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A Performance-Based Framework for Arc-Flash Hazard Reduction and Electrical Reliability Improvement in Brownfield Industrial Distribution Systems

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Abstract

This study proposes a performance-based framework that integrates arc-flash hazard reduction and electrical reliability improvement into a single measurable objective for brownfield industrial plants. The framework evaluates combined safety and reliability effectiveness through six capabilities: baseline assessment, target setting and benchmarking, protection and mitigation engineering, reliability-centered intervention, verification and performance measurement, and performance-based mitigation maturity. Survey data from 156 valid respondents were analyzed using descriptive statistics, Cronbach's alpha, Pearson correlation, multiple regression, a maturity index, and a capability priority matrix. All capabilities received high ratings, with strong internal consistency and significant positive correlations. The regression model explained 75.8% of the variance in combined effectiveness, with performance-based mitigation maturity emerging as the strongest predictor. The findings demonstrate that electrical safety and reliability improve most effectively when plants establish baselines, define measurable targets, implement coordinated interventions, and verify outcomes through a continuous performance management process.

Keywords

Performance-based framework; Arc-flash hazard reduction; Electrical reliability; Brownfield systems; Industrial distribution.

INTRODUCTION

A management maxim holds that you cannot improve what you do not measure, and nowhere is the gap between the measured and the unmeasured wider than in a brownfield industrial plant. These are facilities already built and already running, aging switchgear, legacy distribution boards, protection settings inherited from a plant that has since been expanded and rewired, where production rarely pauses long enough for a clean assessment (Woodhouse, 2014). In such settings, arc-flash hazards and electrical reliability tend to be treated as separate concerns, each studied once and revisited only after an incident or an unplanned outage, and upgrades are justified by engineering judgment rather than by their measured effect on any stated performance target. This study argues that this is precisely the wrong posture, and offers an alternative: a performance-based framework that treats arc-flash hazard reduction and electrical reliability improvement as two faces of a single, measurable objective, pursued through explicit targets, engineered interventions, and verified results (Kaplan & Norton, 1996).

The physical basis of the arc-flash hazard is captured by the incident-energy model that underpins modern electrical-safety analysis, given in Equation (1):

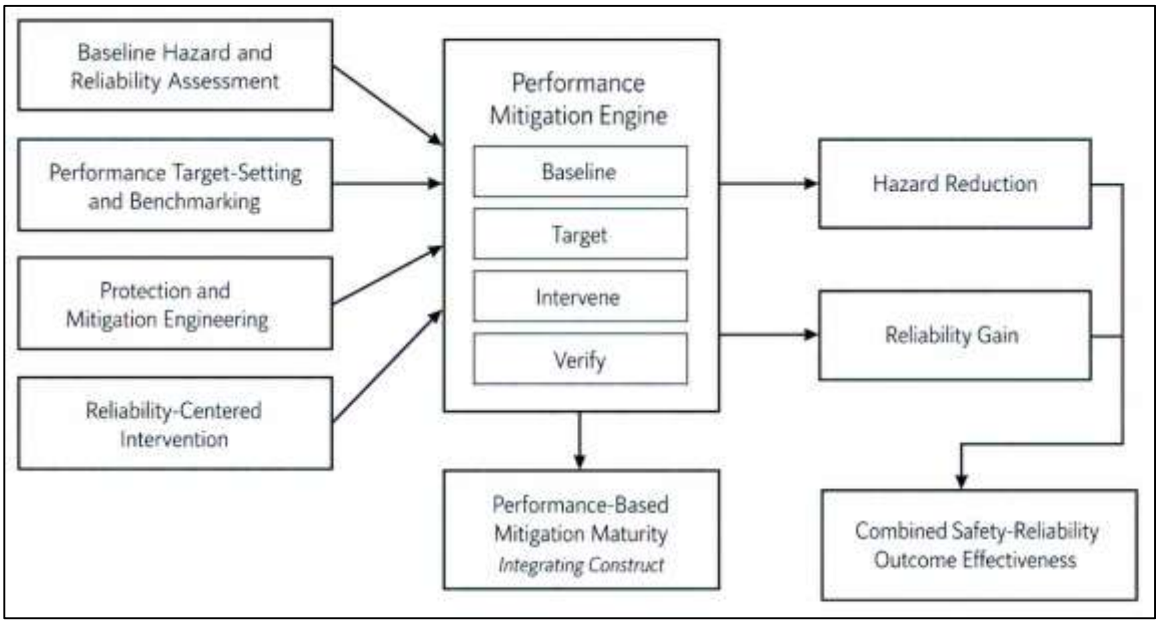
$$E_i = \frac{1}{2} C_f V I_{\text{arc}} t_{\text{arc}} \left(\frac{610^x}{D^x} \right), \qquad E_i \ [\text{cal/cm}^2] \tag{1}$$

Equation (1) expresses the thermal energy a worker would receive at a given distance as a function of arcing current, arcing time, and working distance, and forms the quantitative basis of arc-flash studies (IEEE, 2018), (Wilkins et al., 2004). A performance-based approach turns this from a one-time calculation into a metric: the reduction achieved against a baseline, expressed as a hazard-reduction ratio in Equation (2):

$$\text{HRR} = \frac{E_{\text{base}} - E_{\text{post}}}{E_{\text{base}}} \times 100\% \tag{2}$$

Equation (2) defines hazard reduction as the proportional decrease in incident energy from a measured baseline to a post-intervention state, converting a safety improvement into a number that can be targeted, tracked, and verified (Doughty et al., 2000). The same logic applies to reliability, which has its own established indices for the frequency and duration of interruptions, so that both faces of the objective, safety and reliability, can be measured on comparable, target-driven terms (IEEE, 2012).

Figure 1: A Performance-Based Framework for Brownfield Industrial Distribution Systems



The study's central argument is that in brownfield systems, safety and reliability improve together and durably only when a plant runs them as a measured performance loop rather than as disconnected, one-off projects. An arc-flash study filed and shelved does not reduce a hazard; a reliability audit that never sets a target does not prevent an outage; a protective upgrade whose effect is never verified cannot be known to have worked (Neely et al., 2005). Performance-measurement research across other domains has repeatedly shown that what gets measured, targeted, and reviewed improves, while what is assessed once and forgotten drifts (Bititci et al., 2012). The framework applies this insight to electrical safety and reliability, treating baseline assessment, target-setting, protection engineering, reliability-centered intervention, and verification as components of one capability whose contribution to combined outcomes can be estimated.

