A Systems Dynamics Analysis of Communication Technology Integration in Complex Transactive Energy Systems

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***Abstract*—The transition to renewable energy and the increasing integration of Distributed Energy Resources (DERs) have transformed power systems into complex sociotechnical networks. Transactive Energy Systems (TES) offer a decentralized framework to facilitate energy transactions, yet their implementation faces challenges related to communication, cybersecurity, scalability, and environmental trade-offs. This study explores the potential of Long Range (LoRa) communication technology as an enabler of TES, using a systems dynamics approach to analyze its systemic impacts. Through stakeholder analysis and causal loop modeling, the research identifies key reinforcing and balancing feedback mechanisms shaping TES adoption. Findings highlight LoRa's benefits, including enhanced scalability, reduced operational costs, and improved resilience, while also revealing dynamic trade-offs in cybersecurity and network congestion. By applying systems thinking to emerging technologies, this work provides valuable insights for advancing sustainable and resilient energy systems.**

***Index Terms*—Transactive Energy Systems; LoRa Technology; System Dynamics; Sustainable Energy Solutions.**

I. INTRODUCTION

The global energy landscape is shifting in response to rising demand, rapid urbanization, and the need to address climate change [1]–[3]. As societies transition to sustainable energy sources, power systems must integrate renewable energy while ensuring grid stability and reliability. This challenge is particularly pronounced in developing regions, where growing energy needs intersect with ambitious sustainability goals [4].

Traditional power systems, designed for one-way electricity flow from centralized generators to consumers, are increasingly inadequate for managing Distributed Energy Resources (DERs), such as solar panels, wind turbines, and energy storage systems. While DERs offer environmental and technical benefits through localized energy production, they also introduce variability and bidirectional power flows that complicate grid management [5].

Transactive Energy Systems (TES) provide a framework for addressing these complexities. Defined by the GridWise Architecture Council as "a set of economic and control mechanisms that allow the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter" [6], TES establish decentralized marketplaces where energy transactions are guided by real-time supply, demand, and grid conditions [7] [8]. This approach has shown potential for improving affordability, efficiency, and sustainability in power systems [9].

However, TES rely on robust communication infrastructure to function effectively [10] [11]. Many existing communication technologies struggle to meet TES requirements, particularly in terms of energy efficiency, range, and security. These limitations can hinder deployment, especially in areas with dispersed energy resources or weak infrastructure. Additionally, TES face challenges related to data security, privacy, and system resilience [12] [13].

Low-Power Wide-Area Network (LPWAN) technologies, particularly LoRa (Long Range), offer a promising solution to these communication challenges [14] [15]. LoRa enables long-range, low-power communication, making it well-suited for distributed energy systems [16] [17]. Understanding how LoRa's characteristics align with TES requirements is critical for advancing sustainable energy systems [18].

This paper examines the relationship between LoRa technology and TES using a system dynamics approach. System dynamics analyzes complex systems by modeling their structure, feedback loops, and time-dependent behaviors. Here, "dynamics" refers to interactions and feedback mechanisms between components that drive system behavior over time, expressed through reinforcing loops (amplifying changes), and balancing loops (stabilizing the system). By analyzing causal relationships and feedback mechanisms, we explore how communication technology choices impact TES performance across reliability, security, and scalability [19]. These insights can inform more effective TES implementations and guide future research.

Our contributions are as follows. First, we present a comprehensive system dynamics analysis of LoRa integration in TES, highlighting key feedback mechanisms that influence system performance. Second, we identify and characterize eleven reinforcing and five balancing loops that shape the technical, economic, and environmental outcomes of LoRa-enabled TES. Third, we introduce a stakeholder integration framework that maps interactions among technology providers, energy producers, consumers, and regulatory bodies. Finally, we provide practical insights for system architects and policymakers by identifying key leverage points and implementation challenges. These findings enhance the theoretical understanding of TES communication infrastructure while offering guidance for system design and policy development.

The remainder of this paper is structured as follows. Section II reviews the literature on TES and LoRa technology, iden-

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tifying key challenges and opportunities. Section III presents the system dynamics methodology. Section IV examines relationships between system components through causal loop diagrams. Section V discusses the implications of our findings, and Section VI 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 (with energy consumption being a predominant source of climate change, accounting for more than 60% of total global greenhouse gas emissions), technological advancements (through introduction of renewable energy sources and cleaner energy technologies), and evolving consumer needs (particularly the need for reliable and affordable energy for basic needs and well-being) [1] [2]. 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 [5]. 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 [6] [7] [20] [21]. 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 [22]. 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 [10]. Despite these advantages, TES implementation presents significant challenges, particularly in communication infrastructure, data security, privacy, system scalability, and seamless integration with existing grid operations [12] [13] [18].

