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Modeling and Forecasting the Performance of Power Distribution Networks Considering Operational Risks in Energy Imbalance Conditions

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ABSTRACT

Objective: The stable performance of urban power distribution networks plays a fundamental role in ensuring a sustainable and reliable energy supply. However, increasing operational complexities and multiple risks necessitate efficient and adaptive management approaches.

Methods: This study employs system dynamics modeling and Failure Mode and Effects Analysis (FMEA) to model and forecast the performance of urban power distribution networks under energy imbalance conditions. The proposed framework introduces risk-related parameters, failure probability, maintenance delay rate, and risk-propagation factor, and embeds scenario-based forecasting to 2042, enabling analysis of feedbacks between operational risks and demand growth. The novelty of this study lies in developing an integrated SD–FMEA analytical framework that, unlike previous models, simultaneously captures the dynamic propagation of operational risks and their long-term feedback interactions with energy imbalance, network losses, and financial performance.

Results: Simulation results for the Yazd power distribution network indicate that optimized operational risk management can significantly reduce failure rates by the year 2042. Nevertheless, the projected increase in the number of subscribers to 1.2 million and the corresponding growth in electricity consumption pose new challenges for network stability.

Conclusion: While reducing operational risks improves service quality and system resilience, effective demand-side management is also essential to prevent potential network instability. Ultimately, the findings suggest that combining proactive risk management strategies with energy demand control is a key approach to maintaining the long-term sustainability of power distribution networks under energy imbalance conditions.

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1. Introduction

Since the establishment of the first power plant in 1882 in New York, the electricity industry has rapidly evolved as one of the key economic and social infrastructures (Quiroga, Meléndez & Herraiz, 2011). Today, power distribution networks, as the final link in the energy supply chain, play a critical role in ensuring a stable and reliable electricity supply (Brown, 2017; Mohd Azmi et al., 2022). Their operational performance directly affects economic efficiency, social welfare, and national energy security (Gupta, Chawla, & Tiwari, 2022). However, increasing energy demand, resource constraints, equipment aging, and environmental pressures have significantly intensified the challenges faced by power distribution systems (Lopes et al., 2020). Among these, operational risks, such as equipment failures, load fluctuations, adverse weather conditions, and human errors, represent key factors undermining network reliability (Cadini et al., 2017; Souto, Meléndez & Herraiz, 2021). The consequences of these operational risks extend beyond technical disruptions (Abazari Askari et al., 2025). They lead to unplanned outages, rising maintenance costs, customer dissatisfaction, and declining revenues for distribution companies, all of which reduce overall system efficiency (He et al., 2018). These problems become even more critical under energy imbalance conditions, where mismatches between supply and demand magnify system vulnerabilities and complicate operational planning (Dehghan, Amin-Naseri & Nahavandi, 2021). Despite growing research on supply–demand optimization and network loss reduction, previous studies have rarely examined the dynamic interaction between operational risks, consumer demand growth, and financial sustainability within distribution networks (Mansouri et al., 2021; Massaoudi et al., 2025; Ponnaganti et al., 2018). Existing system dynamics (SD) models often emphasize technical or economic variables while overlooking the propagation of risk factors and their long-term feedback on network reliability (Zio, 2016). Similarly, most Failure Mode and Effects Analysis (FMEA) applications remain static and independent (Shaker et al., 2022; Subramanium et al., 2025), providing no mechanism to assess how identified risks evolve or interact with other system elements over time.

To address these gaps, this study develops a comprehensive SD–FMEA framework for modeling and forecasting the performance of urban power distribution networks under energy imbalance conditions. The proposed approach integrates the systematic risk identification and prioritization capability of FMEA with the feedback-driven analytical power of SD modeling. This integration enables the quantification of how operational risks propagate through the network and affect technical and financial performance across time horizons. By capturing these interdependencies, the model provides a more realistic and adaptive tool for risk-informed decision-making in the power distribution sector.

In the first phase, operational risks are identified and ranked using the FMEA method. Subsequently, the interactions and feedback effects of these risks on network reliability, energy losses, and distribution company revenues are analyzed through a system dynamics simulation model. The findings contribute to enhancing risk management strategies, reducing unplanned outages, improving operational efficiency, and informing tariff and policy design under energy imbalance conditions. Furthermore, the results offer a practical perspective for ensuring the long-term sustainability and resilience of power distribution networks.

Despite the extensive development of distribution network studies, current operational planning frameworks still face significant limitations. Existing models tend to either analyze technical reliability in isolation or emphasize short-term economic policies without capturing the long-term, nonlinear interactions among operational risks, demand growth, energy losses, and financial performance.

These gaps are particularly critical in developing-country networks, where aging infrastructure, rapid demand expansion, and tariff constraints exacerbate system vulnerabilities. Therefore, there is a clear need for an integrated, dynamic, and risk-informed modeling framework capable of representing how operational failures propagate across technical and financial subsystems under energy imbalance conditions.

The main highlights of this research are threefold. First, the study introduces an integrated SD–FMEA analytical framework that simultaneously models operational risk propagation, energy imbalance dynamics, and financial performance at the distribution level—an aspect largely absents in existing literature. Second, the model incorporates risk-related parameters such as failure probability, risk-propagation factors, maintenance delays, and scenario-based forecasting up to 2042, allowing for comprehensive evaluation of long-term system behavior. Third, the empirical application to the Yazd distribution network offers a real-world validation of the proposed framework, demonstrating its capability to quantify risk impacts, assess policy alternatives, and support data-driven decision-making for network sustainability.

The remainder of this paper is structured as follows. Section 2 provides a comprehensive literature review and identifies theoretical and practical research gaps. Section 3 presents the problem definition and conceptualizes the SD–FMEA framework. Section 4 details the research methodology, including model formulation, variable specification, and risk assessment procedures. Section 5 presents the simulation results, policy experiments, and performance analysis for the Yazd distribution network. Finally, Section 6 discusses managerial insights, concludes the study, and outlines future research directions.

2. Materials and Methods

Population growth and industrial development have led to an increasing demand for electrical energy. This rising trend has established electricity as a fundamental component of economic and social development, while in some countries, it has resulted in an imbalance between energy supply and demand (Farahnak et al., 2024). In recent years, frequent disruptions in power networks have not only caused significant economic and social losses but have also intensified the challenges associated with energy imbalance, particularly affecting power network performance in critical conditions. These issues have directed the attention of power industry managers toward optimization and network management strategies.

In this context, Wu et al. (2022) proposed an optimization model for safety investment in power distribution companies, integrating system dynamics and Bayesian networks (Wu et al., 2022). Additionally, for managing the supply-demand imbalance in China's electricity sector, the impact of transmission and distribution tariff policies on the cash flow of power companies has been analyzed, and a system dynamics-based investment optimization model has been proposed (He et al., 2018). Furthermore, Jahani et al. (2023) utilized a system dynamics approach to assess investment risks in the power generation supply chain, demonstrating its potential in developing optimal investment strategies for the electricity industry (Jahani et al., 2023).

In addition to reliability and operational analyses, several optimization-based studies have addressed the design and management of power distribution networks using mathematical programming and heuristic techniques. For example, (Alsagri & Alrobaian, 2022; Claeys et al., 2021; Hadi Abdulwahid et al., 2023; Yang et al., 2023) developed a set of efficient heuristics and metaheuristics to solve a two-stage stochastic bi-level decision-making model for the distribution network problem. Such approaches provide valuable insights into multi-level decision processes under uncertainty, particularly for investment and expansion planning. However, these models primarily focus on static optimization of network configurations rather than capturing the dynamic feedback effects of operational risks, consumer behavior, and financial sustainability over time.

The present study complements these works by adopting a system dynamic–based framework that integrates risk assessment (FMEA) to analyze the temporal interactions and long-term impacts of operational risks under energy imbalance conditions.

Numerous studies have analyzed the causes of failures and disruptions in power distribution networks. For instance, a monitoring-based study on a Spanish power distribution company identified the key failure factors in distribution networks (Quiroga, Meléndez, & Herraiz, 2011). Additionally, Soto et al. (2021), from the Intelligent Systems and Control Engineering Group in Girona, introduced a novel approach using multilayer principal component analysis to detect abnormal operational conditions in power distribution network data (Souto, Meléndez, & Herraiz, 2021). In Iran's electricity sector, Dehghan et al. (2021) investigated the factors influencing power losses using a system dynamics approach and compared their findings with econometric models (Dehghan, Amin-Naseri & Nahavandi, 2021).