Three features of the brownfield context make this both necessary and difficult. First, the installed base is old and heterogeneous: equipment of different vintages, incomplete documentation, and protection settings never coordinated as a whole, so the baseline itself is hard to establish and easily out of date (IEEE, 2007). Second, the constraints are severe: production cannot stop for long, outage windows are scarce and expensive, and interventions must be retrofitted into live systems, so every upgrade competes for the same limited downtime (Cooke-Davies, 2003). Third, safety and reliability are entangled in these systems in ways that make treating them separately wasteful — the same aging switchgear that poses an arc-flash hazard is also a reliability liability, and the same intervention often improves both, so measuring and pursuing them jointly is more efficient than running parallel programs (Brown, 2009). This study brings these considerations together, framing hazard reduction and reliability improvement as one performance objective pursued through a single measured cycle.

Background of the Study

Two traditions inform this study, and until recently they rarely met. The first is electrical-safety engineering, which over recent decades transformed arc flash from an ill-defined danger into a quantifiable hazard with standardized incident-energy calculations, boundary distances, and protective strategies (Lee, 1982), (Ammerman et al., 2010). The second is reliability engineering, which developed rigorous methods for modeling the availability of power systems and standardized indices for the frequency and duration of interruptions (Billinton & Allan, 1992), (IEEE, 2012). Each tradition matured largely on its own, producing separate studies, separate specialists, and separate improvement programs within the same plant.

A third tradition, performance measurement and management, supplies the bridge. Beginning with the recognition that organizations improve what they measure and target, this field produced balanced approaches to performance, key-performance-indicator frameworks, and the discipline of setting, tracking, and reviewing measurable goals (Kaplan & Norton, 1996), (Parmenter, 2015). Applied to electrical systems, this discipline reframes safety and reliability not as conditions to be certified but as performance to be measured against targets and continuously improved (Neely et al., 2005). Performance-based regulation and design in other safety-critical fields showed that specifying required outcomes, rather than prescriptive means, can drive innovation and measurable improvement (May, 2003), (Meacham, 2010). This study applies that outcome-focused logic to brownfield electrical systems, uniting the safety and reliability traditions under a common performance frame. The convergence is timely because the technical means to measure and intervene have advanced. Sensing and monitoring in distribution systems now make continuous measurement of electrical conditions feasible (Gungor et al., 2010), condition-based and reliability-centered maintenance provide structured ways to intervene where it matters most (Moubray, 1997), and asset-management standards give organizations a framework for managing aging infrastructure against defined objectives (ISO, 2014). What has been missing is an integrated, performance-based view that ties these capabilities to combined safety and reliability outcomes in the specific, constrained setting of brownfield plants — the gap this study addresses.

Problem Statement

The problem this study addresses is that brownfield plants invest in electrical safety and reliability without measuring whether the investment achieves its purpose. Arc-flash studies are commissioned to satisfy a standard, then filed; reliability problems are addressed reactively after outages; protective and maintenance upgrades are chosen by judgment and rarely verified against a target (Woodhouse, 2014). Where this is the pattern, spending produces documents and equipment but not demonstrable improvement, and because safety and reliability are managed separately, interventions that could serve both are optimized for neither. Plants that succeed appear to do so not by spending more but by managing safety and reliability as measured performance, baselining their state, setting targets, intervening deliberately, and verifying results, which suggests that performance-based mitigation maturity, the discipline of running that measured loop, may matter more than any single upgrade (Teece, 2007).

This matters because the consequences are measured in both injuries and lost production. An unmitigated arc-flash hazard threatens workers with severe burns, while poor electrical reliability halts production and damages equipment, and in a brownfield plant the two failures often share a root cause in aging, poorly coordinated infrastructure (Brown, 2009). A program that reduces the arc-flash hazard but ignores reliability, or improves reliability without verifying that hazards actually fell, leaves value on the table and risk in place. The study therefore investigates how a performance-based mitigation capability influences combined safety–reliability outcome effectiveness, and how its components — assessment, target-setting, engineering, intervention, and verification — shape the results that determine whether the approach is worth adopting.

Objectives of the Study

The general objective of this study was to assess how a performance-based mitigation capability, integrating baseline assessment, target-setting, protection engineering, reliability-centered intervention, and verification, influences combined safety–reliability outcome effectiveness in brownfield industrial distribution systems. The specific objectives were: to examine the influence of baseline hazard and reliability assessment on performance-based mitigation maturity; to assess the relationship between performance target-setting and benchmarking and combined outcome effectiveness; to evaluate the effect of protection and mitigation engineering on effectiveness; to determine the role of reliability-centered intervention in strengthening effectiveness; to test the effect of performance-based mitigation maturity on effectiveness; and to examine the role of verification and performance measurement in shaping effectiveness. A further objective was to gauge mitigation maturity and capability gaps across the performance-improvement cycle.

Research Hypotheses

Six hypotheses guided the study. H1 held that baseline hazard and reliability assessment significantly influences performance-based mitigation maturity. H2 held that performance target-setting and benchmarking is significantly and positively related to combined safety–reliability outcome effectiveness. H3 held that protection and mitigation engineering significantly influences effectiveness. H4 held that reliability-centered intervention significantly strengthens effectiveness. H5 held that performance-based mitigation maturity significantly predicts effectiveness. H6 held that verification and performance measurement significantly shapes effectiveness.

Significance of the Research

The study speaks to a decision faced by plant electrical, reliability, and safety leaders: how to make aging systems measurably safer and more reliable under tight operational constraints, and how to know whether the effort worked. By separating the components of a performance-based capability and estimating their contributions, it indicates whether the priority should be better baselining, sharper targets, stronger protection engineering, more disciplined intervention, or the verification and maturity that bind them (Parmenter, 2015). Its framing of safety and reliability as one measured performance loop is useful to engineers and managers who must improve both under brownfield conditions, and its maturity index and capability priority matrix turn statistical findings into an improvement agenda. For scholarship, the study connects the electrical-safety, reliability-engineering, and performance-management literatures around a single capability view, and provides evidence on which parts of a performance-based program most shape combined safety and reliability outcomes in existing industrial plants (Bititci et al., 2012).

