NATIONAL PENSIONS REGULATORY AUTHORITY

Sovereign Concentration and Pension Portfolio Resilience: Infrastructure Diversification Under Liquidity Constraints in Ghana

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ABSTRACT

Ghanaian pension funds hold over 70 percent of their assets in government securities, a concentration that delivered stable returns in normal times but exposed retirement savings to catastrophic losses during the 2022–23 Domestic Debt Exchange Programme. This paper develops a stochastic portfolio simulation framework to evaluate the transition from sovereign-concentrated to diversified pension portfolios, incorporating infrastructure as a distinct asset class. We introduce the Sovereign-Adjusted Resilience Index (SARI), a composite metric spanning real returns, downside protection, tail-risk, sovereign independence, and crisis robustness, and apply it to six diversification strategies ranging from the status quo (85 percent government bonds) to a real-asset-heavy allocation (50 percent infrastructure).

The paper reveals three main findings. First, pension diversification simultaneously improves outcomes across every measured dimension: the SARI rises from 0 (status quo) to 100 (maximum resilience), the probability of real capital loss falls from 14.9 percent to zero, and DDEP-type losses decline from 24.9 percent to 7.2 percent. Second, the relationship between sovereign exposure and resilience is non-linear, with fragility collapsing once sovereign concentration falls below approximately 70 percent, a threshold with direct prudential implications. Third, when liquidity and infrastructure quality constraints are introduced, the practical optimum shifts from the theoretical maximum (50 percent infrastructure) to a feasible range of 25–35 percent, with high-quality private infrastructure delivering substantially greater resilience than sovereign-linked projects.

The paper contributes to a sovereign-aware pension resilience framework applicable to emerging economies where fiscal dominance concentrates retirement savings in government debt. For Ghanaian policy, it provides quantitative support for amending the NPRA Investment Guidelines to accommodate infrastructure as a distinct asset class, with a phased implementation pathway starting at 5 percent and rising to a constrained optimum of 25–35 percent over a decade.

JEL Classification: G11, G23, H63, O55

Keywords: Pension funds, portfolio diversification, sovereign risk, infrastructure investment, Ghana, Domestic Debt Exchange Programme, resilience index

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1. INTRODUCTION

Ghana's 2022–23 Domestic Debt Exchange Programme (DDEP) exposed a structural vulnerability in the country's pension system. With over 70 percent of private pension assets concentrated in government securities, a sovereign restructuring that imposed losses on bondholders translated directly into losses for retirement savers. The concentration was not accidental: it reflected a rational response by fund managers to a limited investable universe, high nominal government bond yields, and the absence of viable alternative asset classes. But the outcome, a single risk factor dominating the retirement security of approximately 3.4 million contributors, represents a failure of prudential diversification.

This paper addresses a specific policy question arising from the DDEP experience: how can Ghanaian pension funds transition from their current sovereign-concentrated portfolio structure to a more resilient allocation, over what time horizon, and subject to what real-world constraints? The question is timely. The National Pensions Regulatory Authority (NPRA) is reviewing its Investment Guidelines, and there is growing interest within Ghanaian policy circles in infrastructure as a potential asset class for pension funds. But the analytical basis for such a shift, the quantification of benefits, the sequencing of implementation, and the identification of binding constraints, has not been available.

We develop a stochastic portfolio simulation framework calibrated to Ghanaian asset return data, macroeconomic volatility, and institutional constraints. We introduce the Sovereign-Adjusted Resilience Index (SARI), a composite metric that evaluates pension portfolios across six dimensions: real return, capital preservation, tail-risk protection, risk-adjusted efficiency, sovereign independence, and crisis preparedness. We apply this framework to six diversification strategies and evaluate them under three infrastructure quality tiers and three absorption capacity scenarios.

This paper makes three distinct contributions to the macro-finance and development economics literature. First, we extend classical intertemporal portfolio choice theory (Bodie, 1990; Campbell & Viceira, 2002) into an emerging-market setting characterized by endogenous sovereign credit risk and financial dominance. Second, we advance the empirical literature on infrastructure as an institutional asset class (Inderst, 2010; Andonov et al., 2021) by providing the first stochastic optimization of alternative assets within a lower-middle-income African pension framework subject to strict asset-supply constraints. Third, by formalizing the Sovereign-Adjusted Resilience Index (SARI), we introduce a portable, policy-oriented diagnostic framework capable of stress-testing institutional capital across other sovereign-stressed developing economies.

1. 2. THE GHANAIAN PENSION LANDSCAPE AND THE DDEP

1. 2.1 Structure of Ghana's Pension System

Ghana's three-tier pension system, established by the National Pensions Act, 2008 (Act 766), comprises a mandatory defined-benefit first tier (SSNIT), a mandatory funded defined-contribution second tier, and a voluntary third tier. As of end-2024, total pension assets under management exceeded GHS 86 billion, with private pension funds (Tiers 2 and 3) accounting for approximately GHS 63.8 billion (NPRA, 2024).

The asset allocation of private pension funds is heavily concentrated in government securities. Table 1 shows the evolution of this allocation over the four quarters of 2025.