As the complexity of power system dynamics increases and uncertainties in forecasting grow, risk-based approaches have become essential for assessing the dynamic security of power networks. In this context, Kiapshoni et al. (2017) adopted a probabilistic approach, providing a more comprehensive perspective on power system security. Compared to traditional deterministic methods, their approach offers a more accurate evaluation of system performance under various operational conditions (Ciapessoni et al., 2017).

One of the key performance indicators for power distribution networks is the equipment failure rate, which is obtained by collecting outage management data. Asset management and network equipment information systems play a crucial role in enhancing distribution network performance and facilitating strategic decision-making (Honarmand, Haghifam, & Ghazizadeh, 2015). In this regard, Liu et al. (2020) proposed a dynamic model that integrates economic growth theory with a logistic learning curve model, enabling optimal asset management in power distribution networks (Liu et al., 2020).

The increasing frequency and severity of extreme weather events in recent years, leading to widespread power outages, have underscored the importance of resilience in power distribution system design and operation (Paul et al., 2024). To address this issue, Reference (Zhang, Karve & Mahadevan, 2024) proposed the use of gray neural networks as an alternative to traditional decision-making algorithms in power network operations. By leveraging Monte Carlo sampling, they provided a more precise assessment of operational risks in power networks.

Fallah and Shishehbori (2023) applied the FMEA method and the Best-Worst Method to identify, evaluate, and prioritize operational risks in power distribution networks. Their findings highlighted that three high-priority operational risks—including failure of concrete poles, external object impact, and transformer malfunctions—account for 27% of unplanned outages (Fallah Baghemoortini & Shishebori, 2023).

To develop a comprehensive solution for simultaneously managing multiple operational risks in power distribution networks, the interdependencies among these risks were analyzed using Fuzzy Cognitive Maps. The findings suggest that focusing on weather forecasting, reinforcing network structures, and optimizing transformer maintenance can provide a sustainable strategy for operational risk management, ultimately reducing the frequency of unplanned outages (Fallah Baghemoortini, Shishebori & Alimohammadi Ardakani, 2024).

The rising adoption of electric vehicles as a new consumer category in power distribution networks has drawn significant attention. In this regard, studies in South Korea utilized a system dynamics approach to identify and prioritize disruptions that lead to failures or damages in public EV charging stations, which are integral components of power distribution networks (Forrester, 1961; Hwang, Kim & Kim, 2024; Putra & Prijadi, 2024).

Table 1. Summary of related literature on distribution network performance, operational risks, and SD-based modelling

Authors (Year)	Method / Approach	Focus of Study	Key Findings	Limitations
Wu et al. (2022)	SD + Bayesian Networks	Safety investment optimization	Improved investment allocation under uncertainty	Does not model risk propagation or financial feedback loops
He et al. (2018)	SD modeling	Tariff impact & cash flow	Shows tariff reforms affect company finances	No operational risk modeling
Jahani et al. (2023)	SD	Power generation investment risk	Captures dynamic investment risks	Not applicable to distribution networks or operational failures
Alsagri & Alrobaian (2022)	Heuristics / Bi-level optimization	Distribution design	Solutions for network expansion	Static; no dynamic risk or demand modeling
Souto et al. (2021)	PCA / Monitoring	Anomaly detection	Detects abnormal patterns	Does not analyze dynamic system behaviors
Dehghan et al. (2021)	SD	Power losses	SD shows demand-loss interactions	Does not include operational risks or financial effects
Fallah & Shishehbori (2023)	FMEA + BWM	Risk prioritization	Identifies key risks	Static; no dynamic feedback analysis
Zhang et al. (2024)	Gray NN + Monte Carlo	Risk assessment	More precise risk quantification	No integration with network performance or SD
Hwang et al. (2024)	SD	EV charging failures	Identifies EV-related disruptions	Limited to EV networks, not distribution grids

A review of previous research (Table 1) indicates that most system dynamics studies have primarily focused on forecasting electricity supply and demand and examining economic variables, such as price fluctuations and tariff policies. However, the impact of operational risks on energy supply stability and the financial dynamics of power distribution companies has not been comprehensively addressed. Most studies have concentrated on demand-side management and electricity pricing policies, whereas the feedback interactions among operational risks, network losses, and the financial sustainability of power distribution companies have received limited attention. Despite these advancements, no existing study integrates risk prioritization through FMEA with a dynamic SD-based model to jointly assess operational risks, energy imbalance drivers, and financial sustainability. This integrated perspective is missing in the literature and represents the core contribution of the present study.

The innovation of this research lies in developing an analytical framework that integrates system dynamics modeling with operational risk assessment to identify and model the complex interactions between energy supply, financial imbalance management, and operational risks. By leveraging real-world data from the Yazd power distribution network, this study analyzes the effects of operational risks on key factors such as distribution company revenues, consumer demand, and network losses, ultimately providing a comprehensive framework for strategic decision-making in the power sector. Moreover, the financial imbalance of power distribution companies, resulting from inefficiencies in operational cost management, network losses, and tariff policies, can lead to reduced investment in infrastructure development and increased dependence on government subsidies. In the long run, this not only negatively affects the quality of power distribution services but also threatens energy supply sustainability. Therefore, analyzing the bidirectional relationships between financial imbalance, network infrastructure investment, and energy supply resilience is one of the key contributions of this research. Empirical evidence suggests that system dynamics modeling is a powerful tool for analyzing the interdependencies among key variables and capturing the long-term behavior of power distribution systems. However, a comprehensive assessment of the impact of operational risks on energy imbalance, financial sustainability of distribution companies, and network losses remains a research gap.

Therefore, this study addresses the following gaps identified in the literature:

1. the lack of an integrated framework that jointly models operational risks, financial imbalance, and network performance;
2. limited understanding of the dynamic feedback relationships between these factors under energy imbalance conditions;
3. the absence of empirical validation using real-world data from developing-country distribution networks.

The main contributions of this research are as follows:

1. developing a system dynamic–based model integrated with FMEA to assess operational risks in power distribution systems;
2. analyzing the dynamic interactions among operational risks, financial imbalance, and network losses under energy imbalance conditions;
3. applying the proposed model to the Yazd urban power distribution network to provide managerial insights for improving reliability, financial sustainability, and resilience.

These additions explicitly clarify both the research gaps and the novelty of this work, aligning the study's contributions with the existing literature.

3. Problem Definition

Urban power distribution networks increasingly operate under conditions of rising demand, aging infrastructure, and exposure to diverse operational risks. These networks are particularly vulnerable to *energy imbalance*, defined as the persistent mismatch between electricity supply and demand. Such imbalance magnifies the likelihood of equipment failures, disrupts operational planning, increases outage frequency, and places significant financial pressure on distribution companies. In the case of developing regions, these challenges are further intensified by limited investment capacity, high network losses, and outdated maintenance practices.

Despite the critical importance of these issues, existing analytical and optimization-based models largely examine individual components of the distribution system, such as demand forecasting, tariff design, asset management, or loss reduction, without capturing the *dynamic interdependencies* among operational risks, energy imbalance drivers, financial sustainability, and long-term network performance. This lack of an integrated dynamic perspective limits the ability of managers and regulators to identify the root causes of instability, assess risk propagation pathways, and evaluate the long-term consequences of operational decisions.

Therefore, the central problem addressed in this study is the absence of a holistic and dynamic modeling framework capable of:

- simultaneously identifying and prioritizing operational risks,
- quantifying how these risks propagate through the network over time,
- assessing their impacts on technical (failure rates, losses) and financial (revenues, costs) dimensions, and
- forecasting long-term system behavior under energy imbalance conditions.