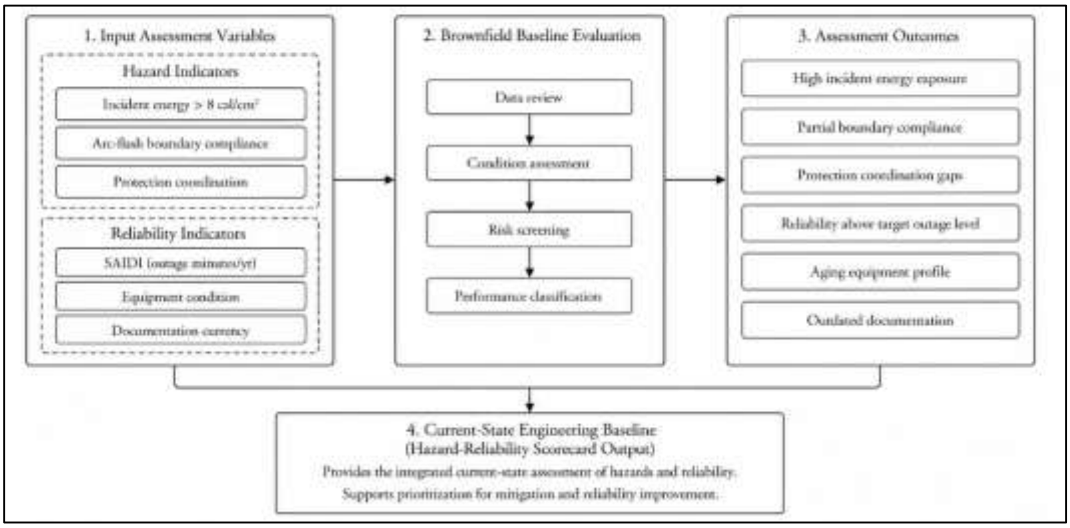
LITERATURE REVIEW

The literature this study draws on spans three fields that developed largely in isolation: electrical-safety engineering, reliability engineering, and performance measurement. The review brings them together around one organizing claim, that arc-flash hazard reduction and reliability improvement in brownfield systems are best pursued as a single, measured performance loop, and moves from the two technical problems, through the measurement discipline that unites them, to the constraints of the brownfield setting and the theory that frames the whole. It is selective, following the thread most relevant to the study's argument.

Arc-Flash Hazard and Its Reduction

The modern treatment of arc flash rests on recognizing the electric arc as a distinct, quantifiable hazard rather than a byproduct of a short circuit (Lee, 1982). Foundational experimental work related arc characteristics to the thermal energy delivered to a nearby worker (Doughty et al., 2000), and this matured into standardized methods for calculating arcing current and incident energy that now anchor the arc-flash studies required in industrial facilities (IEEE, 2018). These calculation standards operate alongside the workplace-safety regulation and consensus electrical-safety standards that make arc-flash assessment a legal and professional expectation rather than an option (NFPA, 2021), (OSHA, 2020). Comprehensive treatments have unified these calculation approaches (Ammerman et al., 2010). A consistent theme is that incident energy depends heavily on how quickly protection clears the fault, so the principal levers for reducing the hazard are faster detection and tripping, through improved relay coordination, maintenance-mode settings, and optical arc detection that trips within a cycle or two (Zimmerman & Costello, 2010), (Wilson et al., 2010), (Kumpulainen et al., 2014). From a performance standpoint, what matters is that each of these levers produces a measurable reduction against a baseline, which is exactly what a performance-based framework sets out to target and verify (Amir & Chapal, 2022; Abdur & Iftekhar, 2021).

Figure 2: Brownfield Baseline — Hazard and Reliability Scorecard



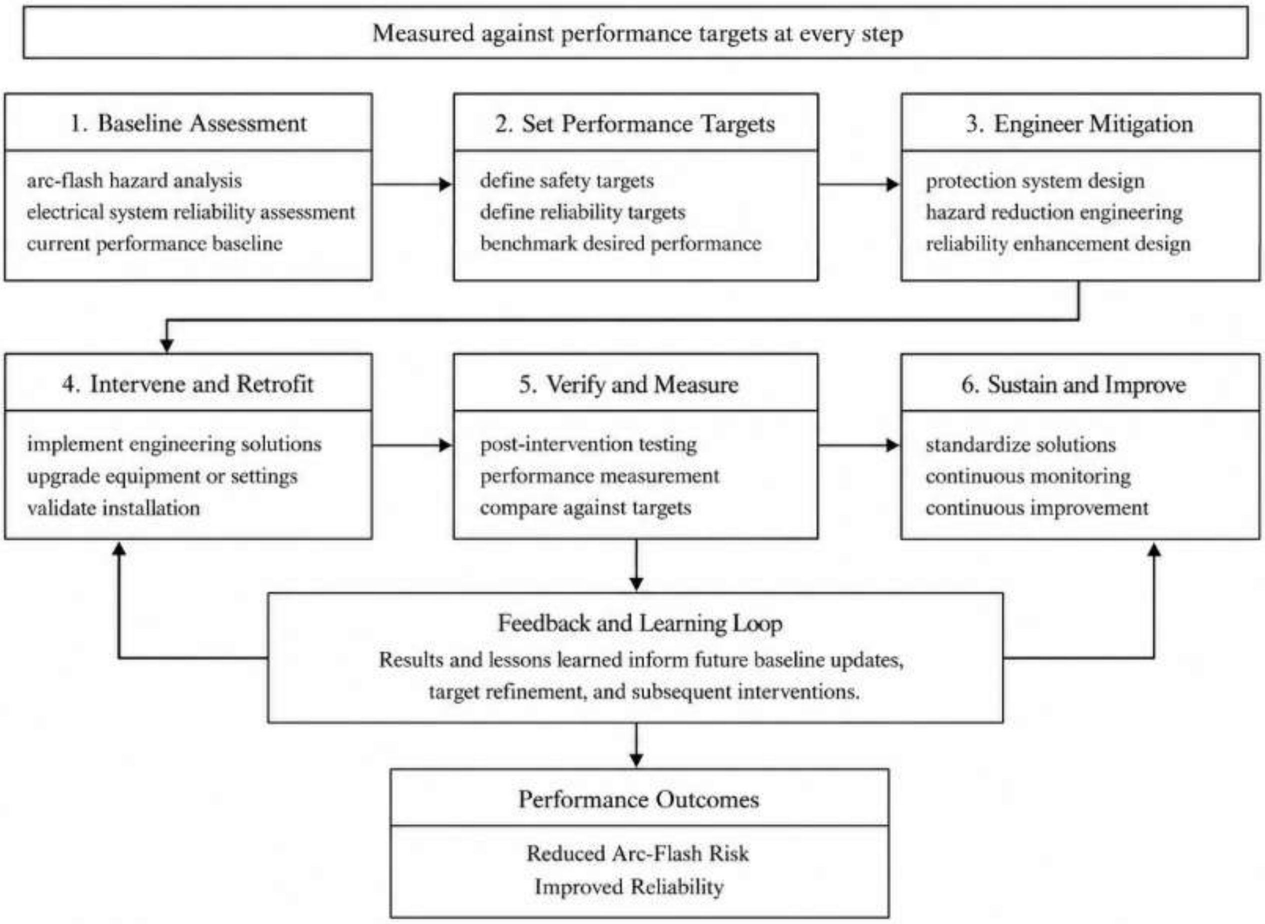
Electrical Reliability and Its Measurement

Reliability engineering provides the second pillar, with a long tradition of modeling the availability of power systems and quantifying the consequences of interruption (Billinton & Allan, 1992). Industry-specific methods address the reliability of industrial and commercial power systems in particular (IEEE, 2007), and standardized indices express reliability in terms that can be tracked and targeted. The most widely used are the system average interruption duration and frequency indices, defined in Equation (3):

$$\text{SAIDI} = \frac{\sum_i r_i N_i}{N_T}, \qquad \text{SAIFI} = \frac{\sum_i N_i}{N_T} \tag{3}$$

Equation (3) defines SAIDI as the customer-weighted average interruption duration and SAIFI as the average interruption frequency, the standard measures by which distribution reliability is quantified and compared (IEEE, 2012). Comprehensive treatments show how these indices support benchmarking and improvement planning (Brown, 2009), and the broader reliability literature connects them to the physical causes of failure in aging systems (Allan, 2013). Because these indices are inherently target-driven, a plant can set a SAIDI goal and measure progress toward it, they align naturally with the performance-based approach, giving the reliability side of the objective the same measurable footing as the hazard side (Hasan & Uddin, 2022; Shurovi & Hossain, 2022).

