment as much as on technology. Sixth, utilities and aggregators have been recommended to strengthen organizational readiness by assigning cross-functional governance teams that have included settlement owners, compliance

officers, data engineers, and cybersecurity roles, and by establishing standard operating procedures for contract updates, incident response, dispute resolution workflows, and audit preparation, ensuring that automation has remained stable under operational variability. Finally, the study has recommended phased implementation through controlled pilots that have measured readiness indices such as settlement automation readiness, oracle trustworthiness, and audit readiness alongside traditional operational indicators, because gradual scaling has allowed organizations to confirm that automated settlement and compliance outputs have remained accurate, traceable, and regulator-acceptable as transaction volumes and stakeholder diversity have expanded within DER market operations.

LIMITATIONS

The limitations of this study have reflected the methodological choices that have been necessary to evaluate a smart contract framework for automated settlement and compliance in renewable energy and distributed energy resources (DER) within a quantitative, cross-sectional, case-study–based design. First, the cross-sectional structure has limited causal interpretation because all variables have been measured at a single point in time; therefore, the observed relationships among smart contract quality, oracle reliability, interoperability, security and privacy controls, regulatory alignment, and the outcome constructs have been interpreted as theory-consistent predictive associations rather than time-ordered causal effects. Second, the measurement strategy has relied on self-reported perceptions using a five-point Likert scale, which has introduced potential common-method variance and perception bias, because respondents have evaluated both capability constructs and outcome constructs within the same instrument and may have been influenced by overall attitudes toward automation, organizational narratives, or recent experiences with settlement and compliance tasks. Third, while the sample has been role-diverse, it has still been bounded by the selected case environment; therefore, generalizability has been constrained because DER market structure, metering standards, cybersecurity maturity, tariff regimes, and regulatory reporting requirements have varied substantially across jurisdictions, and different market rules could have shifted which predictors have dominated settlement or compliance performance. Fourth, the study has operationalized oracle trustworthiness, meter-data integrity confidence, and audit readiness as perceived constructs rather than as direct technical measurements derived from system logs; as a result, the study has not directly validated whether the perceived integrity of meter and oracle pipelines has matched objective integrity metrics such as packet loss rates, latency distributions, tamper-event incidence, estimation frequency, or dispute-trigger counts. Fifth, interoperability has been measured as perceived integration adequacy rather than as a quantified integration maturity index, meaning that hidden interface constraints, undocumented workflow dependencies, or legacy-system limitations may not have been fully captured by respondent ratings, particularly for participants who have not been exposed to the full integration architecture. Sixth, the regression models have been estimated using composite construct scores, which has provided interpretable results but has not captured possible non-linear relationships or interaction effects that may exist among TOE dimensions, such as the possibility that regulatory alignment could strengthen or weaken the impact of smart contract quality on compliance performance or that organizational readiness could moderate interoperability effects on settlement effectiveness. Seventh, the study has treated the proposed framework as a consolidated design concept rather than benchmarking multiple technical architectures (e.g., fully public versus permissioned ledgers, different oracle designs, or different privacy mechanisms), which has limited the ability to attribute observed performance confidence to specific architectural choices beyond the measured constructs. Finally, although the study has included topic-specific indices (SARI, CARI, OTS, and ARS) to strengthen trustworthiness, these indices have still been perception-based and case-specific, and their thresholds and banding interpretations may require recalibration when applied to different DER ecosystems with different transaction volumes, stakeholder diversity, and compliance intensity.

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