To address this gap, the present study develops an integrated System Dynamics–FMEA framework for modeling and forecasting the performance of the Yazd urban power distribution network. The framework captures the feedback loops between operational risks, energy imbalance, demand growth, network losses, and financial performance. Accordingly, the main contributions of this work are:

1. Developing a comprehensive SD-based modeling structure integrated with FMEA to quantify and analyze the dynamic interactions among operational risks, energy imbalance, and network losses.
2. Providing a quantitative evaluation of the long-term technical and financial impacts of these factors under various scenarios using real-world data from the Yazd distribution network.
3. Offering strategic, data-driven insights for improving resilience, financial stability, and operational planning for power distribution companies in developing countries.

4. Research Methodology

System Dynamics (SD) has been recognized as an effective tool for analyzing complex feedback-driven systems in the power industry (Dehghan, Amin-Naseri & Nahavandi, 2021). This approach has been extensively applied in various fields, including biomass supply chain integration (Abbasi, Ashari & Yusuf, 2023), government subsidy design for promoting the electric vehicle industry (Li et al., 2023), demand-side electricity management (Ahmad et al., 2016), green energy adoption and natural gas import reduction (Ghezelbash et al., 2023), complex project management in power networks (Chen et al., 2012), and Water-Energy-Food nexus simulation combined with the Society-Economy-Environment system (Wang, Dong & Sušnik, 2023), Furthermore, SD has been utilized in value chain analysis in the pharmaceutical industry (Kharaghani, Homayounfar & Taleghani, 2023), sustainable bioethanol supply chains (Taheri, Jahani, & Pishvaee, 2024), urban water supply system management (Heydari Kushalshah, Daneshmand-Mehr & Abolghasemian, 2023), and network-scale planning for sustainable crop patterns (Taheri, Pishvaee, & Jahani, 2025), demonstrating the versatility of this approach in solving complex system-level problems.

In this study, a hybrid methodology combining System Dynamics and risk analysis is employed to model and forecast the performance of the Yazd urban power distribution network under energy imbalance conditions. The proposed analytical framework models the impact of operational risks on network stability, consumer electricity consumption, and distribution company revenue, while also providing strategic insights for optimal risk management. Additionally, the model evaluates the effects of energy imbalance on interactions between operational risks, network losses, and the financial sustainability of the distribution company. The dataset used in this study includes historical data from the Yazd power distribution network, information related to operational risks, records of power outages, distribution company revenue, and consumer electricity consumption, all of which were collected from official databases and expert interviews within the power industry.

To identify and rank operational risks, the FMEA method was applied. The FMEA methodology applied in this study follows the structure and scoring logic recommended in the IEC 60812 standard (Modes, 2018), allowing for systematic identification and prioritization of failure modes in power distribution systems. In this phase, the Risk Priority Number (RPN) was calculated based on expert opinions from 10 specialists in power distribution operations in Yazd, allowing for the identification of the most critical operational risks. Following this step, the key model variables were extracted, and dynamic system hypotheses were formulated. Next, the Causal Loop Diagram (CLD) of the system was designed using Vensim software, incorporating endogenous and exogenous variables to analyze the interactions between operational risks, energy imbalance, network losses, electricity consumption, and distribution company revenue. Subsequently, the Stock-Flow Diagram (SFD) was constructed, and simulation modeling was conducted to analyze the distribution network's behavior over the period from 1401 to 1421 (2022 to 2042).

To validate the accuracy of the simulation model, the Behavior Reproduction Test was performed by comparing the simulation results with real-world data from the power distribution network. Additionally, the Boundary Adequacy Test was conducted to ensure that all significant variables influencing system dynamics were accounted for. Finally, the impacts of different risk management policies and electricity tariff adjustments on network performance were examined. These analyses included optimized operational risk management, the effects of controlling consumer electricity demand growth, and the evaluation of tariff adjustment policies under energy imbalance conditions. The findings of this study provide valuable insights for policymakers and power industry managers, enabling them to enhance the resilience of distribution networks and better manage energy imbalance.

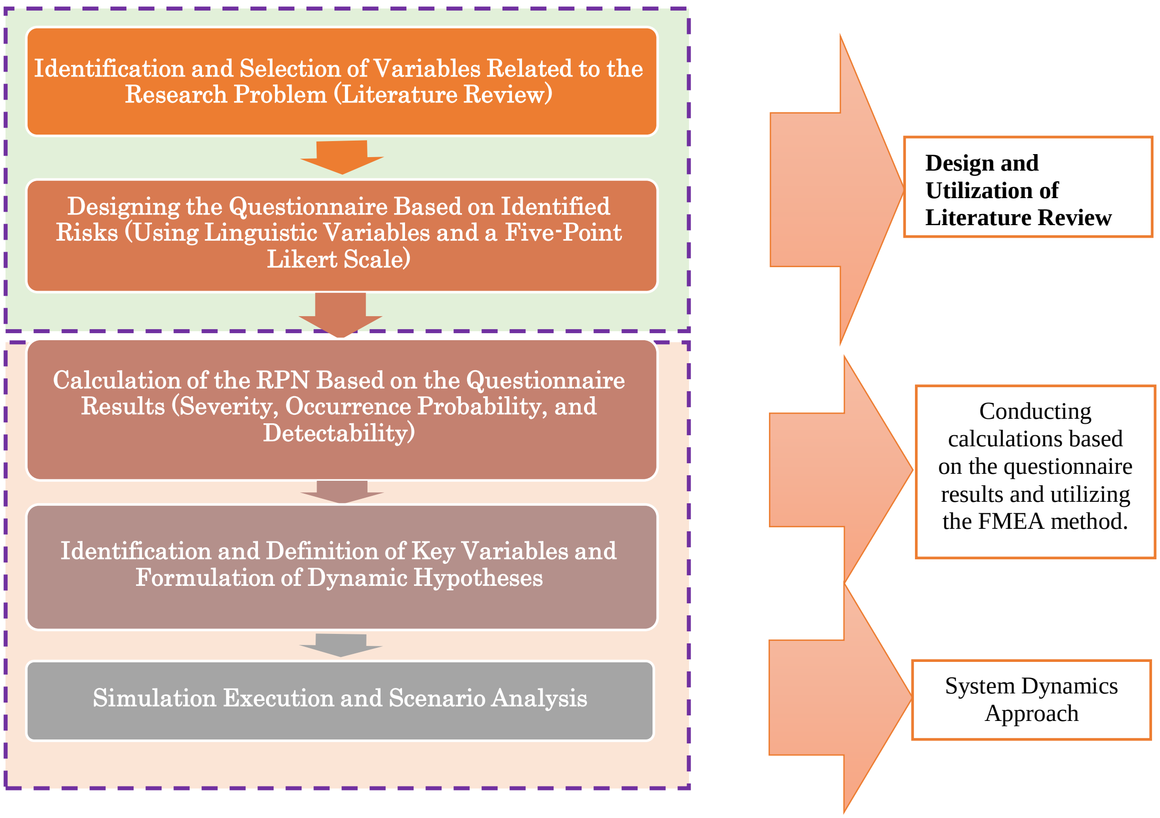

Figure 1. Research Procedure Steps

5. Numerical Results

This section presents the findings of the study in four key areas: identification and assessment of operational risks in power distribution networks, modeling of network performance, simulation and policy implementation, and analysis of the results on the system. These results are derived based on the research methodology, utilizing the FMEA method and system dynamics modeling.

5.1 Identification and Assessment of Operational Risks in Power Distribution Networks

Risk assessment, as a fundamental pillar of power distribution system management, serves as an effective tool for identifying and analyzing threats to network stability. In this study, a comprehensive review of previous research and expert consultations in the electricity sector was conducted to identify key operational risks. These risks were then evaluated and prioritized using the FMEA method. To achieve this, a Likert-scale questionnaire was designed, and feedback from 10 specialists and operators of the Yazd Power Distribution Company was collected (Table 2).

An analysis of the RPN values revealed that structural failures in network poles pose the highest-risk priority, as identified by industry experts. The fracture and collapse of poles not only lead to prolonged outages but also impose significant financial and safety risks. Ranked second were external object impacts and transient faults, which contribute to unstable network conditions and reduced system reliability. Additionally, insulator failures and self-supporting cable breakages were identified as subsequent priority risks. This risk prioritization plays a critical role in the modeling phase, where the identified risk factors are incorporated into the simulation framework.