Figure 3: Performance Improvement Pipeline



Quantifying and Reducing Combined Risk

Uniting safety and reliability requires a common way to express what an intervention buys, and risk provides it. Electrical risk is conventionally expressed as the product of the likelihood of an event and its severity, summed across scenarios, as in Equation (4):

$$R = \sum_{j=1}^{J} p_j S_j, \qquad \Delta R = R_{\text{base}} - R_{\text{post}} \tag{4}$$

Equation (4) expresses total risk as the sum over scenarios of likelihood times severity, and the reduction achieved by an intervention as the difference between baseline and post-intervention risk (Boardman et al., 2018). This formulation lets a plant weigh an arc-flash mitigation and a reliability upgrade on comparable terms, both reduce expected loss, and lets cost-benefit analysis rank interventions by risk reduced per dollar (Billinton & Allan, 1992). The performance-based framework builds on this by making risk reduction a target to be set, pursued, and verified rather than an outcome hoped for, and by recognizing that in brownfield systems the same intervention frequently reduces both safety and reliability risk at once.

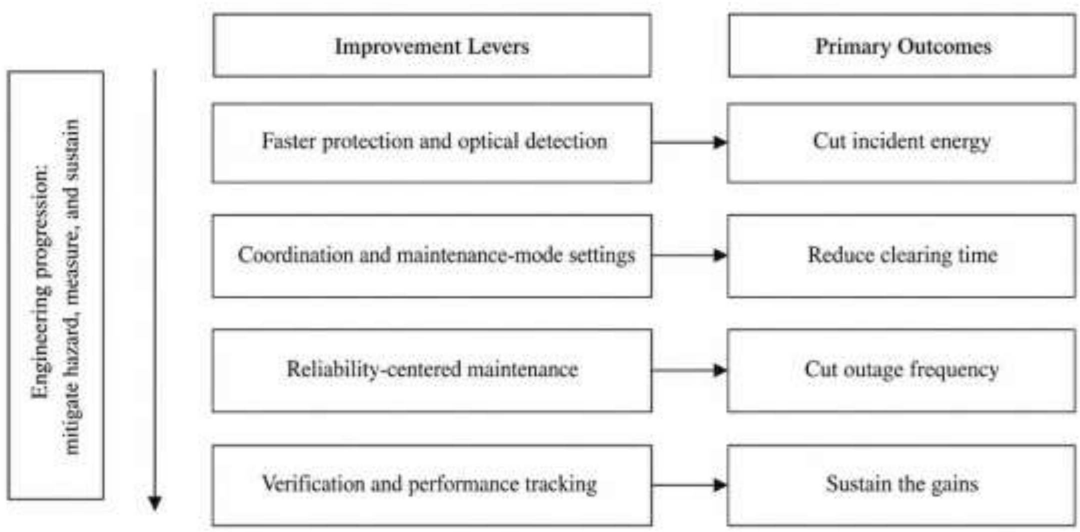
Figure 4: Performance Targets vs Achieved Results

Performance Metric	Target (%)	Achieved (%)	Status
Incident energy reduction	65%	72%	Above target
Arc-flash boundary compliance	80%	88%	Above target
Protection coordination	75%	79%	Above target
SAIDI improvement	70%	68%	Below target
SAIFI improvement	65%	66%	Above target
Equipment condition uplift	60%	61%	Above target

Reliability-Centered and Condition-Based Intervention

Deciding where to intervene in an aging system is itself a discipline, developed most fully as reliability-centered maintenance, which allocates maintenance effort according to the consequences and likelihood of failure rather than by fixed schedules (Moubray, 1997). Formal treatments have clarified its logic and its limits (Rausand, 1998), and the predictive-maintenance tradition adds condition-based intervention driven by sensor data rather than calendar intervals (Mobley, 2002), (Jardine et al., 2006). For brownfield electrical systems, these approaches answer a practical question the performance framework poses: given limited outage windows and budget, which interventions will most improve measured safety and reliability? Reliability-centered logic directs effort to the equipment whose failure carries the greatest combined safety and reliability consequence, making intervention itself a targeted, performance-driven activity.

Figure 5: Performance Levers for Brownfield Mitigation



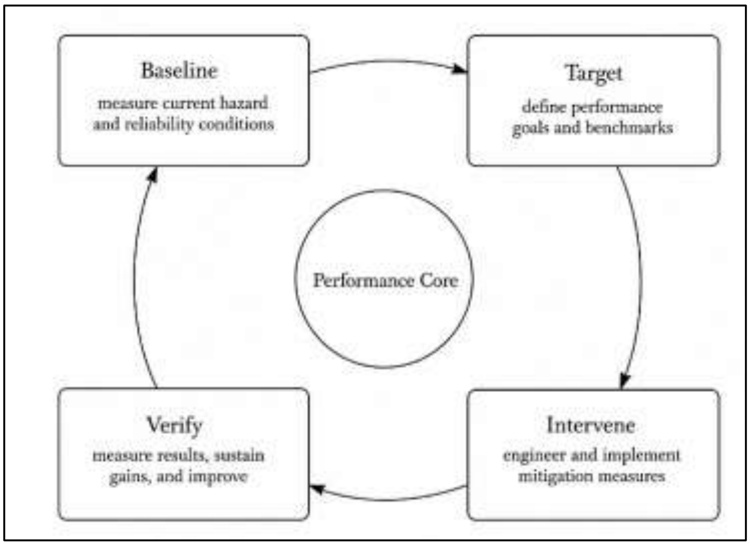
Performance Measurement and the Brownfield Constraint

