Dynamics of Communication Infrastructure in Transactive Energy Systems: A Systems Dynamics Model of LoRa Integration

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***Abstract*—Distributed energy resources (DERs) introduce variability and bidirectional power flows that traditional centralized grids struggle to manage. Transactive Energy Systems (TES) offer a decentralized framework for balancing supply and demand through market-based coordination, but their deployment is constrained by communication infrastructure. This paper investigates Long Range (LoRa) technology as a TES communication solution using a system dynamics approach that models stakeholder interactions and feedback mechanisms. The analysis identifies sixteen feedback loops—eleven reinforcing and five balancing—that shape LoRa-TES integration. Critical technical relationships were empirically validated through packet-level network simulations. Results show that adaptive LoRa configurations reduce network-wide energy consumption by more than 99% compared to fixed-parameter baselines and sustain packet delivery ratios above 90% at low–moderate node counts, but also reveal a scalability ceiling of roughly 800–1000 nodes imposed by congestion. These findings highlight LoRa's potential as an energy-efficient communication layer for small to medium TES deployments, while underscoring the need for hybrid architectures and supportive policy frameworks to overcome scalability and interoperability barriers.**

***Keywords* - *Transactive Energy Systems; LoRa Technology; System Dynamics; Distributed Energy Resources; Energy Markets*.**

I. INTRODUCTION

This paper extends our preliminary work presented at ENERGY 2025 [1], which introduced a systems dynamics framework for analyzing LoRa integration in transactive energy systems. The rapid growth of DERs is transforming the operation of electric power systems. Solar panels, wind turbines, and battery storage create bidirectional power flows and introduce supply–demand variability that centralized grid infrastructure was never designed to manage [2]. These challenges are particularly pronounced in developing regions, where expanding electricity demand must be met alongside ambitious sustainability goals [3].

TES have emerged as a promising response. Instead of relying on centralized control, TES establish decentralized marketplaces where supply and demand are balanced in real time through price signals [4]–[6]. Early demonstrations suggest this approach can improve efficiency and reduce costs [7]. Yet the scalability of TES is constrained by a fundamental bottleneck: the communication infrastructure on which they depend.

Current communication technologies struggle to satisfy three essential TES requirements: energy-efficient operation across geographically dispersed resources, reliable long-range connectivity, and secure exchange of transaction data [8], [9]. These limitations hinder deployment, particularly in rural regions where distributed generation is most needed [10], [11].

Low-Power Wide-Area Network (LPWAN) technologies offer a potential path forward. Among them, LoRa has attracted significant attention for its ability to provide long-range connectivity, low power consumption, and strong signal penetration—characteristics that align well with TES operational needs [12]–[14]. Still, the complex ways in which LoRa's technical properties interact with TES performance remain insufficiently understood [15]. Without such understanding, system architects lack the evidence needed to design robust and scalable implementations.

This paper addresses that gap by analyzing LoRa-enabled TES through a system dynamics perspective. We develop a causal model that traces how communication technology choices propagate through reliability, security, and scalability outcomes [16]. The analysis identifies sixteen feedback loops—eleven reinforcing and five balancing—that structure system behavior, and it situates these dynamics within a stakeholder framework linking technology providers, producers, consumers, and regulators. Building on this model, we employ network simulation to validate critical technical mechanisms, demonstrating both the efficiency gains from adaptive communication and the scalability limits imposed by congestion. Finally, we draw from these insights to highlight leverage points and practical barriers that must be addressed for effective TES deployment.

The current journal version provides substantially deeper analysis across multiple dimensions compared to the preliminary conference paper. We expand the feedback loop analysis to examine sixteen interconnected mechanisms in detail, compared to the initial examination in the conference version. We introduce a comprehensive stakeholder interaction framework that maps the relationships among technology providers, energy producers and consumers, government agencies, and environmental organizations. The environmental implications receive expanded treatment, including detailed analysis of how LoRa enables weather forecasting for renewable energy optimization and reduces electronic waste through extended device lifespans. We also provide network simulation results that validate key technical mechanisms and quantify performance trade-offs. Finally, this version includes extensive discussion of implementation challenges, particularly LoRa's data rate limitations, and offers practical recommendations for hybrid communication architectures that combine LoRa with complementary technologies.

The remainder of the paper is organized as follows. Section II reviews TES communication requirements and LPWAN capabilities. Section III presents the system dynamics methodology. Sections IV and V detail model development, results and validation. Section VI discusses stakeholder and design implications, and Section VII concludes with recommendations for future research.

II. Literature Review

The traditional power grid is undergoing a fundamental transformation, shifting away from its historical one-way electricity delivery from centralized plants to end consumers. This change is driven by environmental concerns, technological advancements, and evolving consumer needs [17], [18]. A major catalyst in this transition is the integration of DERs, such as rooftop solar panels, small wind turbines, and battery storage systems, which are positioned closer to consumption points and enable localized energy production [2]. However, integrating DERs into the grid requires a market framework that allows dynamic energy exchange, leading to the emergence of TES.