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 [23]. 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 [24] [25]. 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 (IoT) applications, LoRa operates on a Low-Power Wide-Area Network protocol, offering long-range connectivity with minimal power consumption and strong interference resistance [14] [15]. Studies have demonstrated its advantages over traditional IoT communication technologies, highlighting superior energy efficiency, scalability, and security features [16] [17] [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 [29] [30] [17].

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 [19]. Previous studies applying this approach to energy systems have demonstrated its value in identifying unintended consequences and optimizing the performance of emerging technologies [19]. By leveraging systems thinking methodologies, such as causal loop analysis, we 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

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 [19]. 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 hierarchical framework comprising three distinct layers, as illustrated in Figure 1. At the core technical level, the system integrates DERs, microgrids, and communication infrastructure. This technical foundation operates within a broader system context characterized by market structures, regulatory frameworks, and economic incentives. The external environment, which includes global energy policies, climate goals, and market trends, provides the overarching context that influences the entire system.

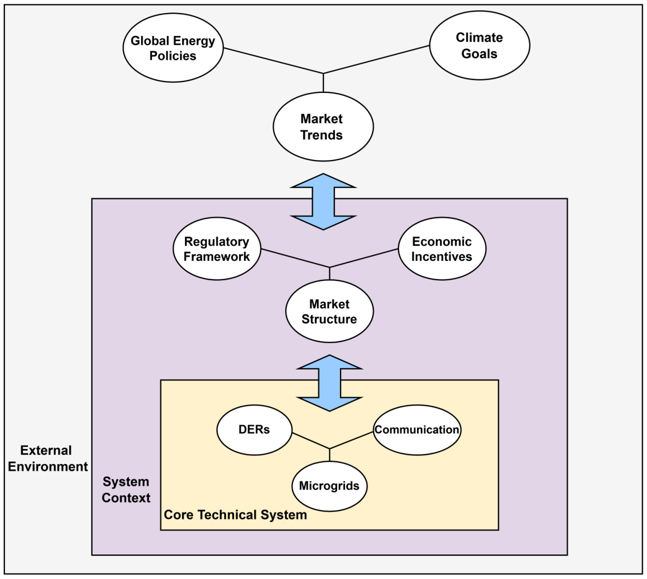

Figure 1. Hierarchical framework of TES: Core Technical System (yellow), System Context (purple), and External Environment (white).

While TES functions within these broader global energy trends, our boundary definition focuses primarily on the interactions between the core technical system and its immediate system context. This approach allows for a targeted investigation into the role of communication technologies while acknowledging the influence of regulatory and market factors that directly impact system operations. The defined boundaries enable us to maintain analytical depth while recognizing the hierarchical nature of TES interactions.

System boundaries are defined based on functional relevance, interdependence, and scalability, but face challenges due to dynamic interactions and evolving technologies. If we were to consider the external environment including global energy policies, market trends and climate goals, our system becomes more complex with multiple variables making it difficult to manage the loops and interactions. For instance, the integration of LoRa as a communication interface is guided by energy efficiency, range, security, and cost-effectiveness. However, boundaries must adapt as TES scale and technology advance, requiring flexible definitions to address emerging interactions and trade-offs. This dynamic approach ensures the analysis remains relevant across different deployment scales and future developments.

The selection of optimal system interfaces, particularly communication means like LoRa, was determined through evaluation of energy consumption profiles, spatial coverage requirements, data throughput needs, and security protocols. One key criterion used for boundary definition was the core technical performance of the LoRa device itself, which helped maintain analytical focus while acknowledging the hierarchical influence of broader factors. The dynamic nature of boundaries becomes particularly important when considering how regulatory changes might trigger cascading effects through market structures into technical operations, or how advancements in communication protocols might enable new market mechanisms that reshape the entire system architecture.

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.