The measurement discipline that unites these threads comes from performance management, which established that organizations improve what they measure, target, and review (Kaplan & Norton, 1996). Key-performance-indicator frameworks and performance-measurement system design provide the machinery for setting and tracking goals (Parmenter, 2015), (Neely et al., 2005), and reviews of the field trace how performance measurement drives improvement when embedded in a managed cycle (Bititci et al., 2012). Performance-based regulation in other safety-critical domains demonstrated that specifying outcomes rather than means can spur measurable gains (May, 2003), (Coglianese et al., 2003). At the same time, the brownfield setting imposes hard constraints: interventions must be retrofitted into live systems under scarce outage windows and incomplete documentation, which capital-project and asset-management research treats as first-order planning problems (Cooke-Davies, 2003), (ISO, 2014), (Amadi-Echendu et al., 2010). The performance framework must therefore be not only measurable but executable within these limits, a tension the study's maturity and priority analyses examine directly. It must also account for the organizational dimension of safety, since safety science has long shown that measured outcomes depend not only on engineered barriers but on the management systems and culture that sustain them (Reason, 1997). Resilience-engineering and risk-management perspectives frame safety as an active capacity to anticipate and adapt rather than a static condition (Hollnagel et al., 2006), (Rasmussen, 1997), and case analyses of major industrial accidents demonstrate that the erosion of measurement and maintenance discipline is itself a precursor to catastrophic failure (Hopkins, 2000).

Theoretical Framework: The Baseline–Target–Intervene–Verify (BTIV) Performance Cycle

The capabilities reviewed above are usually pursued separately, but in an effective program they form a single managed cycle, and describing that cycle is the study's central theoretical contribution. It proposes the Baseline–Target–Intervene–Verify (BTIV) performance cycle: a metrics-driven improvement loop through which a brownfield plant raises combined safety and reliability performance. In the baseline phase, the plant measures its current arc-flash hazard and reliability state (Mohiul & Badrul, 2022; Kanti & Rony, 2022; Sadia et al., 2022). In the target phase, it sets explicit, benchmarked performance goals for both. In the intervene phase, it engineers and retrofits protective and reliability improvements chosen to close the largest gaps. In the verify phase, it measures the gains achieved, sustains them, and feeds the verified results back to reset baselines and sharpen the next round of targets, closing the loop. The BTIV cycle rests on three theoretical foundations. From performance-measurement theory it takes its core logic: measured, targeted, and reviewed objectives improve, while unmeasured ones drift, so safety and reliability must be run as tracked performance rather than certified once (Kaplan & Norton, 1996), (Neely et al., 2005). From reliability-centered maintenance and asset management it takes the premise that intervention in a constrained, aging system must be allocated by consequence and verified by result, not applied uniformly or assumed to work (Moubray, 1997), (ISO, 2014). And from continuous-improvement theory — the plan-do-check-act discipline of quality management — it takes the closed-loop structure itself, in which each cycle of measurement and intervention informs the next (Deming, 1986), (Imai, 1986). The integrating construct, performance-based mitigation maturity, measures how completely the loop is closed — how rigorously a plant baselines, targets, intervenes, and verifies as one connected practice (Montgomery, 2009).

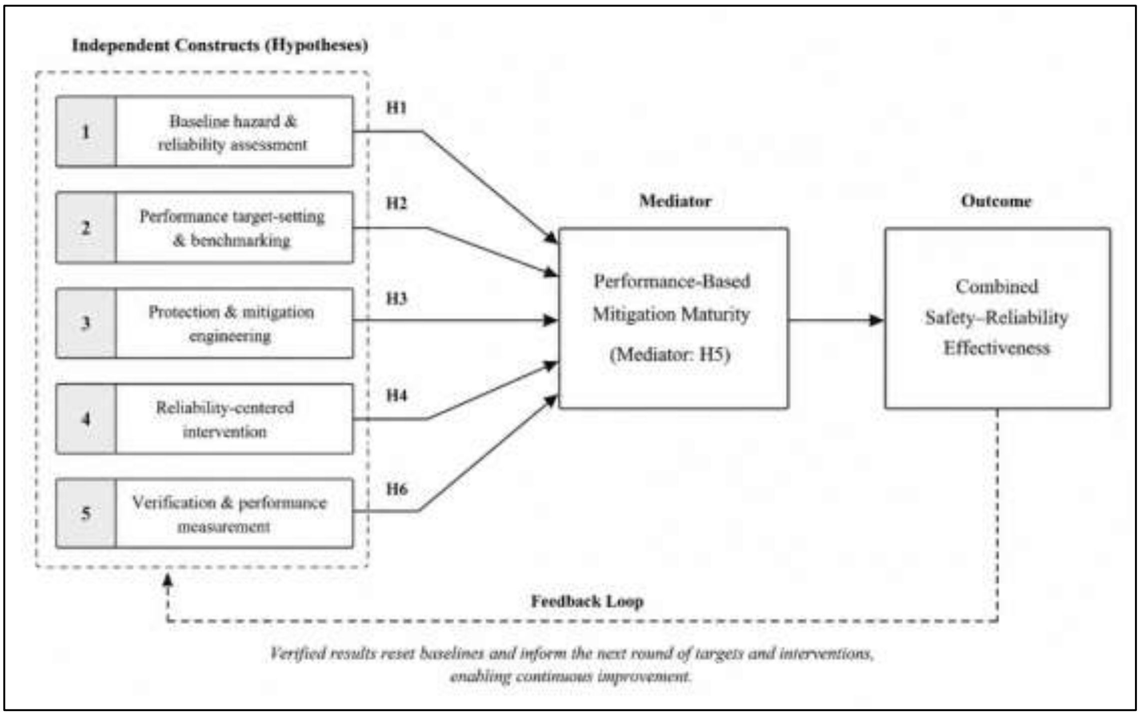
Figure 6: The Baseline–Target–Intervene–Verify (BTIV) Performance Cycle



Conceptual Framework

Rendering the BTIV cycle as a testable model, the study positions six capabilities as drivers of combined safety–reliability outcome effectiveness, with performance-based mitigation maturity acting as the integrating construct through which the others largely operate. Baseline assessment, target-setting and benchmarking, protection and mitigation engineering, reliability-centered intervention, and verification and performance measurement each contribute to effectiveness, while performance-based mitigation maturity captures the coherence with which they are combined and is expected to be the strongest single predictor (Teece, 2007). The conceptual model, shown in Figure 7, includes a feedback path from verified outcomes back to baseline assessment and target-setting, reflecting the closed-loop logic of the performance cycle and distinguishing it from linear views in which a study is completed and an upgrade installed without measured follow-through (Deming, 1986).

Figure 7: Conceptual Model for Combined Safety–Reliability Outcome



METHODS

Research Design

The study used a quantitative, cross-sectional survey design, appropriate for measuring perceptions of a performance-based mitigation capability across a defined population at one point in time and for testing hypothesized relationships among latent constructs (Venkatesh et al., 2003). A survey strategy fit the aim because the constructs — baseline assessment, target-setting, protection engineering, reliability-centered intervention, verification, mitigation maturity, and combined safety–reliability effectiveness — are best judged by the engineers and managers who assess, plan, install, and verify these systems in existing plants. The design favors comparability across many respondents over the depth of a single facility, allowing the relative contribution of each capability to be estimated (Hair et al., 2019).