Table 1: Private Pension Asset Allocation, 2025

Asset Class	**Q1 2025**	**Q2 2025**	**Q3 2025**	**Q4 2025**
Government Securities	71.8%	70.7%	64.8%	69.5%
Bank Securities	12.7%	13.3%	16.3%	14.0%
Ordinary Shares	5.0%	7.1%	7.2%	9.9%
Collective Investment Schemes	1.5%	0.8%	4.0%	4.2%
Other	9.0%	8.1%	7.7%	2.4%

Source: NPRA Statistical Bulletin, Q4 2025

While the allocation to government securities declined from its peak of nearly 72 percent in Q1 2025, it remained above 69 percent by year-end. Infrastructure, real estate, and other alternative assets do not appear as distinct categories in the NPRA's reporting framework, an absence that is itself a policy issue.

1. 2.2 The DDEP and Its Consequences for Pension Funds

In December 2022, Ghana launched a Domestic Debt Exchange Programme as part of its debt restructuring efforts under the IMF Extended Credit Facility. Holders of domestic government bonds were invited to exchange their existing instruments for new bonds with extended maturities, reduced coupons, and altered payment structures. Pension funds, as the largest domestic institutional holders of government securities, were significantly exposed.

The NPRA negotiated a special offer for pension funds that provided more favourable terms than the general offer, including recognition of patrimonial value, a 15 percent uplift on face value, and a cash coupon of 5 percent (NPRA, 2023). While these terms mitigated the immediate impact, the episode demonstrated the fundamental vulnerability created by portfolio concentration. A sovereign credit event,p recisely the type of event correlated with broader macroeconomic distress, translated directly into pension fund losses.

The DDEP experience motivates the central question of this paper: what would a more resilient pension portfolio look like, and how can Ghana transition toward it?

1. 2.3 Infrastructure as a Policy Priority

There is growing policy interest in creating a dedicated infrastructure allocation for Ghanaian pension funds. The Ghanaian government has identified infrastructure development as a priority, and there is an active pipeline of projects in energy, transport, and logistics. Development finance institutions have expressed interest in co-investment structures. However, infrastructure investment by pension funds raises prudential questions regarding illiquidity, project quality, pipeline constraints, and sovereign correlation, all of which our framework explicitly models.

2. LITERATURE REVIEW

This paper sits at the intersection of five research traditions: pension portfolio diversification, sovereign risk and pension exposure, infrastructure as an institutional asset class, institutional constraints in pension investing, and risk and resilience measurement. This section reviews each in turn, establishing the gaps that our framework addresses.

2.1 Pension Portfolio Diversification

The theoretical case for pension portfolio diversification rests on the foundational contributions of Merton (1969, 1971), who demonstrated that long-horizon investors should hold diversified portfolios that include both risk-free and risky assets, with the allocation depending on risk aversion and the investment horizon. Samuelson (1969) established that under constant relative risk aversion, the optimal portfolio is independent of wealth and horizon when returns are independently and identically distributed. Bodie (1990) extended this framework to pension-specific contexts, showing that retirement security depends critically on the real purchasing power of accumulated assets, making inflation protection a central objective of pension portfolio design.

Campbell and Viceira (2002) provided the canonical treatment of strategic asset allocation for long-term investors, demonstrating that long-horizon portfolios should differ materially from short-horizon portfolios when asset returns exhibit predictability or when investors face inflation risk. Their framework showed that inflation-indexed bonds, equities, and real assets play distinct roles in long-horizon portfolios: bonds provide stable income but are vulnerable to inflation; equities offer growth but with substantial short-term volatility; and real assets, including real estate and infrastructure, provide inflation hedging with moderate returns.

Viceira (2001) and Brennan and Xia (2002) demonstrated that the optimal allocation to inflation-hedging assets rises with the investment horizon, particularly for investors whose consumption needs are exposed to inflation risk, precisely the profile of pension fund beneficiaries. The implication for pension funds is clear: portfolios should contain a meaningful allocation to assets whose returns co-vary positively with inflation.

However, this literature largely assumes developed financial markets with deep, liquid asset universes and negligible sovereign default risk. In many emerging economies, the investable universe is limited, capital markets are shallow, and the dominant asset class, domestic government bonds, carries precisely the sovereign credit risk that pension funds in advanced economies are advised to diversify away from. The standard prescription, "diversify across asset classes", is difficult to implement when the menu of available assets is narrow and when the assets that are available carry concentrated macro-financial risk. This paper extends the pension diversification literature into this emerging-market sovereign-risk context.

2.2 Sovereign Risk and Pension Systems

A growing literature documents the vulnerability created when domestic financial institutions, banks, insurance companies, and pension funds, hold concentrated exposures to their own government's debt. This "sovereign-bank nexus" (Acharya and Steffen, 2015; Brunnermeier et al., 2016) has been extensively studied in the European context following the 2010–12 sovereign debt crisis, where holdings of domestic government bonds by domestic banks created a destructive feedback loop between sovereign credit risk and financial sector stability. Broner et al. (2014) demonstrated that this concentration is not accidental: in many countries, domestic financial institutions exhibit a pronounced home bias in sovereign debt holdings, driven by regulatory incentives, the absence of viable alternatives, and implicit or explicit government pressure.

