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Original Research Article

Enhancing Safety and Reliability Policies in Gas Pressure Reduction Stations: A Critical Systems Heuristics Approach

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Abstract

Gas Pressure Reduction Stations (GPRS) play a critical role in natural gas transmission and distribution systems by ensuring safe and reliable pressure regulation at the interface between high-pressure pipelines and downstream networks. Failures in these stations can lead to supply disruptions, equipment damage, safety hazards, and broader societal and environmental impacts. While existing research predominantly addresses GPRS safety and reliability through technical and quantitative approaches, the underlying policy assumptions, boundary judgments, and stakeholder considerations often remain implicit. This study applies Critical Systems Heuristics (CSH) to systematically analyze safety and reliability policies in GPRS as socio-technical systems. The research adopts a qualitative design combining a systematic literature review with semi-structured interviews conducted with experts from operational, maintenance, safety, and regulatory domains. The twelve CSH boundary questions are used within an "is/ought" framework to contrast current policy framings with expert-informed normative expectations. The analysis reveals that prevailing GPRS safety and reliability policies are largely characterized by instrumental purposes focused on operational continuity and regulatory compliance, organization-centered beneficiary definitions, reliance on lagging and compliance-based performance indicators, centralized decision-making structures, and limited mechanisms for learning, challenge, and stakeholder representation. In contrast, experts emphasized that effective safety governance should explicitly prioritize system resilience, public and environmental protection, prevention and learning, transparent governance of trade-offs, and inclusive decision-making. Based on these findings, the study proposes a CSH-informed conceptual framework that synthesizes key boundary gaps and identifies policy enhancement directions aimed at strengthening adaptive capacity and social legitimacy. The results highlight the value of integrating CSH with conventional technical approaches to improve safety and reliability governance in complex and uncertain GPRS contexts.

Keywords: Gas Pressure Reduction Stations (GPRS); Safety and reliability policy; Critical Systems Heuristics; Socio-technical systems; Boundary judgments; Resilience; Safety governance.

1. Introduction

Gas Pressure Reduction Stations (GPRS), also known as pressure-reducing stations, city gate stations, or PRS, play a pivotal role in gas transmission and distribution networks by reducing high-pressure gas to levels suitable for downstream users, including distribution networks, industrial consumers, and other equipment reliant on stable gas supply. These stations typically consist of complex components such as pressure regulators, safety and shutoff valves, heaters, monitoring devices, and control systems. Proper and uninterrupted operation of GPRS is essential for maintaining continuous, safe, and reliable gas delivery to end users, ensuring that both

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residential and industrial demands are met without interruption (Ebrahimi-Moghadam et al., 2020; Wang et al., 2022). Due to their strategic position at the interface between high-pressure transmission lines and lower-pressure distribution networks, any failure in these stations can cascade into significant consequences, including supply disruptions, equipment damage, fires, explosions, environmental hazards, service interruptions for large customer bases, and substantial economic and reputational losses. Consequently, safety and reliability are not merely technical requirements but central objectives in both the design and operational management of these stations (Karimi et al., 2022; Wang et al., 2022).

Several challenges make the development of effective safety and reliability policies particularly complex. Firstly, GPRS are composed of interacting technical subsystems, including mechanical regulators, safety and shutoff valves, sensors, control logic, heaters, relief systems, and human operators. These interacting subsystems can generate cascading failures, making it essential to model their interdependencies accurately to design robust policies (Ebrahimi-Moghadam et al., 2020; Nourian et al., 2019; Wang et al., 2022). Secondly, component degradation, such as valve sealing wear due to repeated actuation and pressure/temperature cycling, increases the likelihood of failures over time, requiring careful maintenance planning and proactive monitoring strategies (Shu-Li et al., 2023). Thirdly, historical failure data are often incomplete, inconsistent, or not representative, and environmental and operational variability introduces additional uncertainty, complicating probabilistic reliability assessments (Karimi et al., 2022; Nourian et al., 2019). Moreover, human and organizational factors, including operator decision-making, maintenance practices, training, and the overarching safety culture, significantly influence operational outcomes. The performance and reliability of GPRS also depend on auxiliary systems such as heaters and power supplies, which themselves have reliability constraints and trade-offs, particularly concerning energy efficiency and operational safety (Ebrahimi-Moghadam et al., 2020; Wang et al., 2022).

Contemporary quantitative tools, such as Monte Carlo simulations, Bayesian networks, control-system strategies, and energy/exergy assessments, effectively address many technical aspects of reliability. However, they often leave implicit the underlying assumptions, system boundaries, and stakeholder impacts. This limitation reduces their effectiveness in informing equitable and adaptive policy design, particularly in complex socio-technical environments where decisions affect multiple stakeholder groups differently (Ebrahimi-Moghadam et al., 2020; Karimi et al., 2022; Nourian et al., 2019; Shu-Li et al., 2023; Wang et al., 2022). This approach involves cycles of stakeholder framing using CSH, quantitative reliability analysis, mapping gaps, co-designing interventions with multi-stakeholder participation, and implementing continuous monitoring and adaptive governance (Ebrahimi-Moghadam et al., 2020; Karimi et al., 2022; Nourian et al., 2019; Ramos et al., 2023; Wang et al., 2022).

Although previous studies have extensively examined the technical reliability and risk assessment of Gas Pressure Reduction Stations (GPRS) using quantitative methods such as Monte Carlo simulations, Bayesian networks, fuzzy logic, and SCADA-based monitoring (Karimi et al., 2022; Nourian et al., 2019; Rafiee et al., 2020), these approaches typically focus on subsystem performance and probabilistic failures, leaving implicit the underlying assumptions, boundary judgments, and stakeholder impacts. As a result, existing governance and safety frameworks often lack a comprehensive socio-technical perspective, overlook the normative dimensions of policy, and provide limited guidance on inclusive and adaptive decision-making.