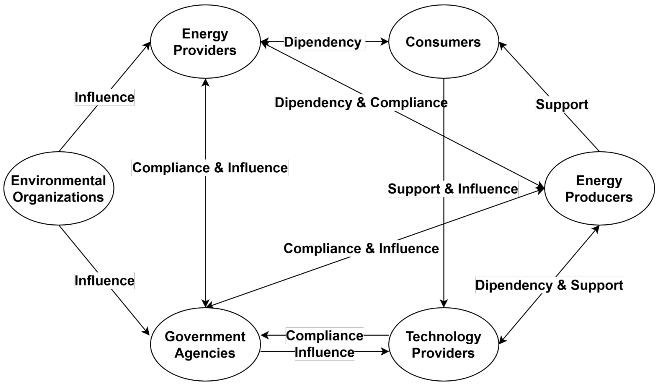

Figure 2. Stakeholder Interest Map in Transactive Energy Systems with LoRa Integration.

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).

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 (Figure 3) 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. SYSTEMS ANALYSIS RESULTS AND DISCUSSION

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 shape system behavior across multiple dimensions. These interconnected feedback mechanisms offer deep insights into how communication technology choices influence system evolution.

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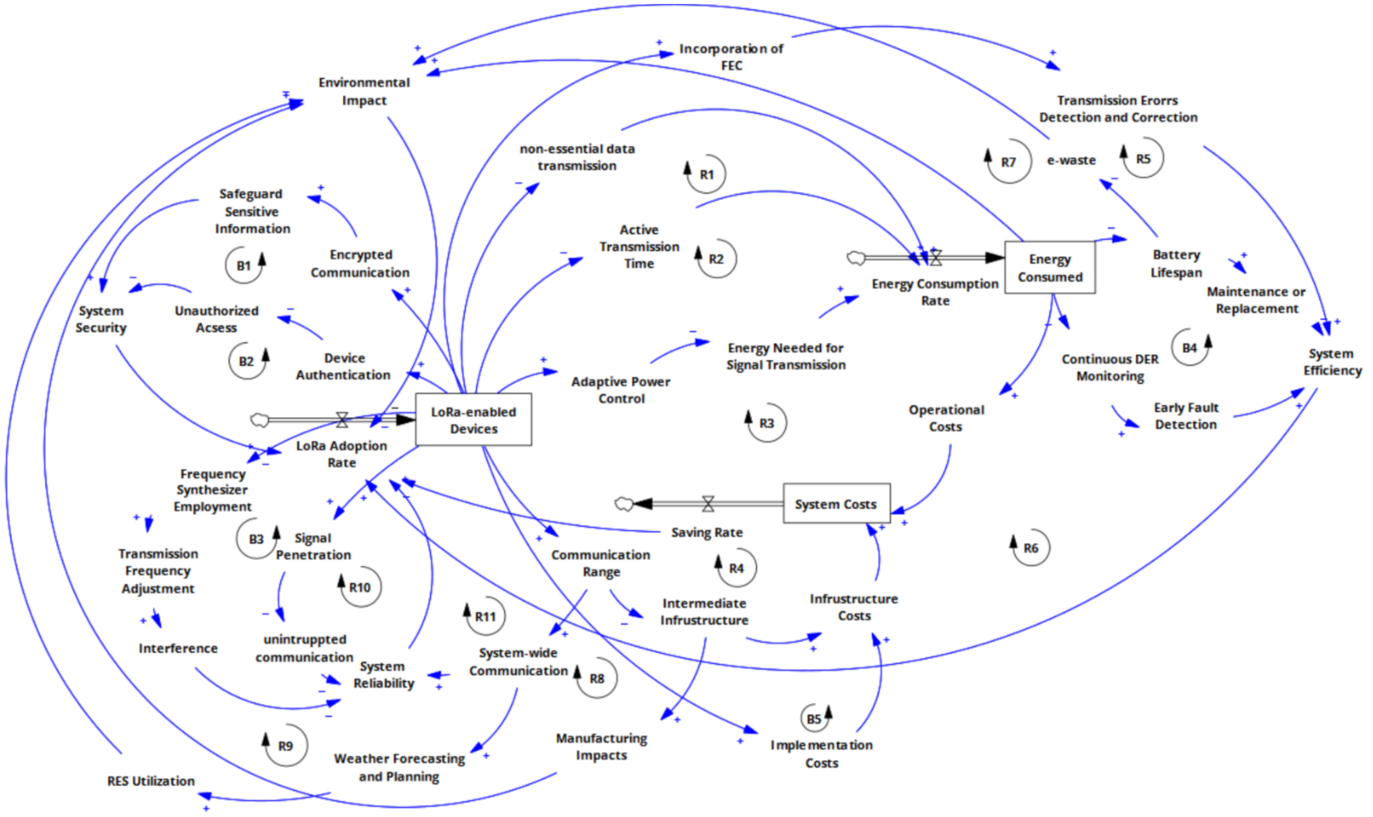

Figure 3. Causal loop diagram of impact of using LoRa on system behavior.