TES facilitate decentralized electricity trading through automated market mechanisms, empowering prosumers—entities that both consume and produce energy—to optimize their energy usage and trade excess generation at competitive prices [4], [5], [19], [20]. Unlike traditional grid structures, where excess energy must be sold to the main grid under regulated tariffs, TES allows prosumers to engage directly with local consumers, promoting flexibility and efficiency [21]. The effectiveness of TES hinges on several interconnected components: microgrids, which can operate independently or in conjunction with the main grid; smart meters, which provide real-time monitoring and automated trading capabilities; and energy management systems, which optimize energy flow and market transactions [8]. Despite these advantages, TES implementation presents significant challenges, particularly in communication infrastructure, data security, privacy, system scalability, and seamless integration with existing grid operations [10], [11], [15].

The communication backbone of TES plays a pivotal role in enabling secure and efficient transactions. Various technologies have been explored to facilitate information exchange among market participants, including WiFi and cellular networks. While WiFi provides a widely available and cost-effective solution, its limitations—such as range restrictions, high power consumption, and susceptibility to interference—hinder its scalability, particularly in dense urban environments [22]. Cellular networks, on the other hand, offer extensive coverage and reliable data transfer but come with high operational costs and significant energy demands, making them less ideal for large-scale TES deployments [23], [24]. These limitations necessitate alternative communication technologies that can balance energy efficiency, cost, and performance.

LoRa technology has emerged as a promising alternative for TES communication networks. Designed for Internet of Things applications, LoRa operates on a LPWAN protocol, offering long-range connectivity with minimal power consumption and strong interference resistance [12], [25]. Studies have demonstrated its advantages over traditional IoT communication technologies, highlighting superior energy efficiency, scalability, and security features [13], [14], [26]. However, trade-offs exist between reliability and energy efficiency, as efforts to enhance data transmission reliability often lead to increased energy consumption of end devices [27], [28]. Research on LoRa scalability has shown that network performance can be improved by adding gateways or adopting dynamic transmission strategies, yet increased deployment density may lead to interference and reduced coverage probability [14], [29], [30].

The integration of LoRa into TES introduces complex interactions among technical, economic, and social factors, necessitating a holistic analytical approach. Systems thinking provides a framework for understanding these interdependencies, emphasizing feedback mechanisms and causal relationships within the energy ecosystem [16]. Previous studies applying this approach to energy systems have demonstrated its value in identifying unintended consequences and optimizing the performance of emerging technologies [16]. By leveraging systems thinking methodologies, such as causal loop analysis, researchers can assess how LoRa influences key TES attributes—efficiency, security, scalability, reliability, and cost-effectiveness—while considering the broader implications of communication technology choices. This perspective is crucial for developing strategic implementation plans and mitigating potential challenges in real-world TES deployments.

III. Methodology

This section presents the methodological framework employed to analyze the integration of LoRa technology within Transactive Energy Systems. The methodology is structured around a systems dynamics approach that progressively builds from conceptual foundations to detailed causal models, enabling a comprehensive examination of the complex interactions between communication infrastructure and energy market dynamics.

A. A Systems Dynamics Approach to Transactive Energy System Analysis

The intricate structure of TES necessitates an analytical framework that captures both direct interactions and emergent system-wide behaviors. Traditional analytical approaches often fall short in accounting for the interdependencies among market participants, communication networks, regulatory frameworks, and technological infrastructures. Systems dynamics offers a robust alternative, enabling a holistic examination of TES by mapping causal relationships, feedback loops, and evolving system states over time [16]. This approach not only facilitates a deeper understanding of TES operations but also provides a structured methodology for assessing the impact of integrating LoRa technology into these systems.

Our analysis unfolds across three progressive stages: defining system boundaries, identifying stakeholder interactions, and constructing causal loop models. Each stage builds upon the previous, culminating in a comprehensive evaluation of how communication infrastructure—specifically LoRa—shapes TES performance, scalability, and sustainability.

B. Defining System Boundaries

Establishing clear system boundaries is fundamental to understanding the scope and limitations of the analysis. In this study, the TES ecosystem is conceptualized as a network of interconnected entities, including energy producers, consumers, prosumers, grid operators, and technology providers. These actors operate within a landscape shaped by both technical components—such as DERs, microgrids, and communication networks—and non-technical factors, including regulatory policies, economic incentives, and market dynamics, as illustrated in Figure 1.