To address these gaps, this study applies Critical Systems Heuristics (CSH) to systematically analyze and enhance safety and reliability policies in GPRS. Specifically, the research seeks to answer the following questions:

1. What implicit assumptions and boundary judgments shape current GPRS safety and reliability policies?
2. How do existing policies align with expert-informed normative expectations regarding resilience, public safety, and stakeholder inclusion?
3. How can a CSH-informed framework guide policy enhancement to improve adaptive capacity, organizational learning, and social legitimacy in GPRS governance?

By combining qualitative expert interviews with a structured CSH boundary analysis, this study offers a novel conceptual framework that goes beyond purely technical assessments. The framework explicitly identifies socio-technical risks, governance gaps, and opportunities for inclusive and adaptive policy interventions, bridging a key gap in the literature by making visible the value-laden assumptions that influence policy effectiveness and legitimacy, an aspect largely unaddressed in prior GPRS safety and reliability studies.

2. Literature Review

Karimi et al. (2022) proposed a reliability assessment approach for natural gas pressure reduction stations using historical data, statistical analysis, and Monte Carlo simulation (MCS). Historical data were used to establish the probability distributions of the system and subsystems, and the Kolmogorov-Smirnov test assessed the goodness-of-fit of these distributions. A Bayesian network (BN) was applied to develop a system failure causality model. Finally, MCS was performed to predict the failure rate and reliability of the stations and subsystems, including regulators, separators, dry gas filters, and shut-off valves. The objective was to provide

numerical reliability indicators to improve system performance and enhance the resilience of natural gas pipelines. Rafiee et al. (2020) proposed an innovative approach to tackle uncertainty in safety risk analysis of process systems, specifically for gas pressure reduction stations. The methodology combined Failure Mode and Effects Analysis (FMEA) with Dempster-Shafer evidence theory (DST) to better capture imprecise information and prioritize failure modes under uncertainty. The approach was applied to the City Gate Station (CGS) of Yazd Province to demonstrate practical validity. The objective was to provide a more efficient and reliable method for identifying and prioritizing potential failures, improving risk assessment and safety management in industrial gas systems. Nourian et al. (2019) designed a fuzzy expert system to control and troubleshoot safety and shutoff valves in gas pressure reduction stations under uncertain conditions. The system utilized expert knowledge encoded as "if … then … else" rules in a CLIPS-based knowledge base, with 164 rules implemented. Decision trees and control flowcharts were applied for certain conditions, while fuzzy logic and certainty factors handled uncertainty. The objective was to enhance the responsiveness, reliability, availability, and safety of the stations while reducing accidents, costs, and natural gas loss. Sharma et al. (2022) developed mathematical models for health monitoring of pressure-regulating stations in gas distribution networks. Two common regulator types, spring-loaded and lever-type, were modeled, considering faults such as filter choking, valve seat damage, and diaphragm deterioration. The methodology used measured data and mathematical models to diagnose faults, predict future conditions, and estimate the remaining useful life of regulators. The approach was demonstrated on real data from an existing distribution network and implemented in a user-friendly dashboard. The objective was to enhance reliability, enable prescriptive maintenance, and ensure uninterrupted gas supply to domestic, industrial, and power plant consumers. Medvedeva et al. (2021) assessed the economic efficiency and operational reliability of natural gas pressure reduction systems based on pressure regulators and monitors. The study employed system analysis, computational mathematics, and engineering synthesis to evaluate different configurations of gas pressure reduction lines. Systems with a single reduction line were found to have limited applicability, while systems with redundant lines demonstrated higher reliability and failure-free operation. Additionally, installation time was shorter for these optimized systems compared to standard configurations. The objective was to identify optimal reduction systems that ensure reliable, failure-free operation while maximizing technological efficiency and cost-effectiveness in gas distribution networks. Ghandi Rouainia et al. (2020) proposed a SCADA-based monitoring and risk mitigation approach for natural gas distribution systems, focusing on gas regulator stations responsible for reducing transmission pressure to safe distribution levels. The study implemented RTUs with flow and pressure transmitters at key points, including mid-stream monitoring between monitor and regular valves, as well as filter differential and flow measurements. The SCADA system provides real-time visibility to detect abnormal or emergency events and assess regulator health. The objective was to enhance predictive risk analysis, improve emergency response, increase system reliability, and support comprehensive maintenance planning for safer gas distribution operations. Grudz et al. (2023) developed methods for optimizing overhaul planning of compressor station equipment to ensure the reliability of gas supply systems. The study proposed a probabilistic approach to determine the optimal maintenance frequency that minimizes total operating costs while maintaining equipment reliability. Equipment aging was modeled using distribution densities for pre-repair, inter-repair, and full-service life, and major repair characteristics were assessed via a quality factor linked to repair costs. The objective was to reduce emergency failures, gas losses, and undersupply to consumers by selecting optimal service life, operation time until planned preventive repair, and repair quality factors, thereby ensuring reliable and cost-effective operation of gas supply systems. Abduev et al. (2022) focused on assessing and predicting the reliability of gas compressor stations and main pipelines. The study highlighted the importance of equipment safety and continuous monitoring of system operating parameters. Automatic equipment, including control rooms and compressor stations, was employed to implement technical solutions for maintaining reliability. The objective was to ensure safe, reliable, and uninterrupted operation of the main gas pipelines. Wang et al. (2025) proposed a reliability analysis method for natural gas station pressure regulating systems by integrating fuzzy fault tree analysis with time-domain Bayesian networks. The approach addresses high fault uncertainty, time-varying dynamics, and non-reversible reasoning, combining component-level reliability models to handle complex structural uncertainties and dynamic failure scenarios. Fuzzy logic captures causal links, while Bayesian inference provides probabilistic predictions over time. The method calculates posterior probabilities and sensitivities to identify weak points affecting system reliability. The objective was to enhance system design optimization and maintenance strategies by identifying critical vulnerabilities and improving the overall reliability of natural gas station regulators. Fomina et al. (2021) analyzed the safety of gas distribution stations (GDS) when increasing their capacity. The study examined accident dynamics and industrial injuries at main hydrocarbon pipelines in Russia and evaluated technological units and safety systems of automated low-performance GDS. Using the “Vesta-GDS” software, a process flow diagram was developed to determine the technically possible throughput under constraints of pressure, temperature, gas velocity, and regulator valve