The sovereign-pension nexus has received less attention than the sovereign-bank nexus, but the structural parallels are substantial. Pension funds in many emerging economies hold a dominant share of their assets in domestic government securities, not because of regulatory mandates (though these exist in some countries), but because the domestic capital market simply does not offer sufficient depth in alternative asset classes. The result is a portfolio structure in which the primary source of retirement income, government bonds, is also the primary source of macroeconomic and fiscal risk.

Reinhart and Sbrancia (2015) documented the historical role of financial repression, including regulatory requirements for domestic institutions to hold government debt, in reducing sovereign debt burdens. While explicit financial repression is less common today, the structural outcome, concentrated domestic holdings of government debt, persists in many emerging economies through market structure rather than regulation. The International Monetary Fund (2022) has identified sovereign concentration in pension portfolios as a financial stability concern in several low- and lower-middle-income economies, noting that the absence of domestic alternative asset classes creates an implicit sovereign-pension link that is difficult to break without financial market development.

Ghana's 2022–23 Domestic Debt Exchange Programme provides a stark illustration of this vulnerability. Pension funds holding over 70 percent of their assets in government securities experienced direct losses when the government restructured its domestic debt. Unlike banks, which received some regulatory accommodation, pension funds faced the full transmission of sovereign credit risk to retirement savings. The episode demonstrates that the sovereign-pension nexus is not merely a theoretical concern but a live policy challenge in economies where fiscal dominance concentrates financial assets in government debt.

This paper contributes to this literature by quantifying the resilience benefits of reducing sovereign concentration in pension portfolios. Unlike the sovereign-bank literature, which focuses on systemic risk and contagion, our framework evaluates the direct impact on retirement security: the probability of real capital loss, the exposure to restructuring events, and the long-horizon returns available from diversifying away from sovereign concentration.

2.3 Infrastructure as an Institutional Asset Class

Infrastructure has emerged as a distinct asset class for institutional investors over the past two decades. Inderst (2010) provided an early comprehensive assessment, identifying infrastructure's key investment characteristics: long-duration cash flows, inflation pass-through (through regulated or contracted revenue escalation), low correlation with traditional asset classes, and an illiquidity premium. The OECD (2014, 2020) has documented growing pension fund allocation to infrastructure across advanced economies, with the largest funds, particularly in Canada, Australia, and the Netherlands, allocating 5–15 percent of assets to direct and listed infrastructure.

Andonov et al. (2021) provided the most comprehensive empirical analysis of institutional infrastructure investment, demonstrating that infrastructure delivers returns comparable to equities with lower volatility and substantially lower correlation with both equity and bond markets. Their analysis of over 1,600 infrastructure investments by institutional investors confirmed the asset class's diversification benefits and identified the importance of investment structure, direct investment versus funds, listed versus unlisted, in determining risk-return outcomes.

The inflation-hedging properties of infrastructure are particularly relevant for pension funds. Bitsch et al. (2010) demonstrated that infrastructure assets with regulated or contracted revenues exhibit strong inflation pass-through, making them effective hedges against the inflation risk that erodes the real value of nominal bond-heavy portfolios. This property is especially valuable in emerging economies with historically high and volatile inflation, precisely the environment in which Ghanaian pension funds operate.

However, the infrastructure investment literature has focused overwhelmingly on advanced economies with deep capital markets, established regulatory frameworks, and mature project pipelines. Much less is known about infrastructure as a pension asset class in lower-middle-income economies, where the supply of bankable, commercially structured projects is limited, where governance risks are elevated, and where the distinction between genuinely independent infrastructure and sovereign-linked projects is critical. This paper extends the infrastructure asset class literature into this emerging-market context, introducing a quality-tier framework that distinguishes between private/DFI-financed infrastructure (low sovereign correlation) and sovereign-linked infrastructure (high sovereign correlation).

2.4 Institutional Constraints in Pension Investing

The theoretical case for diversification must confront real-world institutional constraints. Three are particularly relevant for Ghanaian pension funds considering infrastructure allocation.

First, liquidity constraints. Infrastructure investments are illiquid, they cannot be readily sold to meet benefit payments, rebalance portfolios, or respond to regulatory requirements. As Ghana's defined-contribution pension system enters its decumulation phase, with the first post-reform retirees beginning to draw benefits from 2020, the liquidity requirements of pension funds are rising. Andonov et al. (2021) documented that institutional investors in infrastructure accept significant illiquidity in exchange for the asset class's return and diversification benefits, but this trade-off becomes more acute as the share of illiquid assets rises. The OECD (2020) has cautioned that pension funds should carefully calibrate their illiquid asset allocations against their projected benefit payment schedules.