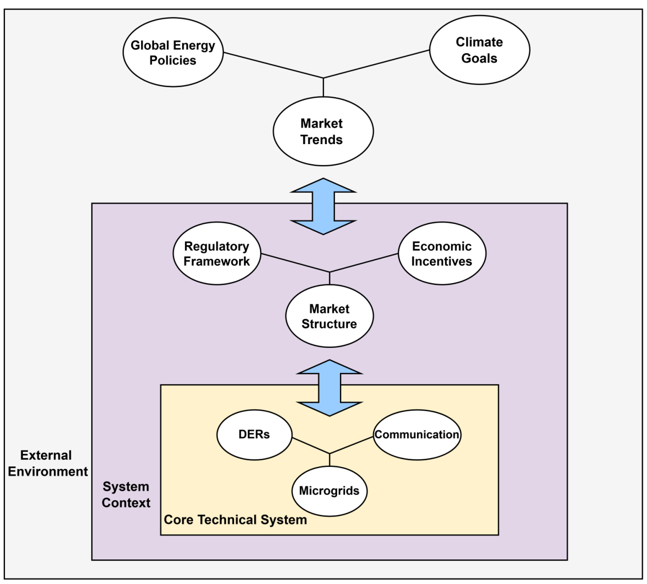

Figure 1. TES boundaries

While TES function within broader global energy trends, our boundary definition focuses on localized system interactions, excluding external influences such as international energy policies or technological developments beyond the direct operational scope of TES. This refinement ensures a targeted investigation into the role of communication technologies while maintaining analytical depth.

C. Stakeholder Interactions and System Dynamics

The complexity of TES arises from the intricate network of stakeholder relationships that shape system behavior and performance. These interactions, depicted in Figure 2, extend beyond direct transactional exchanges, encompassing regulatory influence, technological dependencies, and sustainability considerations. Understanding these dynamics is essential for identifying intervention points, anticipating systemic responses to change, and fostering resilience in energy markets. The diagram illustrates the complex web of relationships between key stakeholders in TES. Arrows indicate primary interaction types: dependency (resource or service reliance), support (financial or operational assistance), compliance (regulatory or standard adherence), and influence (impact on decision-making or behavior).

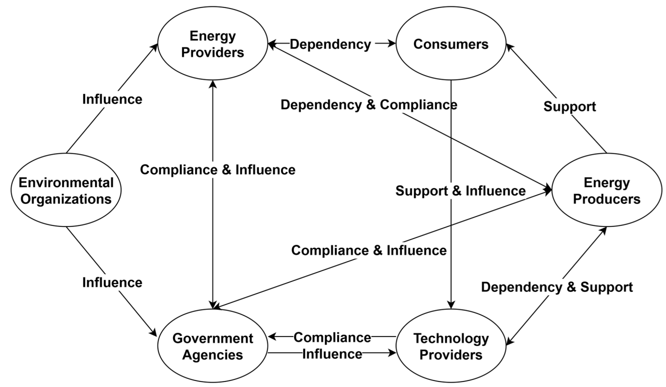

Figure 2. Stakeholder interest map in TES with LoRa integration

At the foundation of TES, the interdependence between Energy Providers and Consumers forms a bidirectional relationship that is fundamental to system stability. Energy Providers ensure a reliable supply of electricity, while Consumers generate the demand that sustains economic viability. This relationship is further shaped by Energy Producers, who serve as both suppliers and market participants. Their operations are driven by demand fluctuations, policy frameworks, and technological advancements that influence production capacity and energy distribution.

Environmental Organizations exert a significant shaping force on the TES landscape, primarily through their advocacy for sustainable energy practices and stringent environmental regulations. Their influence is particularly pronounced in their interactions with Government Agencies and Energy Providers, where they drive policy decisions related to renewable energy integration, emissions reductions, and sustainability reporting. These pressures translate into regulatory mandates that compel stakeholders to align operational strategies with broader environmental objectives.

Government Agencies function as both regulators and facilitators within TES, enforcing compliance while simultaneously shaping market conditions through policy interventions. Their engagement spans multiple stakeholders, including Energy Providers, Producers, and Technology Providers, ensuring that system-wide objectives such as reliability, equity, and sustainability are maintained. This dual role enables Government Agencies to mediate competing interests, balancing economic viability with regulatory imperatives.

Technology Providers play a crucial role in sustaining and advancing TES, offering infrastructure solutions that facilitate energy transactions, enhance grid reliability, and ensure regulatory compliance. Their relationship with Government Agencies is particularly dynamic, as evolving policy frameworks necessitate continuous technological adaptation. Moreover, their support relationships with Energy Producers underscore the increasing reliance on digitalization and smart grid solutions in energy management.

These interconnected relationships give rise to critical feedback loops that reinforce or modify system dynamics. Notable among these are:

- The Compliance-Driven Innovation Loop: Energy Providers, under regulatory pressure from Government Agencies, seek advanced solutions from Technology Providers, leading to innovations that enhance reliability and compliance.
- The Market Development and Adoption Loop: Consumer preferences influence Energy Producers, who in turn engage with Technology Providers to adopt solutions that meet emerging market demands, shaping the trajectory of technological advancements.
- The Sustainability Influence Loop: Environmental Organizations exert pressure on both Government Agencies and Energy Providers, driving legislative changes that enforce sustainability measures, thereby altering operational and investment priorities.