opening. The GDS capacity was found to be 16.37 thousand m³/hour above the design capacity. The objective was to assess accident risks at a Class II hazard GDS, demonstrating that risk remained low and within industry background levels, ensuring safe capacity enhancement. Recent research has highlighted the effectiveness of Critical Systems Heuristics (CSH) in examining complex socio-technical systems. For instance, Etemadi et al. (2025) employed a systems thinking methodology that integrated TSI, CSH, and DEMATEL-ANP within a Society 5.0 framework to enhance stakeholder engagement in the energy sector, underlining participatory governance and long-term sustainability. Similarly, Ebrahimi et al. (2025) applied CSH to assess Iran's Water-Energy-Food nexus, identifying fragmented decision-making, short-term planning horizons, and insufficient interdisciplinary collaboration as major obstacles to sustainable outcomes. In a related study, Fathi et al. (2025) explored stakeholder boundary judgments within an Iranian gas company, revealing gaps between current practices and ideal approaches, and emphasizing the importance of clean energy adoption, modern technological solutions, and multidisciplinary expertise. Collectively, these studies demonstrate how CSH can uncover systemic discrepancies and inform governance strategies in complex socio-technical environments. A summary of recent studies, including their objectives, methodologies, and key contributions, is presented in Table 1, highlighting the breadth of research in this field and the different methodological approaches applied to enhance the reliability and safety of gas pressure reduction stations.

Table 1. Literature Review on Safety and Reliability of Gas Pressure Reduction Stations

Authors	Objective	Methodology	Key Findings / Contribution
Karimi et al. (2022)	Assess the reliability of natural gas pressure reduction stations	Historical data analysis, statistical modeling, Monte Carlo Simulation (MCS), Bayesian Network (BN)	Provided numerical reliability indicators for stations and subsystems; enhanced system performance and resilience of natural gas pipelines
Rafiee et al. (2020)	Address uncertainty in the safety risk analysis of process systems	Combined Failure Mode and Effects Analysis (FMEA) with Dempster-Shafer evidence theory (DST)	Improved identification and prioritization of potential failures; enhanced risk assessment and safety management in industrial gas systems (applied to Yazd Province CGS)
Nourian et al. (2019)	Control and troubleshoot safety and shutoff valves under uncertainty	Fuzzy expert system in CLIPS with 164 rules; decision trees and fuzzy logic	Enhanced responsiveness, reliability, availability, and safety; reduced accidents, costs, and natural gas loss
Sharma et al. (2022)	Health monitoring of pressure regulators in gas distribution networks	Mathematical modeling of spring-loaded and lever-type regulators; fault diagnosis, prediction of remaining useful life; user-friendly dashboard	Improved reliability, prescriptive maintenance, and ensured uninterrupted gas supply for consumers
Medvedeva et al. (2021)	Assess the economic efficiency and operational reliability of GPRS	System analysis, computational mathematics, engineering synthesis	Identified optimal reduction systems with higher reliability, failure-free operation, shorter installation times, and cost-effective gas distribution
Ghandi Rouainia et al. (2020)	Enhance monitoring and risk mitigation in gas distribution	SCADA-based system with RTUs, flow/pressure transmitters	Improved predictive risk analysis, emergency response, system reliability, and maintenance planning
Grudz et al. (2023)	Optimize overhaul planning for compressor station equipment	Probabilistic modeling of maintenance frequency, equipment aging, and repair quality	Reduced emergency failures, gas losses, and undersupply; ensured reliable and cost-effective operation of gas supply systems
Abduev et al. (2022)	Assess and predict the reliability of gas compressor stations and main pipelines	Automated monitoring and control systems	Ensured safe, reliable, and uninterrupted operation of main gas pipelines
Wang et al. (2025)	Reliability analysis of station pressure regulating systems	Fuzzy fault tree analysis integrated with time-domain Bayesian networks	Addressed high fault uncertainty and dynamic failure scenarios; identified critical vulnerabilities and improved system reliability and maintenance strategies
Fomina et al. (2021)	Analyze the safety of gas distribution stations during capacity increase	Process modeling using "Vesta-GDS" software and flow diagrams	Confirmed low accident risk at increased capacity; demonstrated safe enhancement of GDS throughput

3. Research Methodology

This study adopts a qualitative–interpretive research design grounded in the Critical Systems Heuristics (CSH) framework to evaluate and enhance safety and reliability policies in Gas Pressure Reduction Stations (GPRS). The choice of CSH is motivated by the inherently socio-technical nature of GPRS, where technical reliability, human decision-making, organizational routines, regulatory structures, and societal safety concerns interact in complex and often implicit ways. Conventional quantitative reliability methods, while essential, typically focus on technical subsystems and probabilistic failures, leaving underlying assumptions, boundary judgments, and stakeholder perspectives insufficiently examined. CSH provides a structured critical lens to uncover these hidden dimensions and support more robust and legitimate policy design.

3.1 Research Design

The research follows a multi-stage, integrative approach that combines qualitative inquiry with insights from quantitative reliability studies. In the first stage, a systematic review of existing literature on GPRS safety and reliability was conducted to identify dominant analytical approaches, commonly accepted system boundaries, and recurring assumptions in policy formulation. This stage served to contextualize current practices and inform the development of interview protocols.

In the second stage, semi-structured expert interviews were conducted to capture diverse perspectives on safety and reliability policies in GPRS. Experts were recruited using purposive sampling to ensure representation across technical, managerial, operational, and regulatory domains relevant to gas pressure reduction stations. Selection criteria included:

- A minimum of 10 years of professional experience in gas transmission or distribution systems.
- Direct involvement in the operation, maintenance, safety management, or regulation of GPRS.