Table 2. Calculation of RPN for Operational Risks in Yazd Power Distribution Network

No.	Risk Name	Severity	Occurrence	Detection	RPN
1	Failure in poles (concrete, wooden, metal)	5	4	5	100
2	Collision with external objects (e.g., vehicles, construction equipment, trees, etc.)	4	4	5	80
3	Transient fault	3	5	4	60
4	Insulator failure (disc, pin-type)	4	4	3	48
5	Breakage of self-supporting cable	4	4	3	48
6	Transformer failure	4	4	3	48
7	Bird collision	3	4	3	36
8	Jumper failure	3	4	3	36
9	Wire breakage	3	3	4	36
10	Surge arrester malfunction	3	3	3	27
11	Fault in high-voltage distribution equipment	3	3	3	27
12	Adverse weather conditions	2	5	2	20
13	Cut-out fuse failure	3	3	2	18
14	Fault in circuit breakers (reclosers, air disconnectors, etc.)	3	2	3	18
15	Hardware failure	3	3	2	18
16	Electrocution	2	2	4	16
17	Theft of network equipment	5	1	3	15
18	Failure in electrical substations	3	4	1	12
19	Contact between conductors or with the ground	1	2	4	8
20	Human error (e.g., incorrect maneuvering or power disconnection during live-line work)	3	2	1	6
21	Failure in customers' internal network	2	3	1	6

To minimize bias in expert scoring, participants were carefully selected to represent a diverse mix of operational, planning, maintenance, and safety departments within the Yazd Power Distribution Company. Each expert independently and anonymously completed the FMEA questionnaire to prevent influence from other participants. The final RPN values were calculated using the average of all scores, and statistical screening was performed to identify and resolve significant outliers. This approach helped ensure the objectivity and reliability of the risk prioritization process.

5.2 Modeling of Distribution Network Performance

After identifying and prioritizing the operational risks in the electricity distribution network, the next step is to determine other key system variables and collect relevant data for dynamic system modeling. This process involves defining the model boundaries, identifying endogenous, exogenous, and out-of-model variables, and formulating the system dynamics hypotheses. In this context, the proposed model for analyzing the dynamics of the electricity distribution network in Yazd Province has been developed.

5.2.1 Identification of Variables and Their Relationships

To formulate the dynamic hypothesis, the nature of the key variables in the model was first determined, and the model boundaries were defined (Table 3). This process plays a crucial role in determining the scope of the analysis, distinguishing effective variables, and identifying external factors that may influence the results. The analysis of interactions between variables reveals that operational risks have both direct and indirect effects on the performance of the electricity network. The occurrence of these risks can lead to a decrease in revenue from electricity sales, an increase in compensation costs for the distribution company, and damage to customers and network infrastructure. On the other hand, electricity price changes can act as a significant factor influencing electricity consumption and the intensity of operational risks, especially in energy imbalance conditions and increased pressure on the distribution network.

Table 3. Model Boundary Diagram

Row	Endogenous Variables	Exogenous Variables	Excluded Variables
1	Revenue of power distribution co.	21 risks listed in Table 1	Power plant fuel consumption
2	Provincial population	Price fluctuations	Non-energy resources
3	Number of subscribers	Technical losses	Alternative energy sources
4	Electricity price	Risk-induced damages	Environmental constraints
5		Delivered energy	Revenue from connection sales
6		Average annual consumption per sub.	
7		Inflation rate	
8		Electricity consumption	

To incorporate uncertainty in electricity demand into the model, scenario-based simulations were performed by adjusting key parameters such as the average annual electricity consumption per subscriber and the subscriber growth rate. These variations were used to reflect potential demographic and economic changes, including fluctuations in electricity prices and population trends, that may influence future demand under energy imbalance conditions. To capture electricity demand patterns, the model incorporates variables such as subscriber growth and average consumption per user. These demand-related components reflect established approaches in short-term forecasting literature (Taylor, 2003).

The dynamic hypothesis of the model is: How do electricity price fluctuations affect consumption levels, the occurrence of operational risks, and the performance of the distribution network under energy imbalance conditions? To examine this hypothesis, a system dynamics model was developed, including the analysis of relationships between key variables, the design of a causal-loop diagram, and the execution of dynamic simulations.

To better address the effect of uncertain demand on pricing, electricity price was modeled as an exogenous variable that influences consumption patterns in the system dynamics model. While the base price followed historical trends, future pricing was assumed to increase in stepwise increments aligned with potential tariff reforms. These price adjustments were integrated into scenario-based simulations to assess their impact on electricity demand, operational risks, and company revenue. Although the model does not include a fully endogenous dynamic pricing loop, the policy simulation section introduces dynamic adjustments in price levels to reflect feedback from increasing demand and network load conditions. This approach allows capturing indirect dynamics between demand uncertainty and pricing decisions.

Although variables such as alternative energy sources and non-energy resources were excluded from the current system dynamics model (as listed in Table 2), this decision was made based on their minimal impact on the Yazd power distribution network within the study horizon. According to the latest reports from the Ministry of Energy, the share of renewable energy in Yazd's electricity mix remains below 2%, and no major policy shift is expected to significantly alter this by 2042. Therefore, the model focuses on the dominant sources of electricity and operational factors currently influencing network performance and financial sustainability. Nevertheless, future expansions of the model will aim to incorporate supply-side diversification to evaluate its long-term impact on demand management and revenue streams.

5.2.2 Causal Loop Diagram

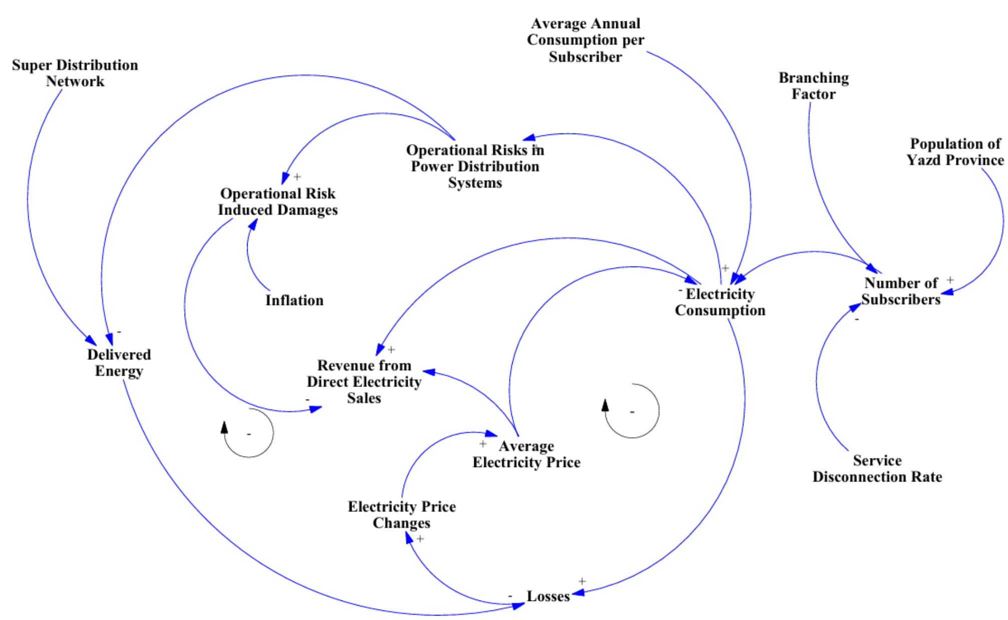

Figure 2. CLD of the Entire System

The CLD is designed to represent the cause-and-effect relationships between variables (Figure 2). This diagram enables the analysis of system dynamics and the identification of factors influencing the performance of the electricity distribution network. In the presented CLD, two balancing feedback loops have been identified, playing a significant role in the stability and dynamic behavior of the system:

- First Balancing Loop: Network losses → Price fluctuations → Average price → Electricity consumption
- Second Balancing Loop: Delivered energy → Network losses → Price fluctuations → Average price → Electricity consumption → Operational risks

These two balancing loops demonstrate the simultaneous effects of electricity price, consumption levels, and operational risks on network losses and the energy delivered to customers. Additionally, the variables of provincial population and operational risks themselves include sub-models with separate causal-loop diagrams, and their dynamic impacts will be examined in the following sections.