Recognizing and analyzing these feedback mechanisms is essential for stakeholders aiming to navigate TES complexities effectively. Identifying points of leverage within these interactions can facilitate targeted interventions that enhance system efficiency, promote technological innovation, and support the integration of emerging solutions such as LoRa technology. Furthermore, a nuanced understanding of stakeholder dynamics enables proactive management of potential resistance to change, ensuring that transitions toward sustainable and resilient energy systems occur smoothly and equitably.

D. Causal Loop Modeling and System Behavior

Building upon stakeholder interactions, we construct causal loop diagrams to map the interdependencies among key system variables, offering a structured perspective on system behavior. This iterative modeling process reveals two fundamental feedback mechanisms: reinforcing loops, which amplify trends within the system, and balancing loops, which introduce constraints that stabilize outcomes. By delineating these relationships, we gain insight into how the integration of LoRa technology influences TES across multiple dimensions.

One crucial aspect is cost dynamics, where energy consumption patterns and infrastructure requirements shape economic feasibility. System performance, particularly communication reliability and security, emerges as another critical factor, influencing the overall resilience of TES. Environmental considerations also come into play, as energy efficiency and resource utilization determine sustainability outcomes. Meanwhile, implementation challenges—including technical requirements and integration complexities—affect the practicality of deploying LoRa technology within existing frameworks.

The resulting causal loop diagram provides a visual representation of these interactions, highlighting leverage points where targeted interventions can optimize TES performance. By capturing the interconnected nature of TES components, this model facilitates scenario analysis, allowing stakeholders to anticipate system behavior under different implementation strategies.

Adopting a systems dynamics perspective in TES analysis offers several key advantages. It uncovers hidden dependencies that conventional assessments might overlook, bringing potential unintended consequences to light before large-scale deployment. Additionally, it provides a structured framework for evaluating trade-offs between technological capabilities, economic feasibility, and regulatory constraints. More importantly, this approach enables an integrated examination of how communication technology choices shape the long-term evolution of TES, equipping decision-makers with the insights necessary to develop resilient, efficient, and sustainable transactive energy markets.

IV. Results

Our systems dynamics analysis, illustrated in Figure 3, reveals a complex web of interactions between LoRa technology integration and TES performance. Through careful examination of the causal loop diagram, we identify eleven reinforcing mechanisms (R1-R11) and five balancing loops (B1-B5) that potentially shape system behavior across multiple dimensions. These interconnected feedback mechanisms offer deep insights into how communication technology choices influence system evolution. Our theoretical model identifies several key feedback mechanisms. The reinforcing loops include energy consumption reduction through low-power operation (R1), adaptive power control optimization (R3), infrastructure cost savings through long-range capabilities (R4), enhanced DER monitoring effectiveness (R6), e-waste reduction through extended battery life (R7), system-wide communication improvements (R8), weather forecasting integration for renewable optimization (R9), system reliability through interference-resistant communication (R10), and additional efficiency and operational loops (R2, R5, R11). The balancing loops encompass security vs adoption trade-offs (B1), authentication overhead effects (B2), network congestion limitations (B3), operational burden scaling effects (B4), and implementation cost constraints (B5).

The integration of LoRa technology influences system efficiency through several interconnected pathways. At the core, continuous monitoring of distributed energy resources creates a primary reinforcing loop (R6) that enhances system performance. When energy consumption decreases through LoRa's low-power operation, devices maintain longer monitoring periods without battery replacement. This benefit is amplified by early fault detection capabilities, creating a positive feedback loop that partially offsets the maintenance burden