Based on these criteria, 15 experts were interviewed, including senior operations managers, maintenance engineers, HSE specialists, and regulatory professionals. This sample size is consistent with qualitative research practices in CSH studies, where analytical depth and diversity of boundary judgments are prioritized over statistical generalization. Interviews were conducted until theoretical saturation was reached, such that additional interviews did not yield substantially new insights.

3.2 Data Collection and Ethical Considerations

Interviews were semi-structured and explicitly structured around Ulrich's twelve CSH boundary questions, enabling respondents to articulate both descriptive ("what is") and normative ("what ought to be") views regarding current safety and reliability policies. Each interview lasted approximately 45–60 minutes and was conducted either in person or via secure online platforms. All interviews were audio-recorded with participants' consent and transcribed verbatim. Participants were assured of confidentiality and anonymity, and all personal identifiers were removed from transcripts.

All participants provided informed consent and were informed that they could withdraw at any time without consequences. All data were stored securely and used solely for research purposes.

To enhance rigor, insights from interviews were triangulated with prior quantitative studies, operational reports, and regulatory documents. This triangulation ensured that subjective expert judgments were contextualized within established technical evidence and operational constraints.

3.3 Critical Systems Heuristics Framework

CSH conceptualizes systems as socially constructed through boundary judgments that define whose interests are served, what values are prioritized, which knowledge counts as legitimate, and who holds decision-making power. The framework operationalizes these judgments through twelve boundary questions grouped into four dimensions:

- Motivation (system purpose, beneficiaries, measures of success)
- Control (decision-makers, resources, environmental constraints)
- Expertise (relevant knowledge, experts, guarantees of competence)
- Legitimacy (affected stakeholders, representation of the marginalized, worldview)

Each boundary question was addressed in two modes:

(i) the "is" perspective, reflecting current policy arrangements and operational realities in GPRS; and

(ii) the "ought" perspective, reflecting ideal or desirable conditions for enhancing safety, reliability, and social accountability.

This dual framing enables a critical examination of implicit assumptions embedded in existing safety and reliability policies and highlights areas where technical optimization may conflict with broader safety, ethical, or societal considerations.

3.4 Data Collection

Data collection was primarily qualitative and consisted of semi-structured interviews with experts directly involved in the design, operation, maintenance, and regulation of GPRS. Interview questions were designed to elicit detailed reflections on policy objectives, risk management practices, decision-making structures, accountability mechanisms, and perceived gaps in current

safety and reliability frameworks. Interviews were conducted until theoretical saturation was achieved, ensuring that no substantially new themes emerged. To enhance the rigor of the study, insights from the interviews were triangulated with findings from prior quantitative studies, operational reports, and regulatory documents. This triangulation helped contextualize subjective expert judgments within established technical evidence and operational constraints.

3.5 Data Analysis

Interview transcripts were coded and analyzed thematically using the twelve CSH boundary categories. For each boundary question, responses were compared across experts to identify convergent and divergent viewpoints. Particular attention was paid to discrepancies between "is" and "ought" statements, as these gaps signal potential sources of systemic risk, policy inconsistency, or stakeholder marginalization.

The analysis did not seek to produce a single optimal solution but rather to illuminate alternative framings and trade-offs inherent in GPRS safety and reliability policies. The resulting insights were synthesized into a set of policy-relevant themes, which informed the development of adaptive and inclusive recommendations.

4. Analysis

The qualitative analysis of expert interviews followed a rigorous multi-step procedure to ensure credibility, transparency, and reproducibility. All interview recordings were transcribed verbatim, and transcripts were coded manually with support from qualitative data analysis software (NVivo). Initial open codes were generated to capture recurring ideas, concepts, and concerns expressed by participants. These open codes were then systematically organized into categories aligned with the four CSH dimensions: Motivation, Control, Expertise, and Legitimacy.

Themes were derived through a process of constant comparison, in which responses across participants were repeatedly examined and contrasted between the "is" (current practice) and "ought" (normative expectation) perspectives. This iterative approach allowed identification of common patterns, divergences, and gaps in current GPRS safety and reliability policies. Each category generated sub-themes reflecting critical insights into policy assumptions, boundary judgments, and stakeholder considerations.

To strengthen the reliability of the coding and theme extraction, two independent researchers conducted parallel coding of all transcripts. Differences in coding or theme interpretation were discussed and resolved through consensus meetings, ensuring that the analytical framework reflected multiple perspectives and minimized individual bias.

The resulting themes were triangulated with findings from prior quantitative studies, operational reports, and regulatory documents. This cross-validation enhanced the trustworthiness of the findings and ensured that the themes were robust, reflective of the socio-technical context, and aligned with empirical evidence. The final set of themes provided a comprehensive and credible representation of expert judgments regarding GPRS safety and reliability governance.

Table 2 and Figure 1 summarize the synthesized themes across the four CSH dimensions, highlighting current practices ("is"), normative expectations ("ought"), and critical reflections derived from the analysis. These results form the basis for the subsequent discussion and policy recommendations.

Table 2 and Figure 1 summarize the synthesized themes across the four CSH dimensions, highlighting current practices ("is"), normative expectations ("ought"), and critical reflections derived from the analysis. These results form the basis for the subsequent discussion and policy recommendations.