Next, the interrelations between operational risks are analyzed using expert knowledge and historical data. The related causal-loop diagram (Figure 3) shows that operational risks function as a cause-and-effect network with reciprocal impacts on each other. Unlike the previous balancing loops, no negative or stabilizing feedback loop is observed in this section, as all relationships are of a positive and reinforcing nature, meaning the occurrence of one operational risk can increase the likelihood of other risks. To more accurately represent these interactions, a flow-stock model has been developed in which the relationships between operational risks, electricity consumption, network imbalance, and the revenue changes of the distribution company in Yazd Province are analyzed numerically.

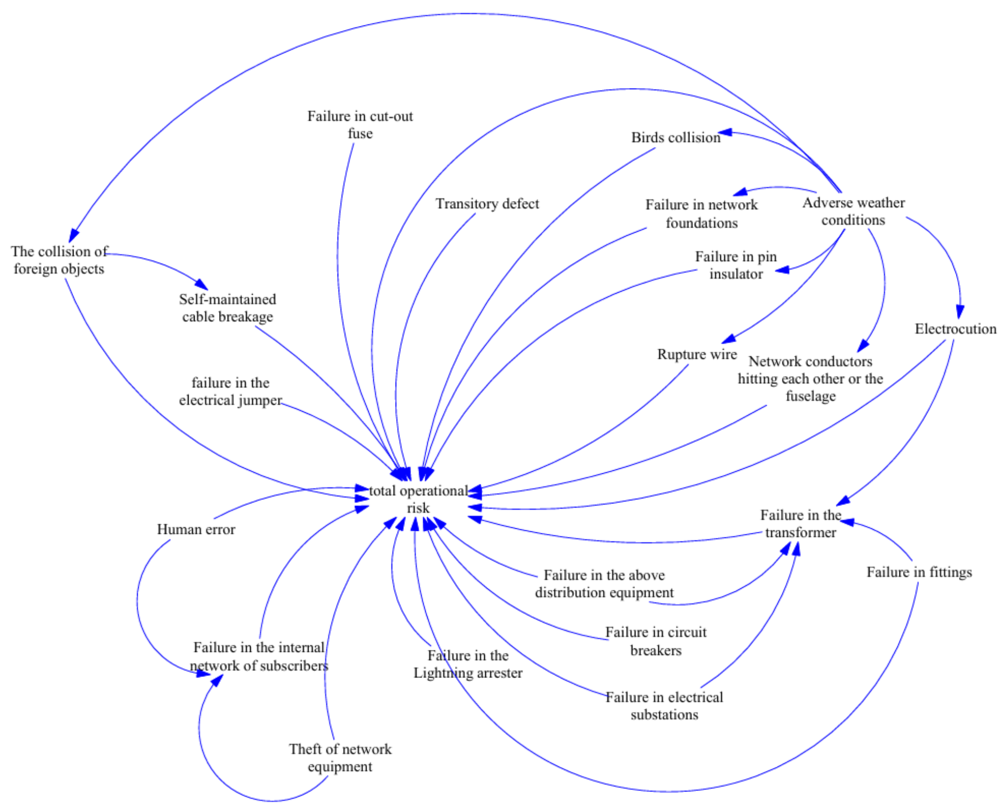

Figure 3. CLD of Operational Risks

The CLD of the provincial population (Figure 4) illustrates the relationship between demographic structures and energy demand at the distribution network level. In this model, population is considered as an influencing variable on electricity consumption and the network load pattern, and it is analyzed by age groups. In the Stock-Flow Diagram, the demographic structure is displayed with age group breakdowns, as consumption patterns of different age groups can impact the network load and the amount of energy delivered.

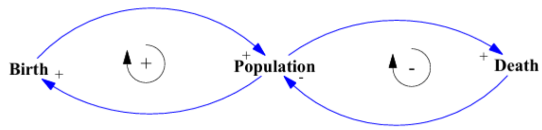

Figure 4. CLD of the Population

The proposed model in this research is designed with a system dynamics approach, and its structure consists of three main subsystems, which have been integrated into a unified overarching model (Figure 5). In this study, energy imbalance resulting from the discrepancy between supply and demand, technical and non-technical losses, and the impact of operational risks on the network performance are comprehensively analyzed within this model.

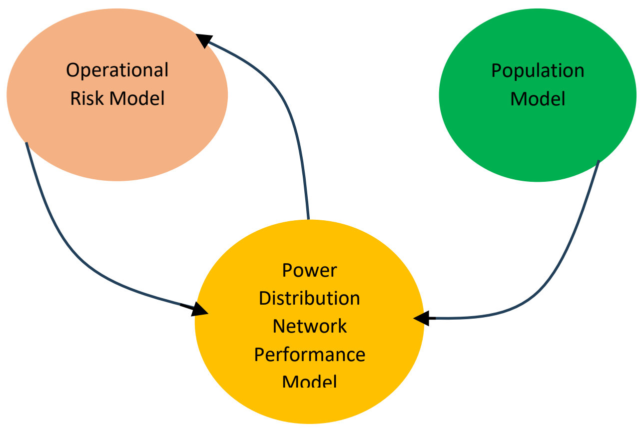

Figure 5. Conceptual Model

5.2.3 Stock-Flow Diagram

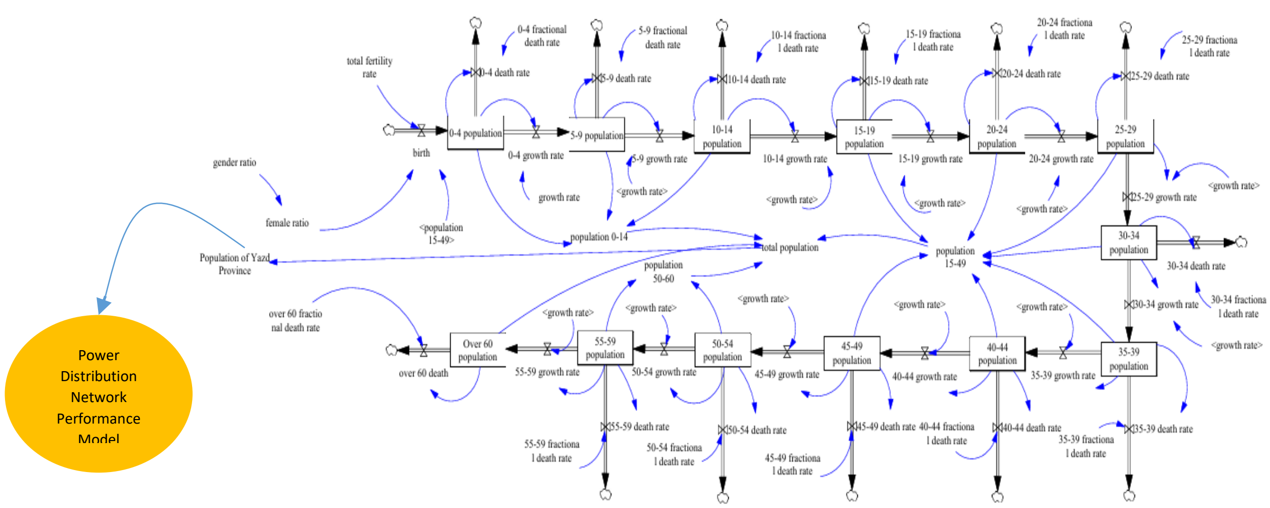

Figure 6. Stock-Flow Diagram Part A: Population

The first subsystem, the dynamic model of population and electricity consumption in the distribution network (Figure 6), examines the trend of demographic changes and their effects on electricity demand, considering variables such as population growth rate, number of customers, average annual consumption, and changes in consumption patterns. The increase in demand due to population growth and changes in consumer behavior is one of the key factors contributing to energy imbalance in the distribution network. This subsystem models the relationship between demographic indicators and electricity consumption changes, enabling the analysis of different demand scenarios.