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 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. LoRa also minimizes non-essential data transmission through event-driven communication and scheduled messaging, ensuring data is transmitted only when critical thresholds or specific events occur (e.g., changes in energy demand, supply, or price). This reduces the energy consumption rate (R1) by lowering active transmission time, as LoRa devices operate with low duty cycles, remaining in sleep mode and only waking briefly to transmit or receive data (R2). Adaptive power control further optimizes energy use by dynamically adjusting transmission power and minimizing airtime (R3). Consequently, this cumulative reduction in energy consumption translates into lower operational costs, reinforcing cost savings and enabling further system expansion. 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 influences overall cost effectiveness.

The security and reliability aspects of the system reveal previously unexplored connections. LoRa's encrypted communication and device-level authentication create strong initial security benefits (B1, B2), ensuring that sensitive information remains confidential and accessible only to authorized devices. These security mechanisms interact with system adoption dynamics, forming balancing loops (B1, B2), where increased security reduces the marginal benefit of adding new LoRa devices solely for security purposes, eventually slowing down adoption rates. Meanwhile, Chirp Spread Spectrum (CSS) modulation supports uninterrupted communication by enhancing resistance to interference and multipath fading. This ensures strong signal penetration (R10), which remains unaffected even as device density increases, reinforcing system reliability. However, increased device density introduces potential interference, requiring careful network management.

Environmental feedback loops in LoRa-enabled TES demonstrate more nuanced benefits than initially apparent, influencing both sustainability and system efficiency. The reduction in e-waste (R7) connects directly to extended battery lifespan, as longer-lasting batteries reduce replacement frequency, minimizing discarded electronic waste and its environmental impact. System-wide communication improvements (R8) also contribute by reducing the need for intermediate infrastructure, thereby lowering the demand for raw materials and decreasing manufacturing-related emissions. Perhaps most significantly, LoRa's long-range communication enables precise weather forecasting (R9), enhancing renewable energy system utilization. By integrating weather sensors across vast areas, LoRa facilitates real-time, high-resolution data collection, allowing smart grids to optimize energy distribution and storage based on changing environmental conditions. This capability strengthens the reliability of renewable energy sources, accelerating the transition toward a cleaner and more sustainable energy ecosystem. These interconnected mechanisms suggest that environmental benefits may accumulate more rapidly than previously understood, with 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. LIMITATIONS AND ASSUMPTIONS

This study's system dynamics analysis is built on several key assumptions and technical constraints that shape its findings. The causal loop analysis presumes relatively stable relationships between system components, allowing for systematic evaluation, though real-world interactions are often more dynamic and nonlinear. It also assumes rational stakeholder behavior, which may not always hold true in complex energy markets. Additionally, the study considers LoRa technology based on its current documented capabilities, though future advancements could shift these parameters, potentially altering the validity of identified feedback mechanisms.

From a technical standpoint, LoRa's limited data rates, ranging from 22 bps to 27 kbps, present significant challenges for real-time data exchange in TES. This constraint becomes particularly problematic during market fluctuations or grid instability, where rapid data transmission is critical. While LoRa's strengths lie in its energy efficiency and long-range capabilities, these benefits come at the cost of substantially lower throughput compared to WiFi or cellular networks. Moreover, LoRaWAN's architecture inherently favors uplink communication from devices to gateways, while downlink capacity remains constrained. This asymmetry complicates TES operations, which require bidirectional communication for control signals, market updates, and system feedback. The combination of low data rates and extended transmission times further limits real-time responsiveness, posing challenges for dynamic price signaling, grid stability management, coordinated demand response, and emergency interventions. Given these constraints, LoRa alone may not fully meet the communication demands of TES, but its advantages in efficiency and coverage suggest that hybrid approaches—integrating LoRa with higher-bandwidth solutions—could offer a more effective path forward.