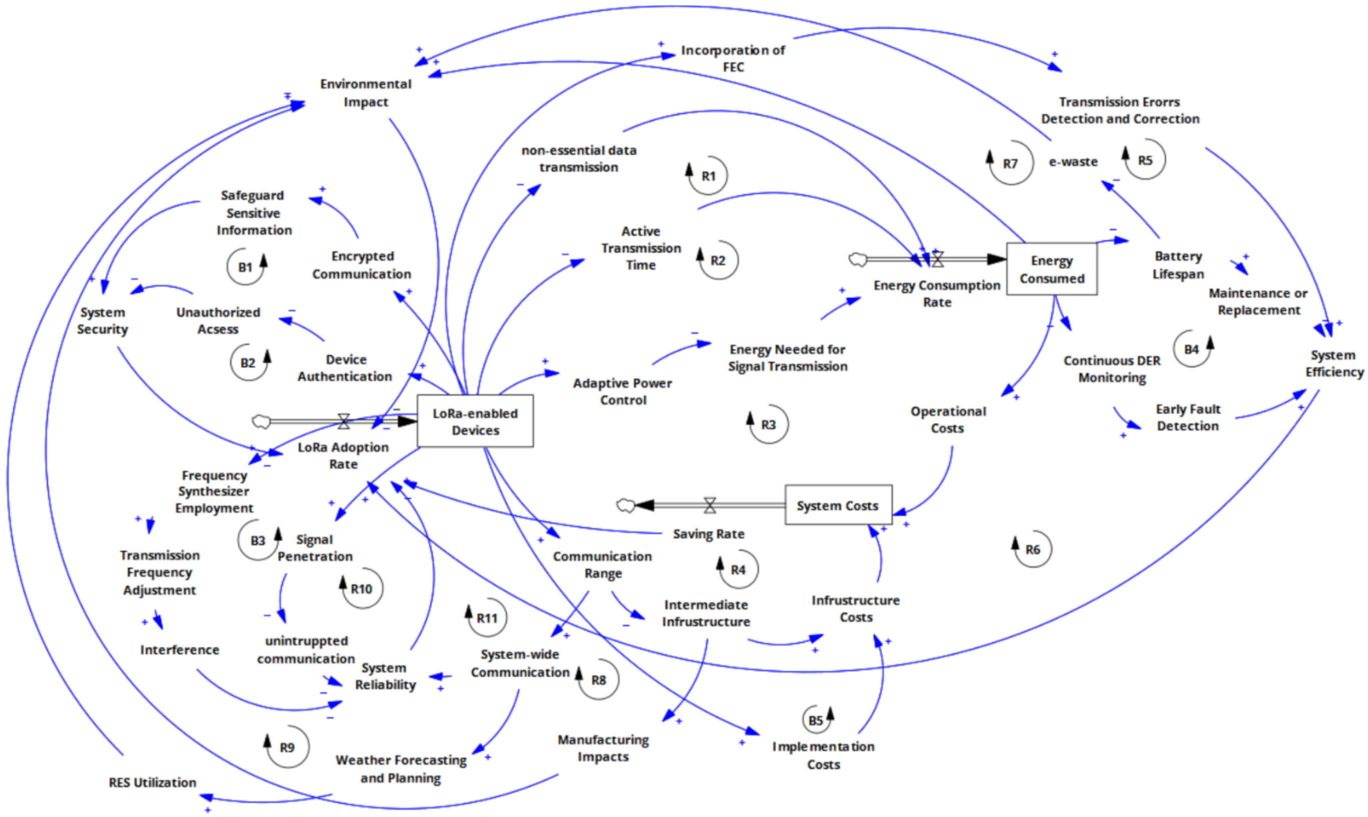

Figure 3. Causal loop diagram of impact of using LoRa on energy consumption behavior

typically associated with large-scale deployments. However, as system scale increases, maintenance requirements (B4) create a counterbalancing effect, suggesting the need for predictive maintenance strategies to optimize this trade-off.

Cost relationships in LoRa-enabled TES demonstrate particularly interesting cascading effects. The technology's long-range capabilities reduce infrastructure requirements through a saving rate mechanism (R4) that interacts with adaptive power control features (R3) to create compound cost benefits. These benefits manifest through reduced operational expenses and decreased infrastructure needs. However, our analysis reveals a sophisticated balancing mechanism (B5) where implementation costs moderate these advantages through multiple pathways involving infrastructure and manufacturing impacts. This interaction suggests that implementation timing and scaling strategies significantly influence overall cost effectiveness.

The security and reliability aspects of the system reveal previously unexplored connections. While LoRa's encrypted communication and device-level authentication create strong initial security benefits (B1, B2), these mechanisms interact with signal penetration capabilities (R10) through frequency synthesizer employment. This interaction suggests that security measures might have unintended consequences on system reliability - a critical consideration for system designers. The reliability analysis further reveals how Chirp Spread Spectrum modulation supports uninterrupted communication, though increasing device density introduces potential interference that must be carefully managed.

Environmental feedback loops demonstrate more nuanced benefits than initially apparent. The reduction in e-waste (R7) connects directly to system efficiency through extended battery lifespan, while system-wide communication improvements (R8) influence manufacturing impacts. Perhaps most significantly, the analysis reveals how weather forecasting capabilities create a direct link to renewable energy system utilization (R9), suggesting environmental benefits might accumulate more rapidly than previously understood. This finding has important implications for long-term sustainability planning.

The multiple pathways affecting system costs and performance indicate the need for careful phasing of technology adoption. Critical intersection points emerge where non-essential data transmission interacts with adaptive power control, suggesting opportunities for optimizing communication strategies. Similarly, the relationship between frequency synthesizer employment and system reliability reveals potential bottlenecks that must be considered in scaling plans.