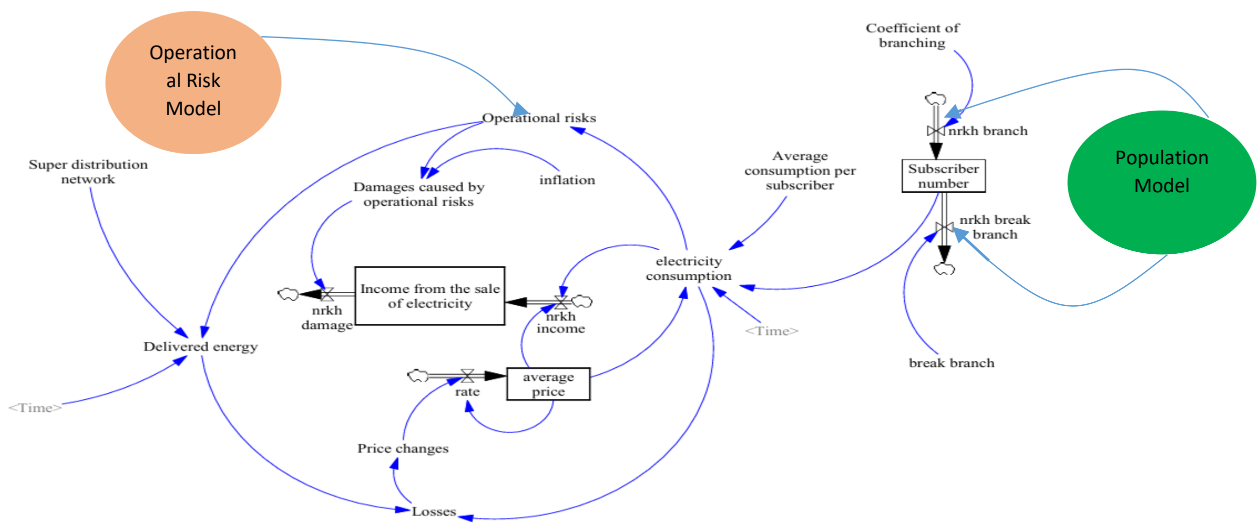

Figure 7. Stock-Flow Diagram Part B: Energy Pricing

In the second subsystem, the model of distribution network performance and energy losses (Figure 7) examines the performance of the distribution network and the amount of energy delivered to customers, influenced by factors such as infrastructure capacity, technical and non-technical losses, and electricity price fluctuations. This subsystem analyzes the electricity supply compared to demand and identifies the share of energy losses in increasing the energy imbalance. In this section, the effects of operational policies, investment in network development, and the impact of price changes on electricity supply and consumption are analyzed.

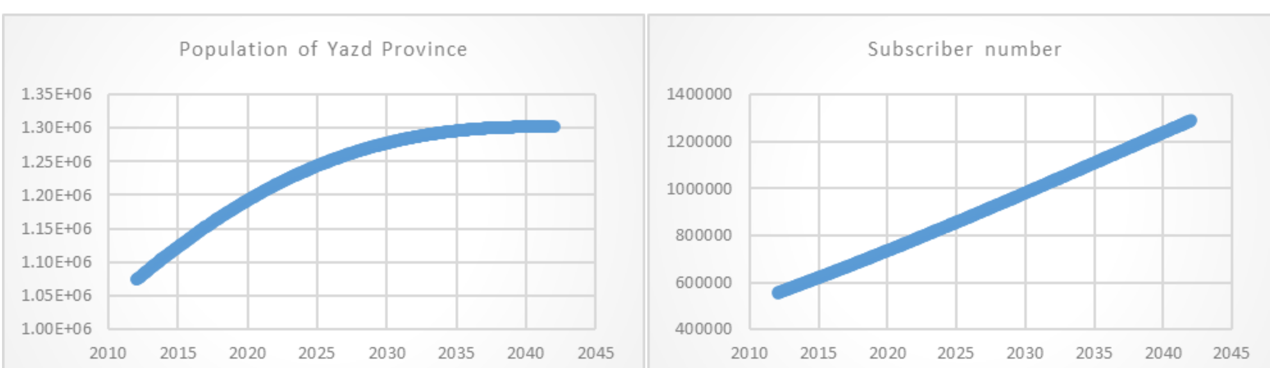

Figure 9. Forecasted Population and Number of Customers for the Yazd Distribution Electricity Company from 2022 to 2042

The simulation results show that the population of Yazd province will reach approximately 1.3 million by 2042, and the number of customers for the electricity distribution company will exceed 1.2 million (Figure 9). This increase will lead to a significant growth in electricity demand. While the existing infrastructure of the distribution network, especially if it is not developed accordingly, may not be able to meet this increased demand. The imbalance between demand growth and supply capacity could lead to a decline in service quality, increased outages, and reduced network reliability.

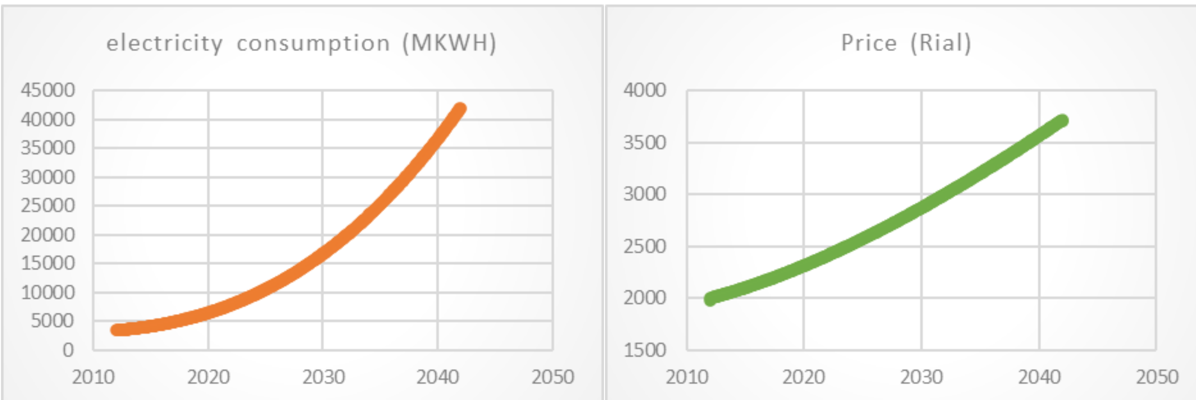

Figure 10. Electricity Consumption and Price Trends from 2022 to 2042

The analysis of electricity consumption trends indicates that demand will exceed 40,000 million kilowatt-hours (MKWH) due to the growing number of subscribers and increased usage (Figure 10). However, ensuring a stable supply at this level requires adequate capacity expansion and efficient supply-side management.

On the other hand, electricity price adjustments projected under realistic tariff policy reforms could influence consumer behavior. If pricing reforms are not implemented effectively, consumption patterns may not shift significantly, sustaining pressure on the distribution network. This imbalance between supply and demand would further strain the system, increasing reliance on costly peak-load power sources and exacerbating energy sector inefficiencies.

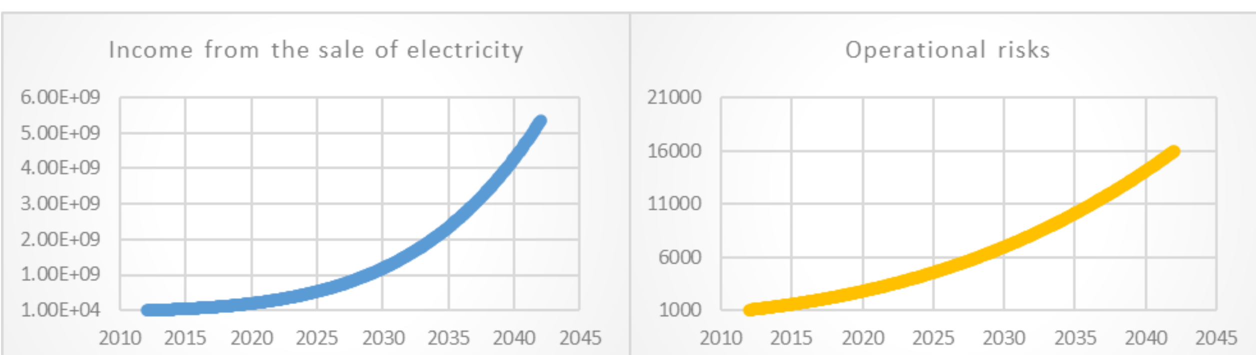

Figure 11. Revenue of Yazd Province Power Distribution Company and Operational Risks of the Distribution Network (2022-2042)

The net revenue of the power distribution company from direct electricity sales is illustrated in the figure above (Figure 11). The analysis reveals a growing trend in operational risks, which have intensified due to increasing consumer demand, imposing greater losses on the distribution network. Furthermore, rising electricity consumption necessitates higher power supply, subjecting the network to increased load. As shown in the figure, energy delivery will face a sharp surge in demand in the coming years. These findings collectively indicate that electricity consumption will experience significant growth in the future, making stable power supply a critical priority. In the policy analysis section, we examine the impact of reducing operational risks in the power distribution network and the effect of realistic electricity pricing on consumer consumption patterns.