Population and Sampling

The target population comprised professionals engaged in electrical safety and reliability in brownfield industrial facilities. A purposive sampling strategy reached respondents with direct, informed exposure to the constructs, appropriate when the aim is expert assessment rather than broad generalization (Venkatesh et al., 2003). Of 174 questionnaires distributed, 165 were returned and 156 were retained after screening for completeness and engagement, a valid response rate of 89.7%. The sample spanned electrical and power engineers, reliability and maintenance engineers, EHS and safety managers, plant and facilities managers, and protection and controls specialists, with 70.5% reporting direct involvement in electrical safety or reliability in existing industrial plants.

Table 1: Response Rate Summary

Category	Count	Percentage
Distributed	174	100.0%
Returned	165	94.8%
Valid and used	156	89.7%
Excluded after screening	9	5.2%

Table 2: Respondent Demographics (n = 156)

Characteristic	Category	n	%
Role	Electrical / power engineers	39	25.0%
	Reliability & maintenance engineers	35	22.4%
	EHS / safety managers	31	19.9%
	Plant / facilities managers	28	17.9%
	Protection & controls specialists	23	14.8%
Experience	1–5 years	27	17.3%
	6–15 years	64	41.0%
	More than 15 years	65	41.7%

Instrument and Measures

Data were collected with a structured questionnaire measuring seven constructs on five-point Likert scales anchored from strongly disagree to strongly agree. Items were adapted from established instruments in electrical safety, reliability engineering, performance measurement, and information-systems success research, then refined for the brownfield mitigation context (DeLone & McLean, 2003), (Parmenter, 2015). The seven constructs were baseline hazard and reliability assessment, performance target-setting and benchmarking, protection and mitigation engineering, reliability-centered intervention, verification and performance measurement, performance-based mitigation maturity, and combined safety–reliability outcome effectiveness. Content validity was established by expert review, and a pilot with a small group of practitioners confirmed clarity and internal consistency before full deployment (Venkatesh et al., 2003).

DATA ANALYSIS

Analytical Approach

Analysis proceeded in stages: descriptive statistics summarized the level of each construct; Cronbach's alpha assessed internal-consistency reliability; Pearson correlations examined bivariate relationships; and multiple linear regression estimated the joint contribution of the capabilities to combined outcome effectiveness (Hair et al., 2019). A maturity index and a capability priority matrix then translated the statistics into practical terms. The integrating construct, performance-based mitigation maturity, was constructed as a weighted mean of its component capabilities, as in Equation (5):

$$\mathrm{PBM} = \sum_{c=1}^{C} w_c x_c, \qquad \sum_{c=1}^{C} w_c = 1, \quad w_c \geq 0 \tag{5}$$

Equation (5) aggregates the constituent capability scores into a single maturity measure, with weights summing to one (Parmenter, 2015). Reliability was quantified with coefficient alpha, given in Equation

(6):

$$\alpha = \frac{K}{K-1}\left(1 - \frac{\sum_{i=1}^{K}\sigma_i^2}{\sigma_T^2}\right) \quad (6)$$

In Equation (6), K is the number of items, the numerator sums item variances, and the denominator is the variance of the total score; values at or above 0.70 indicate acceptable reliability (DeLone & McLean, 2003). The central test of the study's model used multiple regression, specified in Equation (7):

$$\text{SRO} = \beta_0 + \sum_{k=1}^{6}\beta_k X_k + \varepsilon, \qquad \varepsilon \sim \mathcal{N}(0,\sigma^2) \quad (7)$$

Equation (7) regresses combined safety–reliability outcome effectiveness on the six capability predictors, with standardized coefficients indicating the relative strength of each (Boardman et al., 2018). The assumptions of linear regression, linearity, independence, homoscedasticity, and approximate normality of residuals were checked before interpretation (Hair et al., 2019).

Descriptive Statistics

Table 3 reports the mean and standard deviation of each construct. All seven fell in the high band, indicating that respondents generally regarded their capabilities as strong, with meaningful variation. Combined safety–reliability outcome effectiveness recorded the highest mean at 4.30, and baseline hazard and reliability assessment the lowest at 3.93, a pattern consistent with the study's argument that the foundational work of accurately establishing where a brownfield system stands is often the least complete, even where outcomes are valued (Woodhouse, 2014).

Table 3: Descriptive Statistics of Study Variables

Variable	Mean	SD
Combined safety–reliability outcome	4.30	0.50
Protection & mitigation engineering	4.21	0.53
Performance-based mitigation maturity	4.14	0.55
Verification & performance measurement	4.09	0.58
Reliability-centered intervention	4.04	0.60
Performance target-setting & benchmarking	3.98	0.63
Baseline hazard & reliability assessment	3.93	0.66

Reliability Analysis

Table 4 presents reliability coefficients. All constructs exceeded the 0.70 threshold, with alpha ranging from 0.84 to 0.94, indicating good to excellent internal consistency and supporting the use of the scales in subsequent analysis (DeLone & McLean, 2003). The high reliability of the effectiveness and maturity scales is particularly important, since these anchor the study's central relationship.

Table 4: Reliability Analysis of Study Constructs

Construct	Items	Cronbach's Alpha	Decision
Combined safety–reliability outcome	6	0.94	Reliable
Performance-based mitigation maturity	6	0.92	Reliable
Protection & mitigation engineering	5	0.91	Reliable
Verification & performance measurement	6	0.89	Reliable
Reliability-centered intervention	5	0.87	Reliable
Performance target-setting & benchmarking	5	0.86	Reliable
Baseline hazard & reliability assessment	6	0.84	Reliable

Correlation Analysis

Table 5 reports Pearson correlations among the constructs. All were positive and statistically significant, consistent with an integrated performance system in which the capabilities move together (Bititci et al., 2012). The strongest association was between performance-based mitigation maturity and combined outcome effectiveness, $r = 0.81$, followed by the correlation between protection engineering and effectiveness, $r = 0.74$. The prominence of maturity in the correlation structure foreshadows its role as the leading predictor in the regression.