These interconnected feedback mechanisms suggest several important considerations for LoRa integration in TES. Implementation planning must account for both immediate benefits and longer-term scaling effects, particularly where security measures interact with system reliability. System designers should anticipate and plan for transition points where balancing loops begin to counteract initial benefits, while recognizing that environmental benefits may continue to accumulate through multiple reinforcing loops with fewer balancing constraints.

This systems analysis provides valuable insights for future TES development while highlighting areas requiring further investigation. Particularly important is the need to understand how these feedback mechanisms behave under different deployment scales and environmental conditions, especially considering the complex interactions between security, reliability, and system performance.

V. Empirical Validation of Systems Dynamics Model

System dynamics models are designed to capture causal mechanisms and feedback processes, but their credibility depends on showing that these theoretical dynamics correspond to observable system behavior. Our causal model includes sixteen feedback loops spanning technical, economic, and environmental dimensions. A full validation of all loops is beyond the scope of this study, not least because many—such as security/adoption dynamics, cost trade-offs, and environmental impacts—require field experiments or lifecycle analyses that cannot be addressed through simulation alone.

Instead, this study concentrates on the technical core of the model: the feedbacks that govern LoRa's role as a communication layer within TES. These loops are both central to system performance and empirically testable using simulation tools, making them the most effective entry point for validation. By establishing that the physical-layer dynamics behave as expected, we provide a foundation for future work on higher-level socio-economic and environmental interactions.

Our analysis focuses on six loops, organized into two themes that capture the key trade-offs in LoRa-enabled TES:

1) **Energy Efficiency & Operational Viability**: This theme highlights reinforcing mechanisms that make LoRa an attractive option for TES. It encompasses R1 (Energy Consumption Reduction) and R3 (Adaptive Power Control Optimization). Our central hypothesis is that LoRa's adaptive features will cause significant, quantifiable reductions in network-wide energy consumption, validating the powerful reinforcing nature of these loops.
2) **Scalability & Network Reliability**: This theme examines the tension between system expansion and operational limits. It incorporates R6 (DER Monitoring Effectiveness) and R10 (System Reliability) alongside the balancing loop B3 (Network Congestion). Here, the hypothesis is that adaptive configurations improve communication reliability (R6, R10), but only up to a saturation point where congestion effects dominate (B3).

Together, these six loops form the technical backbone of the causal model. They determine whether LoRa can serve as a viable communication layer for TES and can be empirically validated using network simulation. Loops concerning economic trade-offs, environmental impacts, and adoption dynamics remain theoretically specified but are reserved for validation through empirical fieldwork in future studies.

A. Experimental Design

To test the hypotheses derived from the causal loop model, we employed LoRaSim [29], [30], an open-source packet-level simulator widely used to study the scalability, energy efficiency, and reliability of LoRa networks. To capture deployment diversity, the number of participating nodes was scaled from 50 (representative of small microgrid installations) to 1,500 (reflecting larger community-level systems). Each node was modeled as a LoRa-enabled device, such as a sensor or distributed energy resource controller. Simulation runs lasted 1,000,000 ms (approx. 16.7 minutes), a horizon long enough to ensure multiple packet transmissions per node despite LoRa's low duty cycle. Within this framework, we implemented three canonical configurations from the LoRaSim codebase—labeled Experiment 0, Experiment 3, and Experiment 5—that progressively introduce adaptive mechanisms:

- **Condition 1 (Baseline Case - Exp. 0)**: A non-adaptive network with fixed spreading factor (SF12) and fixed transmit power. This case isolates the effects of congestion dynamics (loop B3) by excluding adaptive responses.
- **Condition 2 (Partially Adaptive Case - Exp. 3)**: Adaptive spreading factor with fixed transmission power. This configuration highlights how spectral efficiency improvements influence delivery reliability, directly probing loops R6 (DER Monitoring Effectiveness) and R10 (System Reliability).
- **Condition 3 (Fully Adaptive Case - Exp. 5)**: Joint adaptation of spreading factor and transmit power. This condition represents the optimized system state, where the reinforcing effects of energy efficiency and reliability dynamics operate in tandem.

For each run, we collected five key performance indicators: (i) total packets transmitted, (ii) successful deliveries, (iii) collisions, (iv) packet delivery ratio (PDR), and (v) total energy consumption across nodes. Together, these metrics capture the fundamental trade-off between reliability and efficiency. Finally, the radio environment was standardized across experiments with a carrier frequency of 860 MHz, bandwidth of 125 kHz, and payload size of 20 bytes. These parameters mirror common LoRa configurations reported in prior studies [29], [30], ensuring both comparability and practical relevance.

B. Validation Results

The simulations yielded clear, quantitative evidence that supports the hypotheses and validates the behavior of the core feedback loops. Two sets of dynamics are especially prominent: the reinforcing effects driving energy efficiency, and the tradeoff between network reliability and congestion.