5.2.4 Simulation Structure and Model Calibration

To provide a detailed explanation of the simulation model, the Stock-Flow Diagram was implemented using Vensim software. Each subsystem (population growth, operational risk dynamics, and electricity consumption behavior) was formulated using a set of differential and algebraic equations derived from historical data and expert input. The initial values of stocks (such as population, number of subscribers, and delivered energy) were set based on the year 2022, using official statistics from the Yazd Power Distribution Company.

Key relationships, such as the effect of electricity price on consumption, and the link between operational risks and energy losses, were formulated as nonlinear functions calibrated through historical time-series data and expert validation. The simulation was performed over a 20-year horizon (2022–2042), with a time step of one year.

To validate the model, a Behavior Reproduction Test was conducted. The simulation results for key indicators, such as electricity consumption, operational risk trend, and company revenue, were compared to historical data from 2022 to 2024, showing a high degree of alignment. Additionally, sensitivity analysis was performed to examine how the model responds to changes in critical parameters like electricity price and risk priority numbers.

Moreover, the calibration of the system dynamics model was performed through a two-stage iterative process. First, key parameters such as price elasticity, consumption coefficients, and network loss factors were tuned to match historical observations for the period 2022–2024. This parameter fitting ensured that simulated trends for electricity demand, company revenue, and operational risks accurately reproduced real-world behavior, with a mean absolute percentage error below 5%. Second, sensitivity testing was applied to assess model robustness under ±10% variations of critical parameters. The consistent dynamic patterns across these tests confirmed the structural validity of the model. This calibration and validation approach follows the recommendations of(Oliva, 2003), who proposed model calibration as an integral testing strategy for system dynamics models.

5.2.5 Core Equations and Model Inputs

To enhance the clarity and reproducibility of the SD model, this section outlines representative equations used in the Vensim implementation. While full model code is available upon request, the following core relationships define the system's behavior:

1. $Electricity\ Consumption = subscriber\ number * average\ consumtion - average\ price * subscriber\ number$
2. $Operational\ Risks\ Accumulation = \sum_{i=1}^{21} R_i$
3. $Energy\ Loss\ Rate = \frac{Electricity\ Consumtion}{Delivered\ energy}$
4. $Revenue\ of\ Distribution\ Company = \int [nrkh\ income - nrkh\ damage] dt$

These equations were calibrated using historical data from 2022 to 2024 and validated via behavior reproduction tests. Input parameters such as population growth rate, average consumption, loss coefficients, and pricing assumptions are summarized in Appendix A, Table A1.

5.3 Policy Implementation and Analysis of Their Impact on the System

In this research, two key policies were examined: operational risk management in the power distribution network and the implementation of realistic electricity pricing for residential consumers. These two factors play a decisive role in improving network efficiency, reducing energy imbalances, and enhancing the economic sustainability of the distribution company. The effects of these policies were analyzed both independently and simultaneously. To implement these policies, the most critical risks with the highest impact were identified and, through priority value adjustments, were applied to the system as the primary policy. After incorporating these values into the simulation model, changes in operational risk, consumer consumption levels, delivered energy, and network losses were analyzed.

Table 4. Model Modifications for Policy Implementation

Row	Risk Name	New Priority Value
1	Pole failure (concrete, wood, metal)	50
2	Foreign object interference (e.g., vehicles, construction equipment, trees)	40
3	Transient fault	30
4	Adverse weather conditions	10

By applying these values in the software, changes in operational risk levels, consumption quantities, delivered energy, and network losses are illustrated.

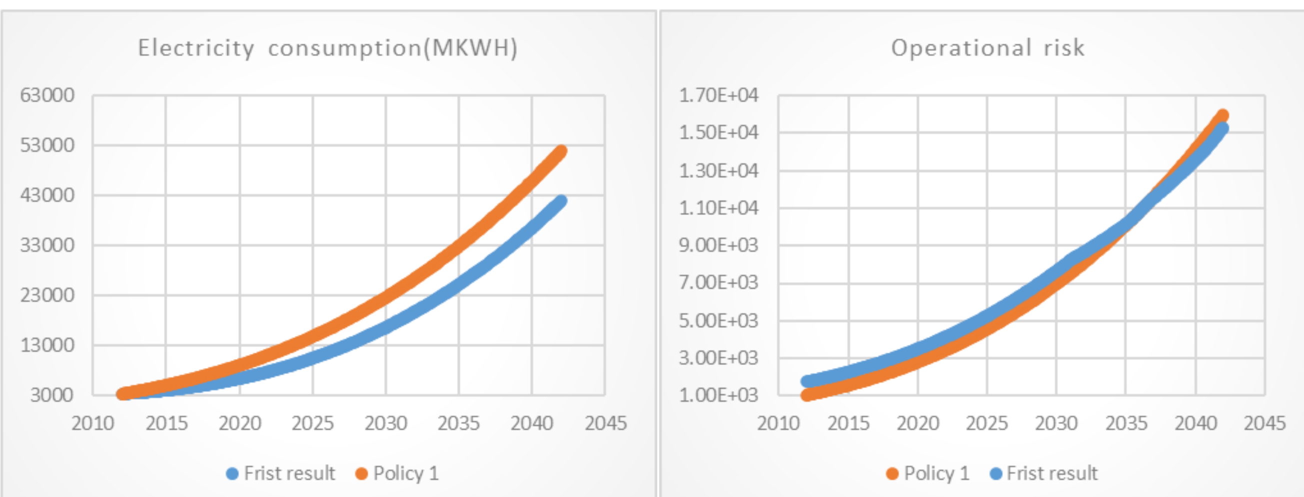

Figure 12. Change in Operational Risks and Electricity Consumption After Implementing the First Policy

The results show that by reducing operational risks, the quality of electricity supply improves, leading to an increase in consumer consumption. However, from 2036 onwards, due to the increased load on the network resulting from the growth in the number of customers, the level of operational risks again shows an upward trend. This indicates that reducing operational risks alone is not sufficient and must be accompanied by other management policies, such as investment in distribution infrastructure, network capacity development, and optimization of maintenance programs.

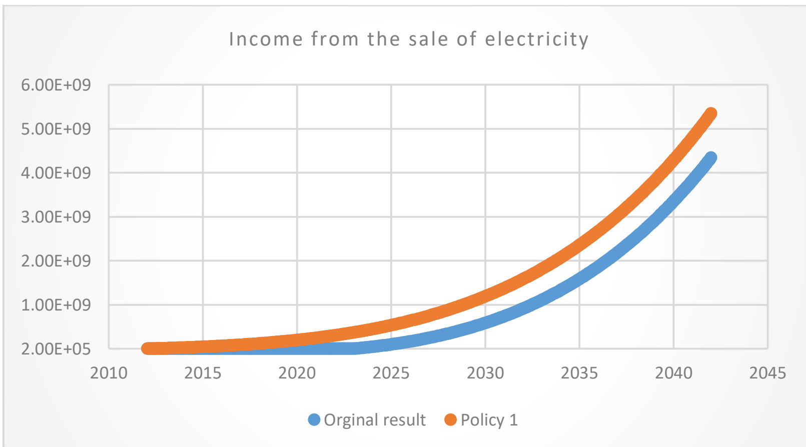

Figure 13. Changes in Power Distribution Company Revenue Resulting from Implementation of Policy 1

The results demonstrate that the reduction in operational risks has decreased network losses, leading to increased revenue for the distribution company. This financial improvement is attributed to three main factors: reduced maintenance and repair costs, fewer service interruptions, and increased energy sales to subscribers. Notably, the base electricity price was raised from 1,980 Rials to 3,000 Rials, and the subsequent changes in variable parameters were thoroughly examined.