Table 2. Summary of CSH Boundary Judgments for GPRS Safety and Reliability Policies

CSH Dimension	Boundary Focus	"What Is" (Current Practice)	"What Ought to Be" (Normative Expectation)	Critical Reflection (Is vs. Ought)	Illustrative Quote
Motivation	System purpose	Ensuring continuous gas supply and preventing major accidents through compliance with technical standards	Enhancing system resilience, public safety, environmental protection, and long-term risk reduction	Safety is framed instrumentally; broader societal and environmental goals remain implicit.	"Our main goal is to ensure uninterrupted supply; resilience and community protection are rarely discussed in operational meetings" (Expert 3, Operations Manager)
Motivation	Beneficiaries	Gas distribution companies and large consumers	Operators, local communities, regulators, and future users	Narrow definition of beneficiaries marginalizes affected communities	"Local communities are rarely considered; our focus is mainly on large consumers and compliance" (Expert 9, Regulatory Specialist)

CSH Dimension	Boundary Focus	"What Is" (Current Practice)	"What Ought to Be" (Normative Expectation)	Critical Reflection (Is vs. Ought)	Illustrative Quote
Motivation	Measures of success	Failure rates, downtime, incident frequency	Proactive risk indicators, near-miss reporting, learning capacity	Reactive metrics dominate; weak emphasis on prevention and learning	"We mostly track downtime and incident frequency; near-misses are not systematically reported" (Expert 6, Maintenance Engineer)
Control	Decision-makers	Senior operational and maintenance managers	Shared governance among operators, safety experts, regulators, and emergency authorities	Centralized control mismatches the distributed risk structure	"High-level managers make strategic decisions; frontline staff rarely have a voice in resource allocation" (Expert 5, HSE Specialist)
Control	Resources	Limited budgets, fixed maintenance schedules	Flexible allocation for preventive maintenance and redundancy	Financial constraints override safety prioritization	"Budget and staffing are tightly constrained; we often have to delay preventive maintenance to avoid interrupting supply" (Expert 2, Operations Manager)
Control	Environmental constraints	Treated as external and uncontrollable	Explicitly addressed through adaptive policy mechanisms	Lack of adaptability shifts risk downstream	"Environmental conditions are often treated as fixed; we rarely have adaptive strategies in place" (Expert 11, Operations Manager)
Expertise	Relevant knowledge	Mechanical and instrumentation expertise	Integration of technical, human, and organizational knowledge	Tacit and experiential knowledge is undervalued	"We rely heavily on engineers' technical expertise; operational and human factors knowledge is undervalued" (Expert 4, Maintenance Engineer)
Expertise	Experts	Engineers and maintenance staff	Cross-functional teams including operators and safety analysts	An overly technocratic view of expertise	"Frontline operators are rarely recognized as experts, even though their experience is critical" (Expert 7, HSE Specialist)
Expertise	Guarantees of competence	Certification and procedural compliance	Continuous training, scenario-based learning	Formal compliance ≠ system competence	"Certification doesn't guarantee competence in abnormal situations; scenario-based training is essential" (Expert 8, Operations Manager)
Legitimacy	Affected stakeholders	Internal organization and regulators	Local communities, emergency services, and public authorities	Affected stakeholders lack a voice in policy framing	"Local communities have no formal channels to challenge policies; they only get involved after incidents" (Expert 12, Regulatory Specialist)
Legitimacy	Representation	Regulatory compliance mechanisms	Transparent communication and stakeholder engagement	Legitimacy reduced to formal approval	"Stakeholder engagement is mostly procedural; real input is limited" (Expert 10, Regulatory Specialist)
Legitimacy	Worldview	GPRS as a technical control system	GPRS as a socio-technical system embedded in society	A narrow worldview limits trust and acceptance	"GPRS is seen as a technical system; social and environmental implications are rarely discussed" (Expert 1, HSE Specialist)

4.1 Responses to Boundary Questions

Boundary Question 1: What is the purpose of the system (and what ought it to be)?

In Critical Systems Heuristics (CSH), the system purpose is treated as a boundary judgment that defines legitimate objectives and what is excluded from the policy agenda. In GPRS, this boundary shapes whether safety–reliability policy is framed mainly around operational continuity and compliance or around broader ends such as public safety, resilience, environmental protection, and accountability.

A) "What is?"

Interviewees described the current purpose as operationally instrumental and technically bounded. Three dominant framings were identified: (i) continuity-first, emphasizing uninterrupted supply and avoidance of shutdowns; (ii) accident-prevention, focusing on preventing high-consequence events (e.g., leaks, fire/explosion) yet often in event-centered terms; and (iii) compliance-first, treating adherence to standards, audits, and documentation as the practical expression of safety. Overall, current success is largely attributed to maintaining flow and pressure targets, minimizing major incidents and unplanned outages, and demonstrating compliance.

B) "What ought to be"

Experts argued that continuity and accident prevention should be embedded in a broader and explicit purpose. Four themes emerged: (i) resilience, defined as sustaining safe function under disturbances and recovering without unsafe improvisation; (ii) explicit public and environmental protection, recognizing communities near stations and downstream users as legitimate ends of safety governance; (iii) prevention and learning, including near-miss sensitivity and systematic response to weak signals (e.g., abnormal pressure behavior, nuisance trips); and (iv) transparent governance of trade-offs, making safety–cost–efficiency conflicts explicit rather than implicitly driven by budget or operational pressure.

C) Critical reflection

The "is/ought" gap suggests policy vulnerabilities: an instrumental purpose narrows what is measured and prioritized, may over-rely on the absence of accidents as evidence of safety, leaves trade-offs implicit (enabling safety drift through deferred maintenance and delayed upgrades), and weakens legitimacy when community and environmental protection are not explicitly within the policy boundary.

Boundary Question 2: Who is the beneficiary of the system (and who ought to be)?

In CSH, beneficiary definitions specify whose interests are prioritized through policy design. In GPRS, this boundary influences objectives, metrics, and accountability.

A) "What is?"

Current policies implicitly define beneficiaries in a narrow hierarchy: (i) operating organizations (asset protection, service continuity, cost minimization) as primary beneficiaries; (ii) large industrial and strategic consumers as priority recipients of stable supply; and (iii) regulators as institutional beneficiaries insofar as policy is shaped to satisfy audits and avoid sanctions. Other affected groups remain peripheral.

B) "What ought to be"

Experts advocated an expanded beneficiary set: (i) local communities near GPRS as explicit primary beneficiaries of hazard reduction; (ii) emergency response and public safety institutions, supported through information sharing and coordinated planning; (iii) frontline operators and technicians as empowered beneficiaries (safe working conditions, realistic procedures, voice in safety governance); and (iv) society and future users, through sustained infrastructure integrity, reduced long-term harm, and preserved public trust.