1) Energy Efficiency Reinforcing Loops (R1, R3): The results in Figure 4 show that adaptive configurations deliver dramatic improvements in energy efficiency, consistent with the reinforcing loops R1 and R3. At 50 nodes, total energy use dropped from 937.22 J in the baseline case (blue) to

11.84 J with adaptive spreading factor (orange) and 8.29 J with full adaptation (green). The greater than 99% reduction observed in the fully adaptive case demonstrates the powerful compounding effect of these loops. Moreover, the additional 30% efficiency gain achieved by moving from spreading-factor adaptation (Condition 2) to joint spreading and power adaptation (Condition 3) isolates the specific contribution of adaptive power control, providing direct empirical validation of loop R3.

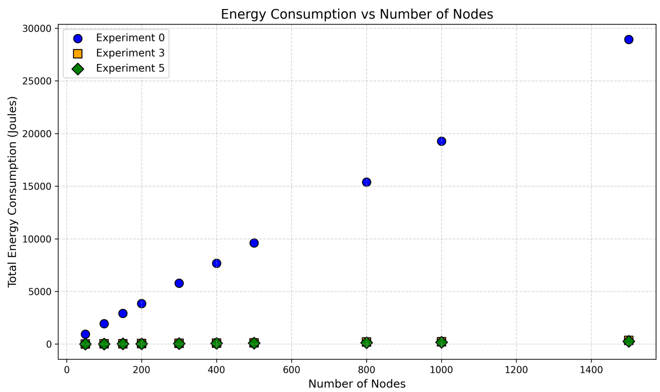

Figure 4. Energy consumption as a function of the number of nodes for Experiments 0, 3, and 5

2) Reliability–Congestion Tradeoff (R6, R10 vs. B3): Adaptive configurations also validated the expected tension between reliability and congestion (Figure 5, Table I). At small scales, LoRa's adaptive features sustained high packet delivery ratios (PDRs), essential for continuous DER monitoring (R6). With 50 nodes, adaptive cases achieved PDRs above 90%, while the baseline collapsed to just 0.14%. This resilience under increasing load confirms the reliability-enhancing role of adaptive mechanisms (R10).

However, the results also reveal the counteracting influence of the congestion loop (B3). In the baseline, the network collapsed completely beyond 100–200 nodes, with collision rates exceeding 99%. Even in adaptive scenarios, performance began to plateau around 800–1000 nodes, with congestion ultimately eroding reliability. These results confirm B3 as a fundamental scalability limit: adaptation delays but does not eliminate the onset of congestion-driven performance decline.

TABLE I. Key Simulation Results at 50 Nodes

Experiment	Packets Sent	Collisions	PDR (%)	Energy (J)
Experiment 0	4147	4141	0.14	937.22
Experiment 3	5002	388	92.0	11.84
Experiment 5	4900	410	91.6	8.29

The simulations provide clear empirical support for the technical core of our system dynamics model. We validated

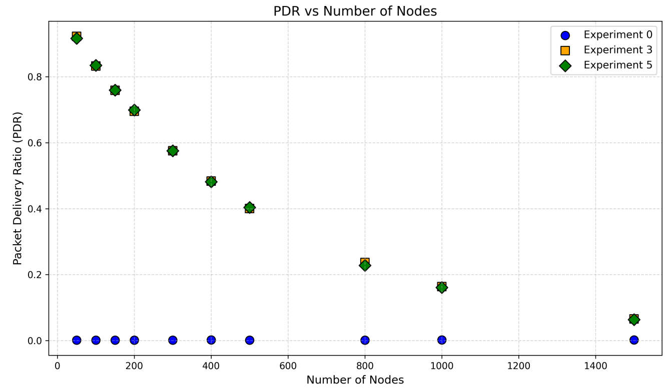

Figure 5. Packet delivery ratio as a function of the number of nodes for Experiments 0, 3, and 5

two central mechanisms: (i) the reinforcing effects of adaptive communication on energy efficiency and reliability, and (ii) the balancing influence of congestion in constraining scalability. Together, these findings confirm that the physical-layer dynamics embedded in loops R1, R3, R6, R10, and B3 behave as theorized.

Grounding these foundational loops in data strengthens the credibility of the broader model. Higher-level socio-economic and environmental mechanisms (e.g., cost trade-offs in R4 and B5, environmental impacts in R7) rely on the assumption that LoRa can provide scalable, efficient communication. With that assumption now empirically established, those loops can be pursued in future studies using methods such as techno-economic modeling, lifecycle analysis, or behavioral research.

For system design, the results indicate two key implications. First, adaptive LoRa should be treated as the baseline configuration for TES: fixed-parameter networks collapse at even modest scales and are therefore untenable in practice. Second, while adaptation substantially extends network viability, the observed performance ceiling at 800–1000 nodes highlights the need for architectural strategies—such as segmentation, clustering, or hybrid communication layers—when scaling beyond community-level deployments.