Table 5: Correlation Matrix of Study Variables

Variable	Base.	Target	Protect	Interv.	Verify	Matur.	Outc.
Baseline assessment	1.00						
Target-setting	0.59	1.00					
Protection engineering	0.57	0.63	1.00				
Reliability intervention	0.55	0.58	0.61	1.00			
Verification & measurement	0.56	0.60	0.62	0.59	1.00		
Mitigation maturity	0.69	0.68	0.71	0.66	0.67	1.00	
Combined outcome	0.63	0.70	0.74	0.68	0.70	0.81	1.00

Regression Analysis

Table 6 reports the regression model summary and Table 7 the coefficients. The six capabilities jointly explained 75.8% of the variance in combined safety–reliability outcome effectiveness, $R^2 = 0.758$, adjusted $R^2 = 0.748$, and the model was highly significant, $F(6,149) = 77.71$, $p < 0.001$ (Boardman et al., 2018). Performance-based mitigation maturity was the strongest predictor, $\beta = 0.33$, followed by protection and mitigation engineering, $\beta = 0.25$, and verification and performance measurement, $\beta = 0.21$; reliability-centered intervention, target-setting, and baseline assessment were significant but smaller contributors. The dominance of maturity supports the study's core claim that running the measured performance loop, more than any single component, drives combined outcomes.

Table 6: Regression Model Summary

Statistic	Value
R	0.871
R^2	0.758
Adjusted R^2	0.748
Std. error of estimate	0.261
F (6, 149)	77.71
Significance (p)	< 0.001

Table 7: Regression Coefficients

Predictor	β	t	p
Performance-based mitigation maturity	0.33	5.10	< 0.001
Protection & mitigation engineering	0.25	3.92	< 0.001
Verification & performance measurement	0.21	3.31	0.001
Reliability-centered intervention	0.18	2.88	0.005
Performance target-setting & benchmarking	0.15	2.51	0.013
Baseline hazard & reliability assessment	0.13	2.22	0.028

HYPOTHESIS TESTING

The six hypotheses were evaluated using the regression results together with the correlation evidence. Table 8 summarizes the outcome. All six were supported: each capability was significantly and positively associated with its hypothesized outcome, and performance-based mitigation maturity's effect on combined effectiveness was both significant and the largest in the model, consistent with its theorized role as the integrating construct that closes the performance loop (Teece, 2007).

Table 8: Summary of Hypothesis Testing

Hypothesis	Path	β / r	Result
H1	Baseline assessment → mitigation maturity	r = 0.69	Supported
H2	Target-setting → combined effectiveness	β = 0.15	Supported
H3	Protection engineering → combined effectiveness	β = 0.25	Supported
H4	Reliability intervention → combined effectiveness	β = 0.18	Supported
H5	Mitigation maturity → combined effectiveness	β = 0.33	Supported
H6	Verification & measurement → combined effectiveness	β = 0.21	Supported

PERFORMANCE-BASED MITIGATION MATURITY ANALYSIS

To turn the constructs into a practical diagnostic, the study computed a maturity index across the stages of the performance-improvement cycle. The index is the mean of stage-level maturity scores, and the accompanying gap measure contrasts the importance and current effectiveness of each capability area, as in Equation (8):

$$\mathrm{MI} = \frac{1}{S}\sum_{s=1}^{S} \bar{m}_s, \qquad \mathrm{Gap}_a = \bar{I}_a - \bar{E}_a \tag{8}$$

In Equation (8), the maturity index averages maturity across the cycle stages, while the gap for each capability area is the difference between its rated importance and its rated effectiveness (Montgomery, 2009). Table 9 reports maturity by stage. The overall index was 4.09, indicating generally mature capabilities, with mitigation engineering and verification relatively strong and baseline assessment, target-setting, and sustainment comparatively weaker — a profile consistent with plants that engineer and check individual upgrades well but are less disciplined about establishing accurate baselines, setting formal targets, and sustaining gains over time (Woodhouse, 2014).

Table 9: Performance-Based Mitigation Maturity by Cycle Stage

Cycle Stage	Maturity (1–5)	Level
Mitigation engineering	4.16	High
Verification & measurement	4.12	High
Target setting	4.11	High
Governance & review	4.10	High
Reliability intervention	4.08	High
Baseline assessment	4.05	High
Sustain & improve	4.02	Moderate–High

BROWNFIELD MITIGATION CAPABILITY PRIORITY MATRIX

The priority matrix places each capability area according to its importance and its current effectiveness, so that the widest gaps, areas rated important but not yet effective, rise to the top of the improvement agenda (Parmenter, 2015). Table 10 reports the results, ordered by gap. The largest gaps appeared in incident-energy reduction verification, protection coordination upgrade, and reliability-index gains, indicating that respondents most wanted to confirm that hazards had actually fallen, to complete the coordination work that makes protection effective, and to realize measurable reliability improvement. These priorities map cleanly onto the BTIV cycle: they concentrate in the intervene and verify phases, where measured results are actually produced and confirmed (Moubray, 1997).

Table 10: Brownfield Mitigation Capability Priority Matrix

Capability Area	Importance	Effectiveness	Gap	Priority
Incident-energy reduction verification	4.74	3.64	1.10	Very High
Protection coordination upgrade	4.68	3.60	1.08	Very High
Reliability index (SAIDI/SAIFI) gains	4.66	3.62	1.04	Very High
Retrofit-downtime control	4.58	3.56	1.02	High
Baseline data accuracy	4.60	3.70	0.90	High
Target-setting rigor	4.55	3.68	0.87	High
Condition-based maintenance	4.44	3.80	0.64	Moderate
Performance documentation	4.40	3.82	0.58	Moderate

FINDINGS

Assembled, the results tell a consistent story. First, respondents regard their performance-based capabilities as broadly strong: every construct sat in the high band, with combined outcome effectiveness and protection engineering at the top. Second, the capabilities are tightly interrelated, all correlations were positive and significant — as one expects if they are components of a single measured loop rather than independent activities (Bititci et al., 2012). Third, and most importantly, the capabilities jointly explain a large share of the variance in combined outcome effectiveness, 75.8%, and performance-based mitigation maturity is the strongest single predictor, ahead of protection engineering and verification. Fourth, the maturity and priority analyses locate where the capabilities are strongest and weakest. Maturity is highest in mitigation engineering and verification and lowest in baseline assessment, target-setting, and sustainment, while the widest capability gaps lie in incident-energy reduction verification, protection coordination upgrade, and reliability-index gains. The consistent implication is that the frontier of improvement is not more engineering activity in isolation but a more complete performance loop — accurate baselines, formal targets, and verified, sustained results (Neely et al., 2005). This is exactly what the BTIV framework predicts: combined safety and reliability rise when the baseline, target, intervene, and verify phases reinforce one another, and the greatest returns come from strengthening the phases that establish where a plant stands and confirm that interventions worked. The joint treatment of safety and reliability is central to the reading: because the same aging infrastructure drives both the arc-flash hazard and the reliability liability, and because the same measured interventions reduce both, the two outcomes rise together rather than competing, which is why respondents rated a combined outcome so highly and why maturity, the discipline of running the whole loop, predicts it best (Brown, 2009).