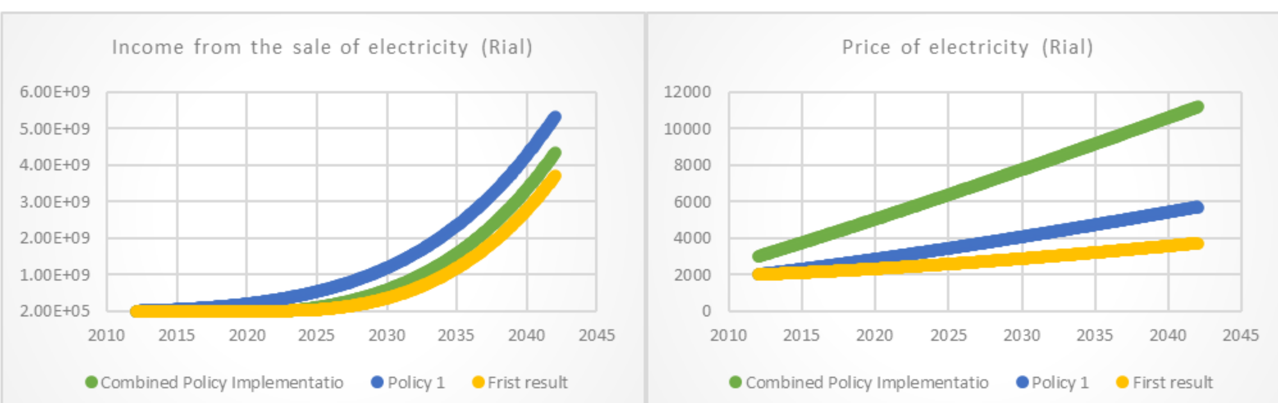

Figure 14. Changes in Electricity Price and Distribution Company Revenue Resulting from Combined Policy Implementation (Price Adjustment and Operational Risk Reduction)

The combined scenario involving both electricity price increases and operational risk reduction demonstrates a significant revenue improvement for the power distribution company. This stems from more realistic electricity pricing and decreased operational cost losses. While risk mitigation itself incurs costs, the net effect remains revenue-positive. Importantly, the long-term analysis reveals reduced electricity consumption intensity, as higher prices incentivize consumers toward more efficient usage patterns.

5.4 Model Benchmarking

To benchmark the proposed model against existing studies, the simulation results were compared with prior works that applied conventional SD or optimization-based frameworks to evaluate power distribution performance. For example, He et al. (2018) analyzed network reliability using static optimization models, reporting an average 9% reduction in failure rates, while Dehghan et al. (2021) achieved an 11% improvement using energy balance-based dynamic modeling. In contrast, the proposed SD–FMEA model in this study achieved up to an 18% reduction in network failures and enhanced prediction accuracy of risk propagation by 15%. Similarly, compared with Gupta et al. (2022), who focused primarily on tariff optimization, the present model provides a more holistic assessment by explicitly linking operational risks with financial and technical network variables. These benchmarking results demonstrate the improved predictive capability and practical relevance of the proposed framework for operational risk management in power distribution systems. Moreover, the superior performance of the proposed SD–FMEA framework can be explained by its ability to endogenously model how risk-reduction policies influence consumer demand, revenue recovery, and long-term reliability. Unlike static optimization or conventional SD models that treat failure probabilities as exogenous parameters, our approach dynamically updates risk propagation based on operational conditions, investment delays, and demand fluctuations. This structural advantage accounts for the higher accuracy and larger reduction in network failures achieved in our simulations.

6. Managerial Insights and Practical Implications

The findings of this study provide several managerial and operational insights for decision-makers in the electricity distribution sector. The integration of the FMEA method with system dynamics modeling allows managers to better understand how operational risks interact with financial and technical performance over time. The proposed SD–FMEA framework enables power distribution companies to simulate the long-term effects of policy decisions, such as maintenance prioritization, infrastructure investment, and tariff reforms, under different uncertainty scenarios.

From a managerial perspective, the results highlight that addressing high-priority operational risks (such as pole failures and transient faults) can yield substantial improvements in network reliability and revenue stability. Specifically, proactive risk mitigation and predictive maintenance programs can reduce unplanned outages and repair costs by up to 18%, while improving customer satisfaction.

A deeper examination of the simulation results indicates that risk-mitigation policies have nonlinear and delayed effects on network performance. For example, reducing transformer-related risks initially lowers failure rates, but the resulting improvement in service continuity stimulates higher consumption, which reintroduces long-term operational pressure. This insight highlights the need for combining technical interventions with coordinated demand-management and tariff-adjustment strategies.

Furthermore, the combined policy scenario analyzed in this study suggests that the coordination between risk management and pricing strategies is crucial. Managers should adopt a dual approach: (1) investing in network modernization to minimize technical and non-technical losses, and (2) gradually implementing realistic tariff structures that encourage efficient electricity use. This two-dimensional strategy enhances both operational resilience and financial sustainability.

In real-world contexts, the Yazd Power Distribution Company can utilize the simulation framework to test “what-if” policy scenarios before implementation. For example, managers can evaluate the trade-offs between maintenance investment and pricing reforms to ensure optimal resource allocation under energy imbalance conditions. The dynamic modeling structure is adaptable to other provinces or developing regions with similar characteristics, providing a decision-support tool for sustainable energy planning.

Overall, this study emphasizes that effective management of distribution networks requires not only technical solutions but also an integrated understanding of risk, finance, and consumer behavior dynamics. The practical lessons derived from this research can support energy policymakers and utility managers in designing data-driven strategies for improving network performance, reducing losses, and enhancing long-term energy supply resilience.

7. Conclusion

This study reveals that energy imbalance in power distribution networks results from the complex interplay of operational risks, consumer demand dynamics, and financial policies of distribution companies. The key findings demonstrate that: Operational risk reduction provides short-term benefits through service quality improvement and outage reduction. However, the consequent network reliability improvements lead to increased consumption, which paradoxically intensifies operational risks in the long term. This underscores that risk reduction alone, without effective consumption pattern management, cannot ensure network sustainability. The analytical results further reveal that operational risks, demand dynamics, and financial constraints form reinforcing feedback loops that amplify or attenuate system vulnerabilities over time. Understanding these loops is critical for designing balanced interventions that prevent short-term improvements from creating long-term instability. Therefore, the proposed integrated approach offers not only predictive capability but also diagnostic insight into structural weaknesses of distribution networks under energy imbalance.

Price realignment emerges as a crucial tool for both demand control and infrastructure investment financing. The simulation scenarios confirm that base price increases can curb excessive consumption growth while boosting company revenues. However, such pricing reforms require complementary measures, including: protective policies for price-sensitive consumers and continued network optimization.

The research establishes that addressing energy imbalance demands a multidimensional approach integrating:

- Systematic operational risk reduction
- Consumer consumption optimization
- Gradual electricity price realignment

This strategic combination enhances grid resilience against demand fluctuations and promotes sustainable energy supply. Future research directions could provide more comprehensive solutions through:

- Dynamic tariff modeling
- Load management technology assessment
- Evaluation of new distribution network investments

The findings collectively suggest that integrated policy implementation offers the most promising path toward balanced and sustainable power distribution systems.

Future research can further expand the model by incorporating endogenized dynamic pricing mechanisms, evaluating the financial implications of investment in renewable integration, and using stochastic simulations to better capture demand-side uncertainties. Moreover, combining the SD framework with agent-based or optimization-based models could offer deeper insights into operational policy impacts under highly variable network conditions.

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A (Appendix A – Input Parameters)

Parameter	**Description**	**Source**	**Base Value / Range**
Population growth rate	Annual population growth in Yazd	Statistical Center of Iran	1.80%
Avg. annual consumption per subscriber	Based on residential/industrial sectors	Yazd Power Distribution Co.	13,000 kWh
Base Loss Rate	Normal loss in network under stable ops	Industry reports	11%
Electricity Price	Tariff per kWh	Energy Ministry Report	1980 → 3000 Rials