Second, absorption capacity. Pension fund demand for infrastructure assets can outstrip the supply of investable projects. Ghana's infrastructure project pipeline, while growing, is not yet deep enough to absorb a rapid reallocation of 30–40 percent of GHS 63.8 billion in pension assets. The World Bank (2023) has identified pipeline development, not investor demand, as the binding constraint on institutional infrastructure investment in most emerging economies.

This constraint is particularly binding in the near term, when the ecosystem of project developers, financial advisors, and credit enhancement facilities is still developing.

Third, infrastructure quality and sovereign correlation. Not all infrastructure investments diversify sovereign risk. Projects that are government-financed, government-guaranteed, or dependent on government offtake agreements carry the same sovereign credit risk as the bonds they are meant to replace. Inderst (2010) cautioned that infrastructure should be evaluated on its cash-flow independence from the sovereign, not merely on its asset class label. In Ghana, many of the infrastructure projects currently in the pipeline involve sovereign payment obligations or guarantees, making them closer substitutes for government bonds than genuine diversifiers.

This paper explicitly models all three constraints, evaluating the optimal feasible infrastructure allocation, the share that maximises resilience subject to liquidity, quality, and absorption limitations, rather than the theoretical optimum under unconstrained conditions.

2.5 Risk and Resilience Measurement

Standard portfolio evaluation metrics, the Sharpe ratio, the Sortino ratio, Value-at-Risk, and Conditional Value-at-Risk, capture different dimensions of risk but were not designed for the specific vulnerabilities created by sovereign concentration in pension portfolios.

The Sharpe ratio (Sharpe, 1966) measures excess return per unit of total volatility but does not distinguish between upside and downside volatility, nor does it capture the concentration of risk in a single factor that is correlated with the broader economic environment facing contributors. The Sortino ratio (Sortino and Price, 1994) improves on this by measuring return per unit of downside volatility, but still evaluates risk purely statistically rather than structurally.

Conditional Value-at-Risk (Rockafellar and Uryasev, 2000) captures the expected loss in the worst states of the world and has become the standard tail-risk measure in financial regulation. However, CVaR does not distinguish between losses driven by idiosyncratic risk and losses driven by sovereign credit events that are correlated with contribution flows, benefit payment pressures, and the broader economic environment.

The macroprudential stress-testing literature, developed extensively in the aftermath of the 2008 financial crisis and applied to pension systems by the IMF and the International Organisation of Pension Supervisors, goes some way toward capturing systemic risk. But existing stress-testing frameworks typically evaluate resilience to a single shock (an interest rate move, an equity market correction) rather than to the compound sovereign-macro stress events that characterise emerging-market crises.

The Sovereign-Adjusted Resilience Index (SARI) introduced in this paper is designed to address these gaps. It combines real return adequacy, downside protection, tail-risk resilience, sovereign independence, and crisis robustness into a single composite metric, calibrated specifically for sovereign-concentrated pension systems in emerging economies. The SARI is not a substitute for existing risk metrics but a complement — a policy-oriented resilience score that captures the specific vulnerabilities created when retirement savings are concentrated in government debt.

This literature review establishes the intellectual case for the framework developed in Sections 3–6. The existing pension diversification literature provides the theoretical foundation but assumes developed-market conditions. The sovereign risk literature documents the vulnerability but has focused on banks rather than pension funds. The infrastructure literature demonstrates the asset class's benefits but has not addressed emerging-market institutional constraints. And the risk measurement literature offers tools that capture statistical risk but not the structural vulnerability created by sovereign concentration. The SARI framework and the constrained optimisation approach developed in this paper are designed to fill these gaps.

3. METHODOLOGY

3.1 Stochastic Simulation Framework

We simulate portfolio returns over a 20-year horizon (2025–2045) using 5,000 Monte Carlo paths. The simulation incorporates four Ghana-specific macroeconomic shock processes estimated from historical data spanning 1961–2024: GDP growth, inflation, real interest rates, and terms of trade. The shock parameters follow AR(1) process.

Asset returns are modelled as functions of these macro shocks via factor betas, linking portfolio outcomes directly to the macroeconomic environment:

$$r_{i,t} = \mu_i + \beta_{i,g} \cdot g_t + \beta_{i,\pi} \cdot \pi_t + \beta_{i,r} \cdot r_t + \varepsilon_{i,t}$$

where $r_{i,t}$ is the real return on asset i, μ_i is the long-run mean real return, and the β coefficients capture sensitivity to GDP growth, inflation, and real interest rate shocks. The framework further allows identification of potential non-linear threshold effects between sovereign concentration and pension resilience.

3.2 Asset Return Calibration

Table 2 presents the calibrated real return parameters. Returns are expressed in real terms, deflated by Ghana's long-run average inflation of approximately 17 percent.