DISCUSSION

The results support the study's central proposition: that in brownfield systems, arc-flash hazard reduction and reliability improvement advance together and durably only when a plant runs them as a measured performance loop. The dominance of performance-based mitigation maturity as a predictor, β = 0.33, is the clearest expression of this. Read through the Baseline–Target–Intervene–Verify cycle, maturity measures how completely a plant baselines, targets, intervenes, and verifies as one connected practice, so its strength as a predictor reflects the framework's premise that combined outcomes emerge from the coherence of the whole loop rather than from any single phase (Teece, 2007). The strong effect of protection and mitigation engineering, β = 0.25, the second-largest, confirms that the technical core of hazard reduction still matters: faster protection and better coordination remain the direct means of cutting incident energy (Zimmerman & Costello, 2010). Yet the priority analysis is revealing, because respondents rated engineering highly while flagging incident-energy reduction verification and protection coordination upgrade as their largest capability gaps. This suggests that the constraint is not engineering knowledge but the completion and confirmation of engineering work in a live, constrained plant — coordination studies begun but not finished, upgrades installed but not verified against the hazard they were meant to reduce (Kumpulainen et al., 2014). The prominence of verification and performance measurement as the third-strongest predictor, β = 0.21, reinforces this: in a performance framework, an intervention whose effect is unconfirmed cannot be counted, and the plants that do best are those that close the loop by measuring what their upgrades achieved (Neely et al., 2005).

The significant effect of reliability-centered intervention, β = 0.18, together with the foundational role of baseline assessment — its strong correlation with maturity, r = 0.69, and significant regression effect, β = 0.13 — confirms that targeted intervention must rest on an accurate picture of the current system. That baseline assessment recorded the lowest mean of any construct, 3.93, while remaining a significant driver and carrying a substantial capability gap, mirrors a persistent difficulty in brownfield work: establishing an accurate baseline in an aging plant with incomplete documentation is genuinely hard, yet everything downstream — targets, interventions, and verified gains — depends on it (Woodhouse, 2014). Plants appear to recognize accurate baselining as both essential and incomplete, which is precisely the profile of a foundational capability warranting renewed investment (ISO, 2014).

The significant contribution of performance target-setting and benchmarking, β = 0.15, though the smallest, reinforces the framework's logic: without explicit targets there is nothing to measure interventions against, and improvement becomes a matter of activity rather than result (Kaplan & Norton, 1996). The comparatively lower maturity of baseline assessment, target-setting, and sustainment, and the persistence of gaps in verification, together sketch a clear pattern: brownfield plants are relatively strong at the engineering middle of the cycle — designing and installing upgrades — but weaker at its measurement ends, establishing accurate baselines and formal targets before, and verifying and sustaining results after (Deming, 1986). This is the imbalance the BTIV framework warns against, because a performance loop with weak measurement ends cannot know whether it is improving. Crucially, the study's central premise — that safety and reliability should be pursued jointly — is borne out: respondents rated the combined outcome highest of all constructs, and maturity, the discipline of running the joint loop, predicted it most strongly, indicating that treating hazard reduction and reliability improvement as one measured objective is not merely tidy but effective (Brown, 2009). The efficiency argument follows directly: because the same aging switchgear that poses an arc-flash hazard is also the reliability weak point, a single measured intervention often improves both, so a joint performance program extracts more value from each scarce outage window than parallel safety and reliability efforts would (Billinton & Allan, 1992).

CONCLUSION

This study set out to assess how a performance-based mitigation capability, understood as an integrated system, influences combined safety–reliability outcome effectiveness in brownfield industrial distribution systems. Using a quantitative, cross-sectional design and responses from 156 electrical, reliability, and safety professionals, it found that all six hypothesized relationships held and that the capabilities together explained 75.8% of the variance in combined effectiveness. Performance-based mitigation maturity emerged as the strongest predictor, underscoring that the discipline of running a complete measured loop matters more than any single element. Protection and mitigation engineering and verification and performance measurement followed, while reliability-centered intervention, target-setting, and baseline assessment were significant but smaller contributors.

The study concludes that arc-flash safety and electrical reliability in brownfield plants are best pursued not as separate, one-off projects but as two faces of a single measured performance objective. The Baseline–Target–Intervene–Verify cycle offers a way to see that objective whole: a plant measures where it stands, sets explicit targets, engineers and retrofits interventions, and verifies the gains, feeding results back to sharpen the next round. Combined outcomes rise when these phases reinforce one another, and the evidence here indicates that the phases most in need of strengthening are the measurement ends of the cycle — accurate baselining and rigorous verification — rather than the engineering middle. Importantly, the study finds that safety and reliability move together rather than competing: because the same aging infrastructure drives both, the same measured interventions improve both, and a joint program uses scarce downtime more efficiently than parallel efforts. For plants, the practical message is to run safety and reliability as one measured loop — baseline, target, intervene, verify — rather than as disconnected studies and upgrades; for scholarship, the study shows the value of joining the electrical-safety, reliability-engineering, and performance-management literatures around a single, measured capability view of brownfield electrical improvement.

RECOMMENDATIONS

Several recommendations follow from the findings. First, plants should invest in accurate baselining, treating the measurement of current arc-flash hazard and reliability as a first-order activity rather than a formality, since baseline assessment was both the lowest-rated capability and the foundation on which targets, interventions, and verified gains all depend. Second, they should set explicit, benchmarked performance targets for both safety and reliability, so that interventions have something concrete to be measured against and improvement is judged by result rather than by activity.

Third, plants should close the loop through disciplined verification, measuring what each intervention actually achieved against its target rather than assuming success, since verification was among the strongest predictors and the widest capability gaps concerned confirming that hazards had fallen. Fourth, they should complete protection coordination and mitigation engineering work rather than leaving it partial, attacking the incident-energy reduction that respondents rated most important. Fifth, they should pursue safety and reliability jointly, using reliability-centered logic to select interventions that improve both and thereby extract more value from each scarce outage window. Finally, plants should manage the whole as one performance capability, using a maturity assessment and a capability priority matrix to direct effort toward the weakest phases of the Baseline–Target–Intervene–Verify cycle — typically the measurement ends — and pursuing live dashboards and continuous review as the path to sustaining gains over time.

LIMITATIONS OF THE STUDY

This study has several limitations. First, the cross-sectional design captured perceptions at a single point in time and cannot establish causal direction or track how capabilities and outcomes co-evolve; a longitudinal design would allow stronger causal inference and better capture the closed-loop dynamics central to the BTIV framework. Second, the study relied on perceptual, self-reported measures completed by professionals, so the results reflect informed assessment rather than objective measurement of incident energy, reliability indices, or injury and outage rates; future work could pair perception data with hard metrics such as calculated incident energy, measured SAIDI and SAIFI, recordable injury rates, and downtime hours.

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