C) Critical reflection

A beneficiary boundary centered on organizations and key consumers can marginalize those bearing the greatest consequences of failure, reinforce compliance-driven safety at the expense of proactive risk reduction, weaken emergency coordination, and undermine long-term legitimacy when public value is not clearly articulated.

Boundary Question 3: What are the measures of success of the system (and what ought they to be)?

Measures of success define what counts as evidence of safety and reliability and thereby shape incentives, visibility of risks, and resource allocation.

A) "What is?"

Current measures are largely technical and retrospective: (i) failure and downtime metrics (unplanned shutdowns, repair frequency); (ii) compliance indicators (audit closure, inspection completion); and (iii) incident statistics (absence of major accidents, reportable events). These metrics privilege outcomes after failures rather than precursors.

B) "What ought to be"

Experts emphasized broader and leading indicators: (i) proactive signals (near-miss trends, abnormal pressure behavior, recurring alarms, heater anomalies); (ii) preventive maintenance effectiveness (backlog trends, timeliness/quality of corrective actions); (iii) learning capacity (quality of investigations, integration of lessons learned, training updates); and (iv) preparedness (drills, response readiness, coordination with external agencies). Success should reflect prevention, resilience, and learning, not only the absence of failure.

C) Critical reflection

Over-reliance on lagging and compliance metrics limits early intervention, may mask degraded conditions despite "good" audit performance, discourages investment in learning/preparedness, and can incentivize underreporting of near-misses.

Boundary Question 4: What resources are controlled by decision-makers (and what ought to be controlled)?

Resource control specifies what actions are feasible in practice financially, temporally, informationally, and organizationally, and thus conditions the implementation of safety policy.

A) "What is?"

Experts described restricted and fragmented control: (i) budgets and staffing constrained by short-term cost pressures; (ii) maintenance time limited by supply-continuity demands, which postpones or compresses shutdown windows; and (iii) data and information collected via SCADA and logs but used mainly for compliance reporting rather than diagnosis and learning.

B) "What ought to be"

Normatively, experts called for: (i) flexible preventive investment (early replacement, redundancy, critical subsystem upgrades); (ii) authority over maintenance windows and trade-offs, legitimizing safety-driven shutdowns; (iii) control over diagnostic and learning resources, including trend analysis, near-miss integration, and root-cause feedback loops; and (iv) capability investment, such as training and scenario-based exercises.

C) Critical reflection

Constrained resource control fosters short-term optimization, normalizes deferred maintenance, forces reactive management due to limited diagnostic capability, and weakens resilience when organizational learning and training are under-resourced.

Boundary Question 5: Who are the decision-makers (and who ought to be)?

This boundary judgment identifies who has authority to define objectives, allocate resources, and accept risk, shaping accountability and decision quality.

A) "What is?"

Decision-making is largely centralized and segmented: operational and maintenance managers dominate day-to-day trade-offs; strategic investments are decided at higher managerial levels; and regulators function mainly as external constraints through audits and enforcement rather than as partners in preventive governance.

B) "What ought to be"

Experts advocated a distributed model: (i) shared decisions across operations, maintenance, HSE, and regulators for non-routine/high-risk issues; (ii) structured inclusion of frontline perspectives; (iii) clearer alignment of authority and accountability; and (iv) integration of emergency/public authorities for high-consequence planning.

C) Critical reflection

Centralization increases implicit risk acceptance under production pressure, reduces the practical validity of decisions by excluding frontline knowledge, reinforces compliance-driven culture, and weakens transparency when trade-offs are made within silos.

Boundary Question 6: What conditions are outside the control of decision-makers (and how ought they to be addressed)?

External conditions define the system environment; CSH asks whether these are treated as fixed constraints or actively managed uncertainties.

A) "What is?"

Experts identified regulatory shifts, economic volatility, procurement/supply-chain constraints, infrastructure dependencies (power/communications), and environmental variability as largely external and handled reactively, often through short-term compliance responses rather than anticipatory planning.

B) "What ought to be"

Normatively, experts argued these conditions should be internalized through scenario-based planning and sensitivity analysis; adaptive and flexible policy mechanisms; proactive dependency management (supplier diversification, critical inventories, infrastructure resilience); and integration of environmental stressors into design, maintenance, and preparedness.

C) Critical reflection

Treating external conditions as immutable reduces adaptability, promotes superficial compliance reactions, increases cascading-failure vulnerability through unmanaged dependencies, and undermines preparedness for predictable seasonal and climatic stressors.

Boundary Question 7: What kind of expertise is relevant (and what ought to be)?

This boundary judgment determines what knowledge counts as legitimate for framing problems and shaping safety–reliability policies.

A) "What is?"

Relevant expertise is defined primarily as technical engineering knowledge (mechanical/instrumentation/control) and

procedure/standards familiarity, with limited formal recognition of experiential, organizational, and contextual knowledge from operators and technicians.

B) "What ought to be"

Experts advocated an integrative expertise base: technical knowledge complemented by human factors and human–machine interaction, recognition of tacit/experiential knowledge, organizational and safety-culture understanding, and competencies in risk communication and learning systems.

C) Critical reflection

A technocratic expertise boundary can overlook socio-technical risk drivers, weaken early detection by discounting frontline insight, reinforce silos, and constrain translation of lessons learned into policy improvement.

Boundary Question 8: Who is considered an expert (and who ought to be)?

Beyond "what knowledge counts," CSH asks "whose voice counts," affecting learning, accountability, and legitimacy.

A) "What is?"

Expert status is largely assigned to credentialed engineers, senior managers (often by authority), and regulators/auditors (as institutional interpreters of compliance), while frontline staff are rarely formal policy participants.

B) "What ought to be"

Experts argued for broader recognition of operators and technicians as legitimate experts, inclusion of cross-functional safety specialists, acknowledgement of collective/distributed expertise within teams, and selective inclusion of external contextual experts (e.g., emergency responders, independent reviewers) for high-risk decisions.