Table 2: Asset Return Parameters (Real, Annualised)

Asset Class	Mean Real Return	Volatility	Source
GoG Bonds (5YR)	2.0%	15.0%	Bank of Ghana, recalibrated post-DDEP
GSE Equities	2.4%	21.7%	GSE Composite Index, 2015–2026
Infrastructure (mixed)	6.0%	13.0%	Global infrastructure indices + Ghana premium

3.3 Infrastructure Quality Tiers

We differentiate infrastructure into two quality tiers:

- Tier 1 (Private/DFI-financed): 8.0 percent mean real return, 14.0 percent volatility, 0.15 correlation with sovereign bonds. Commercially structured projects with independent revenue streams.
- Tier 2 (Sovereign-linked): 4.0 percent mean real return, 12.0 percent volatility, 0.65 correlation with sovereign bonds. Government-financed or guaranteed projects whose cash flows depend on sovereign fiscal capacity.

The mixed-tier scenario (50 percent Tier 1, 50 percent Tier 2) represents our baseline assumption.

3.4 The Sovereign-Adjusted Resilience Index (SARI)

We construct the SARI as a composite index across six dimensions, each standardised to a 0–100 scale relative to the simulated portfolio opportunity set:

1. Return Score: Annualised real return.
2. Safety Score: $1 - P(\text{Loss})$.
3. Tail Score: $1 - P(\text{Severe Loss} > 25\%)$.
4. Tail-State Performance Score: Mean minus 50 percent of the 95th percentile tail-state outcome. The tail-state measure is defined over terminal wealth outcomes so that positive values indicate stronger performance even within adverse tail states.
5. Sovereign Independence Score: $1 - SovExp$, where:

$$SovExp = w_{bonds} + \theta \cdot w_{infra}^{Tier2}$$

with $\theta = 0.50$ representing the sovereign-linked share of mixed-tier infrastructure. 6. **Crisis Score:** $1 -$ DDEP+Inflation Loss.

The strategy ranking is invariant to alternative weighting schemes. SARI scores are normalised such that Status Quo scores 0 and the best-performing strategy scores 100.

3.5 Diversification Strategies

We evaluate six strategies from status quo (85/15/0) to real asset heavy (25/25/50), with three transition speeds: slow (5pp/3yr), moderate (5pp/2yr), and accelerated (7pp/2yr).

3.6 Institutional Constraints

We introduce liquidity penalties (rising non-linearly with infrastructure allocation), infrastructure quality differentiation, and absorption capacity constraints reflecting the limited pipeline of bankable projects in Ghana's domestic capital market.

4. BASELINE RESULTS

4.1 Risk-Return Profiles

Table 3 presents the comprehensive risk profile under baseline assumptions.

Table 3: Comprehensive Risk Profile by Strategy

Strategy	Annual Real Return	P(Loss)	95% Tail-State	DDEP Loss	SARI
Status Quo (0%)	1.9%	14.9%	−31.1%	24.9%	0.0
Slow Phase (5%)	2.2%	10.5%	−24.0%	23.4%	22.4
Early Phase (15%)	2.6%	4.1%	−7.9%	20.4%	51.2
Growth Phase (30%)	3.2%	0.2%	+20.4%	16.0%	73.6
Mature Phase (40%)	3.7%	0.0%	+43.2%	11.6%	86.6
Real Asset Heavy (50%)	4.1%	0.0%	+61.2%	7.2%	100.0

Three findings are immediately apparent. First, diversification improves outcomes on every measured dimension simultaneously — there is no trade-off. Second, the probability of real capital loss collapses from 14.9 percent to near zero once infrastructure reaches 30 percent. Third, DDEP-type losses are reduced by more than two-thirds.