At a real-world scale, this systems dynamics analysis approach and proposed LoRa integration is applicable in small to medium urban districts, particularly in microgrid networks serving 1,000-5,000 users where phased deployment of TES is planned. The framework is especially suitable for areas requiring low-power, long-range communication coverage with modest bandwidth requirements, and locations with mixed energy generation sources. Smart cities represent another key application area, especially communities developing new energy management systems and cities transitioning to renewable energy sources, where systematic analysis of stakeholder interactions is important and cost-effective communication infrastructure is required.

VI. CONCLUSION AND FUTURE DIRECTIONS

This systems dynamics analysis of LoRa technology integration in transactive energy systems reveals complex interdependencies that shape system performance and evolution. Through careful examination of feedback mechanisms, we identify several key insights that inform both theoretical understanding and practical implementation of communication infrastructure in modern energy systems.

The analysis demonstrates that communication technology choices influence TES performance through multiple interconnected pathways. LoRa's technical characteristics create both reinforcing and balancing feedback loops across system efficiency, cost, security, and environmental dimensions. While initial benefits in areas, such as energy consumption and infrastructure costs encourage adoption, counterbalancing forces emerge as systems scale. This suggests the existence of optimal implementation scales that maximize benefits while managing complexity.

These findings have important implications for TES development. System architects must consider not only immediate technical benefits but also longer-term scaling effects when designing communication infrastructure. The emergence of balancing loops at larger scales indicates the need for careful planning and potentially hybrid approaches that combine multiple communication technologies to address different system requirements.

Several areas warrant further investigation. First, the causal loop generated in this work still needs rigorous validation. To this end, quantitative modeling could provide more precise understanding of the transition points where balancing loops begin to dominate system behavior. Second, real-world case studies could validate and refine our understanding of these feedback mechanisms under various deployment conditions. Third, investigation of hybrid communication architectures, as recommended in this work, might reveal ways to maintain benefits while mitigating scaling challenges.

Additionally, future research should examine how these system dynamics might evolve under different regulatory frameworks and market structures. The interaction between technical feedback loops and institutional constraints could reveal important considerations for policy development and market design.

The transition to more sustainable and efficient energy systems requires careful consideration of how individual technologies influence overall system behavior. This analysis demonstrates the value of systems thinking in understanding these relationships while highlighting the importance of considering both immediate and longer-term effects of technology choices in complex energy systems.

REFERENCES

[1] R. G. Newell and D. Raimi, “Global energy outlook comparison methods: 2020 update,” *Resources for the Future*, pp. 20–06, 2020.

[2] Y. Sugiawan and S. Managi, “New evidence of energy-growth nexus from inclusive wealth,” *Renewable and Sustainable Energy Reviews*, vol. 103, pp. 40–48, 2019.

[3] N. Khraief, M. Shahbaz, H. Mallick, and N. Loganathan, “Estimation of electricity demand function for algeria: Revisit of time series analysis,” *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 4221–4234, 2018.

[4] P. Koukaras *et al.*, “Integrating blockchain in smart grids for enhanced demand response: Challenges, strategies, and future directions,” *Energies*, vol. 17, no. 5, pp. 1–18, 2024.

[5] M. A. Tabar, M. A. Jirdehi, and M. Shaterabadi, “Impact of bi-facial pv panels’ presence as the novel option on the energy management and scheduling of the interconnected grids: Comprehensive outlook,” *Journal of Building Engineering*, vol. 90, p. 109495, 2024.

[6] F. Lezama *et al.*, “Local energy markets: Paving the path toward fully transactive energy systems,” *IEEE Transactions on Power Systems*, vol. 34, no. 5, pp. 4081–4088, 2019.

[7] M. Daneshvar, M. Pesaran, and B. Mohammadi-Ivatloo, “Transactive energy in future smart homes,” in *The Energy Internet*, W. Su and A. Q. Huang, Eds. Woodhead Publishing, 2019, pp. 153–179.

[8] Z. Liu, L. Wang, and L. Ma, “A transactive energy framework for coordinated energy management of networked microgrids with distributionally robust optimization,” *IEEE Transactions on Power Systems*, vol. 35, no. 1, pp. 395–404, 2020.

[9] B. H. Rao and P. S. M, “Prosumer participation in a transactive energy marketplace: A game-theoretic approach,” in *2020 IEEE International Power and Renewable Energy Conference*, Oct. 2020, pp. 1–6.

[10] S. Zhang, D. May, M. Gül, and P. Musilek, “Reinforcement learning-driven local transactive energy market for distributed energy resources,” *Energy and AI*, vol. 8, 2022.