C) Critical reflection

Narrow expert recognition marginalizes operational reality, substitutes hierarchy for competence, limits cross-functional learning, and reduces emergency preparedness and public credibility.

Boundary Question 9: What guarantees competence and success (and what ought to guarantee it)?

This boundary judgment concerns the institutional basis of assurance, which is treated as sufficient evidence that safety governance is competent.

A) "What is?"

Current guarantees are primarily compliance-based: adherence to standards/procedures, certification and training records, and retrospective confidence derived from limited major incidents.

B) "What ought to be"

Experts emphasized dynamic guarantees: continuous training (including scenario-based exercises), performance-in-use validation (drills and stress testing of safeguards), robust learning loops from incidents/near-misses, and independent/reflective review beyond checklist audits.

C) Critical reflection.

Compliance-as-assurance can mask capability gaps in abnormal conditions, retrospective safety can ignore aging and emerging risks, weak learning loops allow recurrence of latent failures, and limited independent review increases normalization of deviance.

Boundary Question 10: How can affected stakeholders challenge the system (and what ought to be)?

This legitimacy boundary concerns whether those affected by risk can contest assumptions, decisions, and trade-offs in safety governance.

A) "What is?"

Challenge opportunities are limited: internal hierarchical reporting is culturally and practically constrained; regulatory audits are episodic and compliance-oriented; and meaningful challenge often emerges only after major incidents through public scrutiny.

B) "What ought to be"

Experts advocated protected internal challenge mechanisms (including anonymity and independent review), structured engagement of external stakeholders (communities, emergency services), transparency and access to understandable risk information, and continuous anticipatory challenge processes embedded in routine governance.

C) Critical reflection

Restricted challenge suppresses weak-signal learning, sustains reactive safety culture, weakens accountability to those bearing risk, and increases normalization of deviance.

Boundary Question 11: Who represents the interests of marginalized stakeholders (and who ought to)?

CSH asks how less powerful groups are represented when they bear risk but lack decision authority.

A) "What is?"

Representation is mainly indirect: regulators are assumed to represent public interest; organizational HSE units act as internal proxies but are constrained; and marginalized interests become visible episodically after incidents via external scrutiny.

B) "What ought to be"

Experts argued for structured community representation, independent oversight/advocacy, explicit inclusion of vulnerable/transient workers (e.g., contractors), and transparent articulation of whose interests are prioritized and why.

C) Critical reflection

Proxy representation can miss local concerns, internal proxies may be compromised by incentives and authority limits, incident-triggered representation undermines prevention, and weak representation erodes legitimacy and trust.

Boundary Question 12: What worldview defines the system (and what ought to define it)?

Worldview integrates boundary judgments by defining how the system is fundamentally understood and justified.

A) "What is?"

Current governance reflects a technocentric worldview: GPRSs are treated as controllable technical installations; risk is often framed in linear, event-based terms; and organizational/societal factors are treated as secondary or external.

B) "What ought to be"

Experts advocated a socio-technical worldview that recognizes interdependence among technology, humans, organizations, regulation, and society; treats complexity and emergence as inherent; explicitly foregrounds ethical and societal accountability; and maintains reflexivity through continuous questioning of assumptions.

C) Critical reflection

A narrow worldview can misattribute systemic failures to isolated technical causes, constrain preparedness for non-linear scenarios, weaken trust when societal impacts occur, and stabilize outdated assumptions that impede adaptive governance.