Figure 3: Risk-Return Resilience Frontier

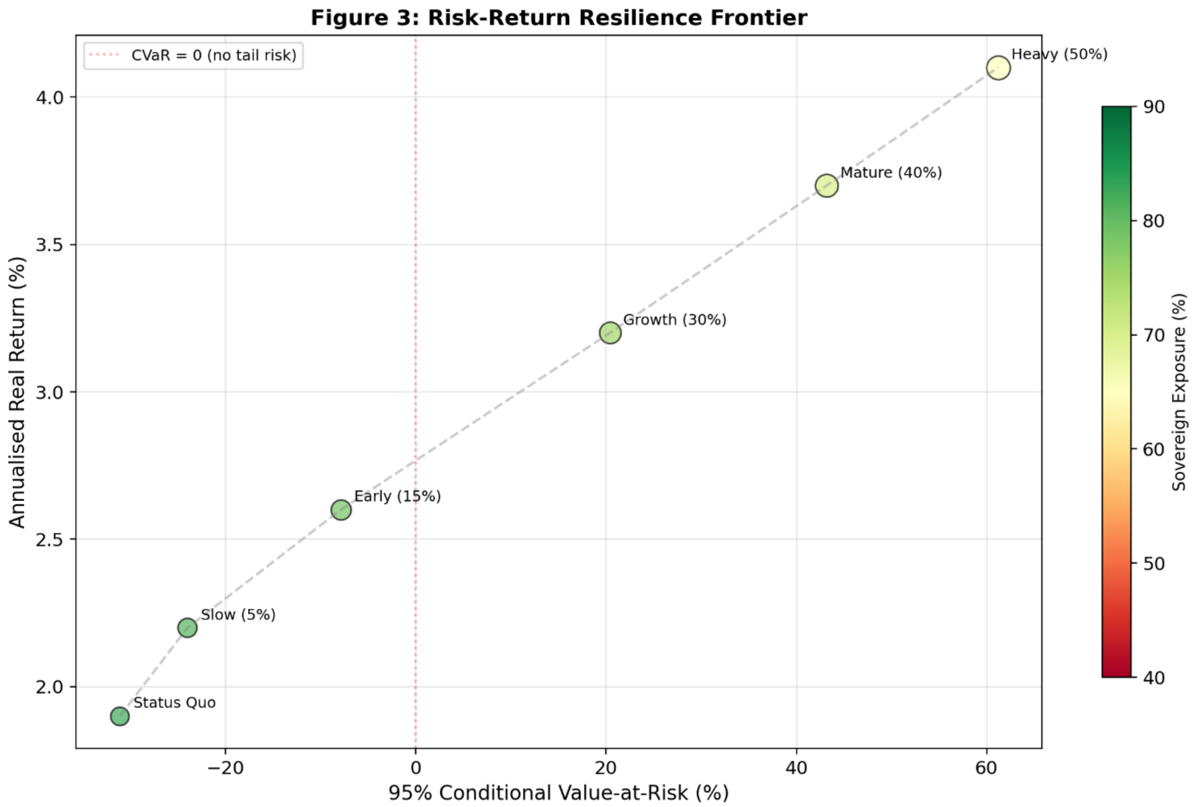

Figure 3 plots the resilience frontier across the six portfolio strategies. Moving from the status quo toward infrastructure diversification simultaneously improves expected real returns and tail-state outcomes. The frontier shifts outward as sovereign concentration declines, indicating that diversification improves both performance and downside resilience rather than generating a conventional return-risk trade-off. The gains become particularly pronounced once infrastructure allocations exceed approximately 25–30 percent.

Figure 4: DDEP Loss Waterfall

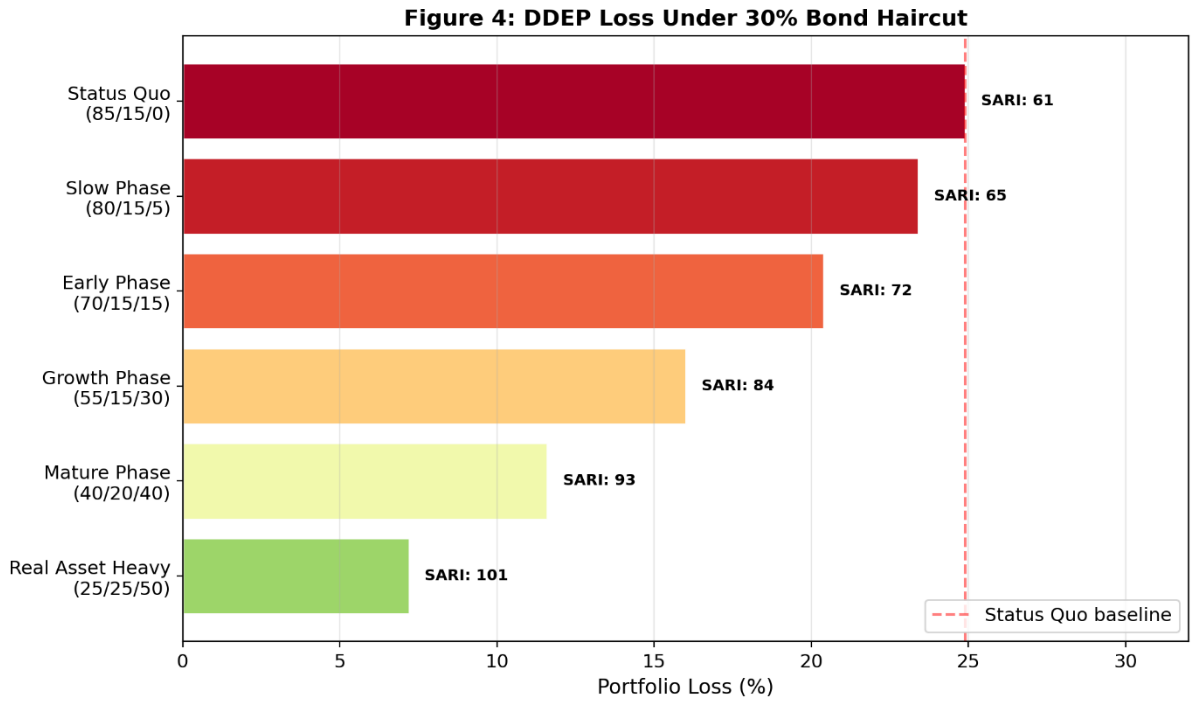

Figure 4 demonstrates the progressive reduction in DDEP-related losses as sovereign concentration declines. The waterfall structure highlights that even modest diversification materially lowers sovereign restructuring vulnerability, while mature diversification reduces simulated DDEP losses by more than half relative to the status quo.