Table II summarizes the validation status of the full causal model, clarifying both the technical scope achieved here and the remaining loops reserved for future empirical investigation.

VI. LIMITATIONS

This study's findings are shaped by several assumptions and technical constraints that must be acknowledged. The causal loop analysis assumes relatively stable interactions between system components and rational stakeholder behavior. In practice, energy markets exhibit nonlinear dynamics and bounded rationality, which could alter outcomes. The study also evaluates LoRa based on its current documented capabilities, though future protocol or hardware advancements may shift its role in TES communication.

From a technical perspective, LoRa's low data rates (22 bps to 27 kbps) and asymmetric uplink/downlink design constrain

TABLE II. Mapping of Feedback Loops to Simulation Validation

Loop	Description	Simulation Test	Input Parameters	Expected Outcome	Actual Result	Status
R1	Energy consumption reduction	Exp 0, 3, 5	Fixed SF/Power vs Adaptive SF/Power	Lower energy with adaptive configuration	Exp 0: 937.22 J → Exp 3: 11.84 J → Exp 5: 8.29 J	Validated
R3	Adaptive power control	Exp 3 vs 5	With vs Without Power Control	Further energy reduction	Exp 3: 11.84 J → Exp 5: 8.29 J	Validated
R6	DER monitoring effectiveness	All experiments	PDR across node densities	Higher PDR with adaptive configuration	Exp 0 PDR: 0.14% → Exp 3: 92% → Exp 5: 91.6%	Validated
R10	System reliability	All experiments	PDR vs Node Density	Reliability maintained under higher load	PDR sustained longer in Exp 3 & 5	Validated
B3	Network congestion	Exp 0	High collision rates with increasing nodes	PDR degradation at higher node counts	PDR collapsed after ∼100–200 nodes	Validated
B4	Operational burden	Not modeled	N/A	Maintenance limits scalability	Not simulated – LoRaSim lacks battery replacement model	Not validated
B1	Security vs adoption	Not modeled	N/A	Security saturation effects	Not simulated – LoRaSim lacks security/authentication modules	Not validated
R4, R7–R9, B5	Various (cost, e-waste, forecasting)	Not modeled	N/A	Economic/environmental benefits	Not measured in current setup	Not validated

its suitability for real-time TES operations. While LoRa excels in coverage and energy efficiency, its limited throughput makes it less capable of supporting functions such as dynamic price signaling, rapid control actions, or emergency interventions. The results therefore suggest LoRa is best positioned as part of a hybrid communication architecture rather than a standalone TES backbone.

The simulated environment excluded several real-world factors that could affect performance. Physical effects such as attenuation, multipath interference, or weather conditions were not modeled, nor was coexistence with other technologies (e.g., Wi-Fi, LTE, or co-located LoRa networks) [29]. Node mobility and asynchronous traffic patterns were also omitted, as all nodes transmitted at fixed intervals. Energy consumption estimates relied on simplified transmission models rather than detailed discharge profiles. Adaptive power control and spreading factor assignment were implemented using approximated link-quality metrics (RSSI, SNR) rather than dynamically computed values. These simplifications likely overstate the stability and efficiency of the simulated system.

Validation was restricted to communication-layer performance—packet delivery, collisions, and energy use. Higher-level feedback loops identified in the system dynamics model remain unvalidated. These limitations indicate that while the study provides robust insights into LoRa's role in TES, it does not capture the full complexity of real-world deployments. The results should be interpreted as establishing the technical feasibility and constraints of LoRa-based TES communication under idealized conditions, rather than as a definitive performance benchmark.

VII. Conclusion and Future Directions

This systems dynamics analysis of LoRa integration into TES reveals how communication technology choices shape performance through intertwined reinforcing and balancing feedback loops. While LoRa's efficiency and cost advantages encourage adoption, scaling introduces congestion and throughput constraints that limit its effectiveness. These dynamics suggest that TES performance is governed not by linear improvements but by scale-dependent trade-offs.

Simulation experiments reinforced this perspective. Adaptive configurations—particularly those combining spreading factor adjustment and power control—delivered dramatic improvements in energy efficiency and reliability, validating the reinforcing loops predicted in the model. Yet, as node density rose, congestion effects eroded these gains, highlighting a scalability ceiling and confirming the balancing mechanisms. LoRa thus appears well suited for small to medium deployments but insufficient alone for larger systems, where hybrid architectures with higher-bandwidth technologies are required.

These findings carry implications for both design and policy. System architects must account for long-term scaling effects rather than relying solely on early efficiency gains, and researchers should investigate hybrid communication models to extend LoRa's utility. Future work should also refine the tipping points between reinforcing and balancing dynamics through quantitative modeling, field validation, and exploration of institutional factors such as regulation and market design. More broadly, this study demonstrates the value of systems thinking in energy technology evaluation, linking communication-layer performance to the socio-economic and environmental dimensions of sustainable energy transitions.

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