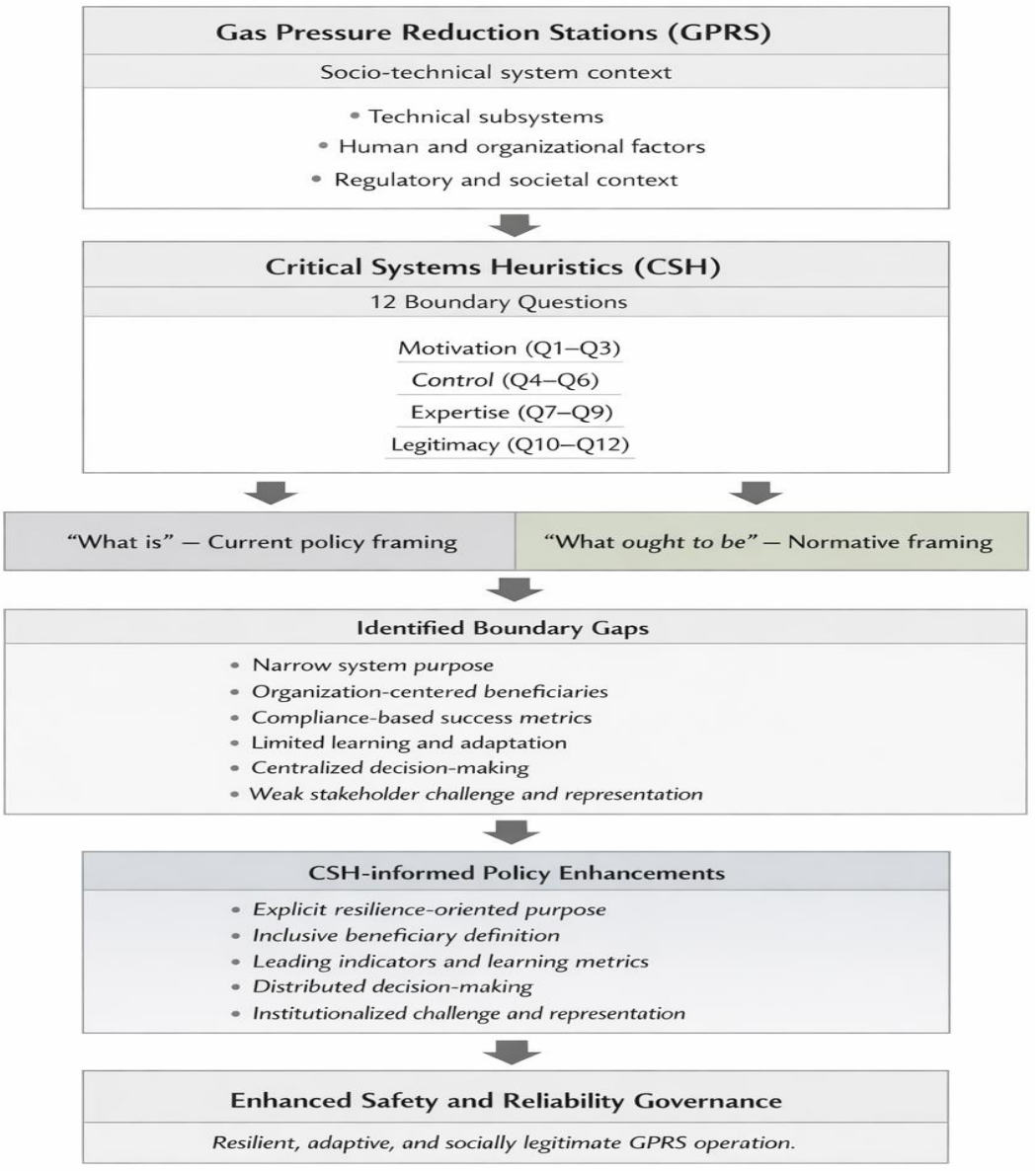

Figure 1. Boundary-based analysis of safety and reliability policies in Gas Pressure Reduction Stations using Critical Systems Heuristics

5. Discussion and Conclusion

This study employed Critical Systems Heuristics (CSH) to examine safety and reliability policies in Gas Pressure Reduction Stations (GPRS) as socio-technical systems. The analysis demonstrates that many persistent safety and reliability challenges cannot be fully explained by technical limitations alone, but are deeply shaped by implicit boundary judgments that define system purpose, beneficiaries, success criteria, decision authority, and legitimacy. By systematically comparing "what is" and "what ought to be" across the twelve CSH boundary questions, the study reveals structural misalignments between current policy configurations and expert-informed normative expectations. A central finding is that existing GPRS safety and reliability policies are predominantly framed around operational continuity and regulatory compliance. While these objectives are necessary for system functioning, they tend to narrow the policy boundary by prioritizing measurable and auditable outcomes such as downtime, incident counts, and inspection results. This instrumental framing can obscure systemic risks that accumulate gradually through equipment degradation, human–automation interaction, and organizational adaptation. As a result, the absence of major accidents may be misinterpreted as evidence of safety, even when underlying resilience and learning capacities remain limited. The analysis further shows that current policies implicitly define beneficiaries in organization-centered terms, privileging operating entities, key industrial consumers, and regulatory institutions. In contrast, experts emphasized that communities located near GPRS facilities, frontline personnel, emergency responders, and future system users bear substantial risk externalities and should be explicitly recognized as beneficiaries of safety governance. Failure to acknowledge these groups weakens legitimacy and constrains the range of perspectives informing policy design, thereby reducing the system's ability to anticipate and manage diverse risk pathways.

Another significant finding concerns how success and competence are defined and assured. Current practice relies heavily on lagging indicators and compliance-based assurances, which provide limited insight into emerging risks and adaptive capacity. Experts argued that safety and reliability policies should instead be evaluated through leading indicators, effectiveness of preventive maintenance, preparedness for abnormal conditions, and the system's ability to learn from near-misses and minor anomalies. This shift implies a redefinition of success from the absence of failure toward the sustained ability to operate safely under uncertainty. The study also highlights structural constraints in resource control and decision-making. Short-term budget cycles, limited authority over maintenance windows, and fragmented control of information resources restrict preventive action and reinforce reactive safety management. Decision-making authority is often centralized and separated from frontline expertise, increasing reliance on informal workarounds and implicit risk acceptance. Experts therefore advocated for more distributed and transparent decision structures that integrate operational, safety, and regulatory perspectives, particularly for non-routine and high-consequence decisions.

From a legitimacy perspective, the findings indicate that opportunities for challenge and representation of marginalized stakeholders are limited and largely reactive. Internal reporting channels are constrained by organizational culture, regulatory scrutiny is episodic and compliance-oriented, and community concerns often gain visibility only after incidents. Experts emphasized that robust safety governance requires institutionalized, protected, and continuous mechanisms for challenge, alongside explicit and independent representation of affected communities and vulnerable workers. Without such mechanisms, safety policies risk losing social trust and becoming insulated from critical feedback.

Taken together, these findings suggest that enhancing safety and reliability in GPRS requires not only technical improvements but also a fundamental shift in policy framing and governance. Based on the results, several policy-relevant recommendations can be derived. First, safety and reliability policies should explicitly articulate system purpose in terms of resilience, public and environmental protection, prevention, and learning, rather than relying implicitly on continuity and compliance. Second, policy frameworks should broaden beneficiary definitions to include local communities, frontline personnel, emergency services, and future users, thereby strengthening legitimacy and accountability. Third, success metrics and assurance mechanisms should be revised to incorporate leading indicators, performance-in-use validation, and organizational learning outcomes. Fourth, decision-makers should be granted greater flexibility and authority to allocate resources for preventive maintenance, system upgrades, and capability development, even when these actions temporarily conflict with supply continuity objectives. Finally, governance arrangements should institutionalize opportunities for challenge and representation through protected reporting channels, stakeholder engagement processes, and independent review mechanisms.

Overall, this study demonstrates that CSH provides a powerful and complementary lens for diagnosing hidden vulnerabilities in safety and reliability policies by making explicit the value-laden boundary judgments that shape socio-technical systems. By integrating CSH insights with existing technical reliability and risk assessment methods, policymakers and practitioners can develop more robust, adaptive, and socially legitimate safety governance for GPRS. Future research should focus on operationalizing the identified boundary shifts into concrete policy instruments and indicators, and on evaluating the effectiveness of CSH-informed policy

reforms through longitudinal and comparative studies across different gas infrastructure contexts.

Conflict of interest

No conflict of interest has been expressed by the authors.

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