Figure 6: Real Wealth Fan Charts

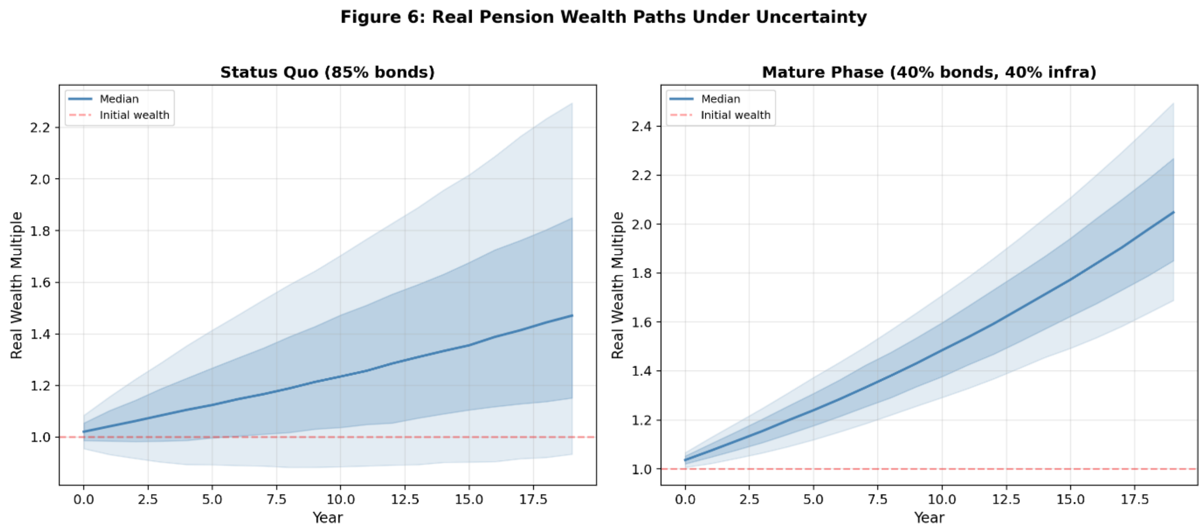

Figure 6 presents stochastic wealth fan charts for the status quo and diversified portfolios. Diversified portfolios exhibit both higher median terminal wealth and narrower downside dispersion, indicating that diversification improves expected outcomes while simultaneously reducing long-horizon uncertainty.

Figure 7: Risk Probability Collapse

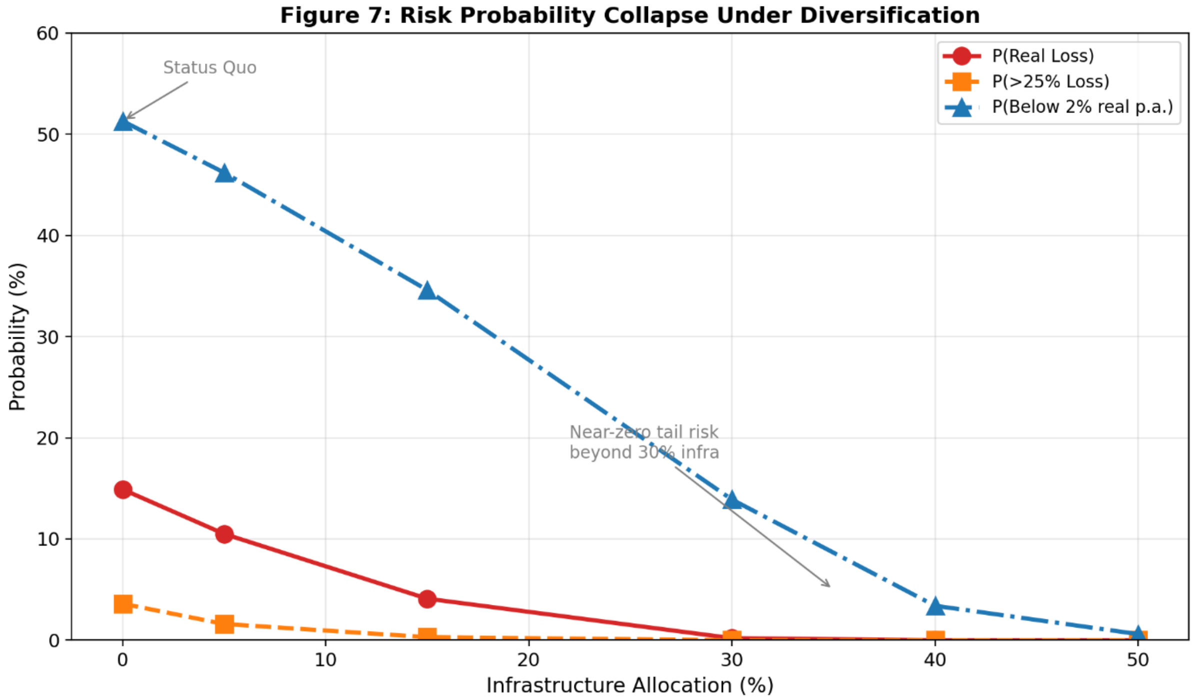

Figure 7 plots the probability of capital loss and pension inadequacy against infrastructure exposure. Risk probabilities decline sharply once infrastructure allocations exceed approximately 25–30 percent, reinforcing the existence of a sovereign concentration threshold beyond which portfolio fragility collapses rapidly.