[11] D. Xu *et al.*, “Peer-to-peer multienergy and communication resource trading for interconnected microgrids,” *IEEE Transactions on Industrial Informatics*, vol. 17, no. 4, pp. 2522–2533, 2021.

[12] P. Siano, G. Marco, A. Rolán, and V. Loia, “A survey and evaluation of the potentials of distributed ledger technology for peer-to-peer transactive energy exchanges in local energy markets,” *IEEE Systems Journal*, vol. 13, no. 3, pp. 3454–3466, 2019.

[13] O. Abrishambaf, F. Lezama, P. Faria, and Z. Vale, “Towards transactive energy systems: An analysis on current trends,” *Energy Strategy Reviews*, vol. 26, p. 100418, 2019.

[14] Z. Sun *et al.*, “Recent advances in lora: A comprehensive survey,” *ACM Transactions on Sensor Networks*, vol. 18, no. 4, 2022.

[15] J. P. S. Sundaram, W. Du, and Z. Zhao, “A survey on lora networking: Research problems, current solutions, and open issues,” *IEEE Communications Surveys and Tutorials*, vol. 22, no. 1, pp. 371–388, 2020.

[16] C. Li and Z. Cao, “Lora networking techniques for large-scale and long-term iot: A down-to-top survey,” *ACM Computing Surveys*, vol. 55, no. 3, 2022.

[17] O. Georgiou and U. Raza, “Low power wide area network analysis: Can lora scale?” *IEEE Wireless Communications Letters*, vol. 6, no. 2, pp. 162–165, 2017.

[18] O. Tooki and O. M. Popoola, “A comprehensive review on recent advances in transactive energy system: Concepts, models, metrics, technologies, challenges, policies and future,” *Renewable Energy Focus*, vol. 50, 2024.

[19] N. Dhirasasna and O. Sahin, “A system dynamics model for renewable energy technology adoption of the hotel sector,” *Renewable Energy*, vol. 163, pp. 1994–2007, 2021.

[20] M. Mallaki, M. S. Naderi, M. Abedi, S. D. Manshadi, and G. B. Gharehpetian, “A novel energy-reliability market framework for participation of microgrids in transactive energy system,” *International Journal of Electrical Power and Energy Systems*, vol. 122, 2020.

[21] K. Polat and A. Ozdemir, “Impacts of transactive energy trading on the load point reliability indices of lv distribution system,” *IEEE Access*, vol. 11, pp. 132 119–132 130, 2023.

[22] M. Jalali, K. Zare, and S. Tohidi, “Designing a transactive framework for future distribution systems,” *IEEE Systems Journal*, vol. 15, no. 3, pp. 4221–4229, 2020.

[23] H. Zhou, B. Li, X. Zong, and D. Chen, “Transactive energy system: Concept, configuration, and mechanism,” *Frontiers in Energy Research*, vol. 10, pp. 1–14, 2023.

[24] X. Ge *et al.*, “Spatial spectrum and energy efficiency of random cellular networks,” *IEEE Transactions on Communications*, vol. 63, no. 3, pp. 1019–1030, 2015.

[25] L. Fu *et al.*, “Joint optimization of multicast energy in delay-constrained mobile wireless networks,” *IEEE/ACM Transactions on Networking*, vol. 26, no. 1, pp. 633–646, 2018.

[26] S. Devalal and A. Karthikeyan, “Lora technology—an overview,” in *2020 International Conference on Communication and Signal Processing*, July 2020, pp. 1215–1219.

[27] X.-C. Le, B. Vrigneau, M. Gautier, M. Mabon, and O. Berder, “Energy/reliability trade-off of lora communications over fading channels,” *IEEE Communications Letters*, vol. 25, no. 3, pp. 1015–1019, 2021.

[28] S. S. Borkotoky, J. F. Schmidt, U. Schilcher, P. Battula, and S. Rathi, “Reliability and energy consumption of lora with bidirectional traffic,” *IEEE Communications Letters*, vol. 25, no. 11, pp. 3743–3747, 2021.

[29] M. Bor, U. Roedig, T. Voigt, and J. M. Alonso, “Do lora low-power wide-area networks scale?” in *MSWiM 2016 - Proceedings of the 19th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems*, Nov. 2016, pp. 59–67.

[30] R. Marini, K. Mikhaylov, G. Pasolini, and C. Buratti, “Lorawansim: A flexible simulator for lorawan networks,” *Sensors*, vol. 21, no. 3, pp. 1–19, 2021.