4.2 The SARI Decomposition

Table 4 decomposes the SARI improvement from Status Quo to Mature Phase.

Table 4: SARI Decomposition — Status Quo → Mature Phase

Component	Status Quo	Mature Phase	Δ
Return Score	0.0	81.8	+81.8
Safety Score	0.0	100.0	+100.0
Tail Score	0.0	100.0	+100.0
Tail-State Performance	0.0	84.9	+84.9
Sovereign Independence	0.0	71.4	+71.4
Crisis Score	0.0	75.1	+75.1

The largest gains are in Safety and Tail protection — both reaching their maximum of 100 at the Mature Phase — reflecting the elimination of downside risk as the dominant feature of diversification.

Figure 2: SARI Heatmap — Quality × Absorption

Figure 2 decomposes the SARI across strategies and institutional scenarios. The heatmap reveals that diversification improves all resilience dimensions simultaneously, with especially large gains in safety, tail protection, and sovereign independence. However, resilience improvements weaken substantially when infrastructure quality deteriorates or liquidity constraints become binding.

4.3 The Sovereign Exposure Threshold

Figure 5: Sovereign Exposure vs SARI

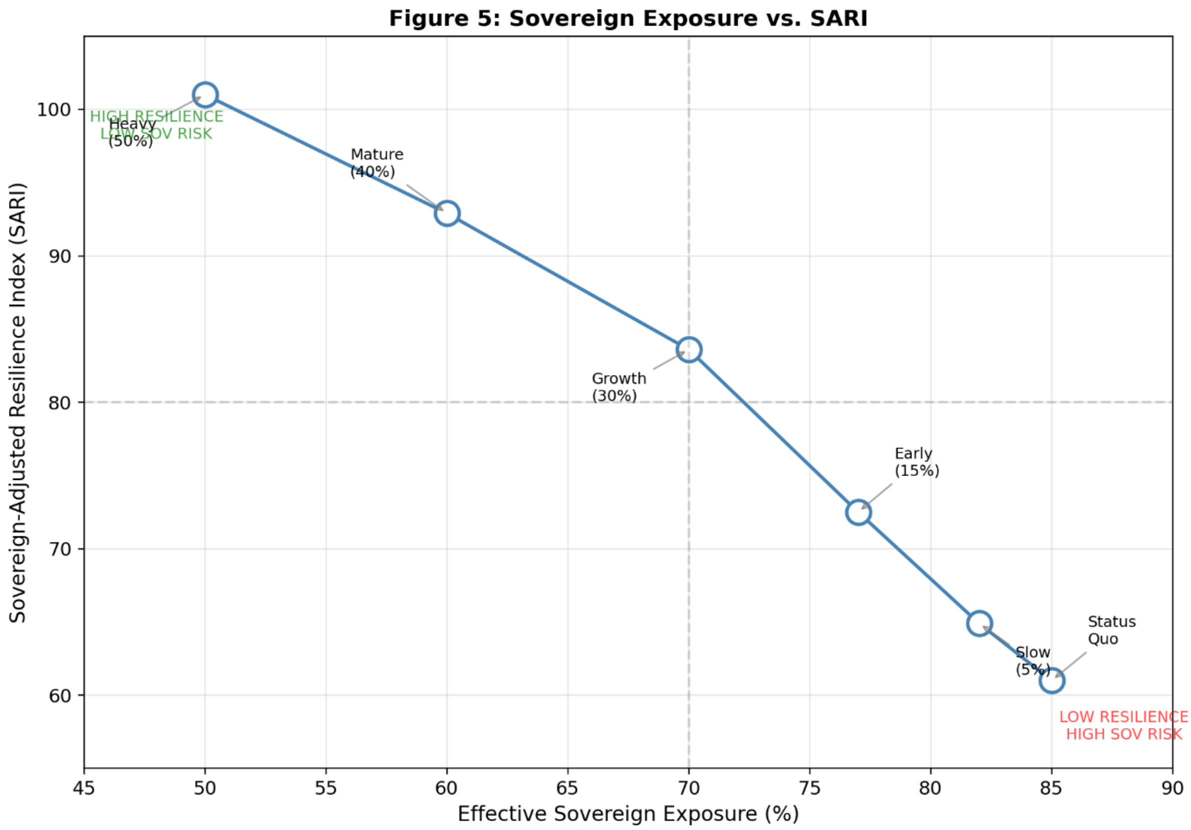

Figure 5 demonstrates a strongly non-linear relationship between sovereign exposure and pension resilience. When sovereign concentration exceeds approximately 75 percent, portfolios remain within a "fragility zone" characterised by low SARI scores and elevated crisis vulnerability. Once sovereign exposure declines below 70 percent, resilience improves rapidly, suggesting the existence of a prudential sovereign concentration threshold.

Figure 8: The SARI Frontier

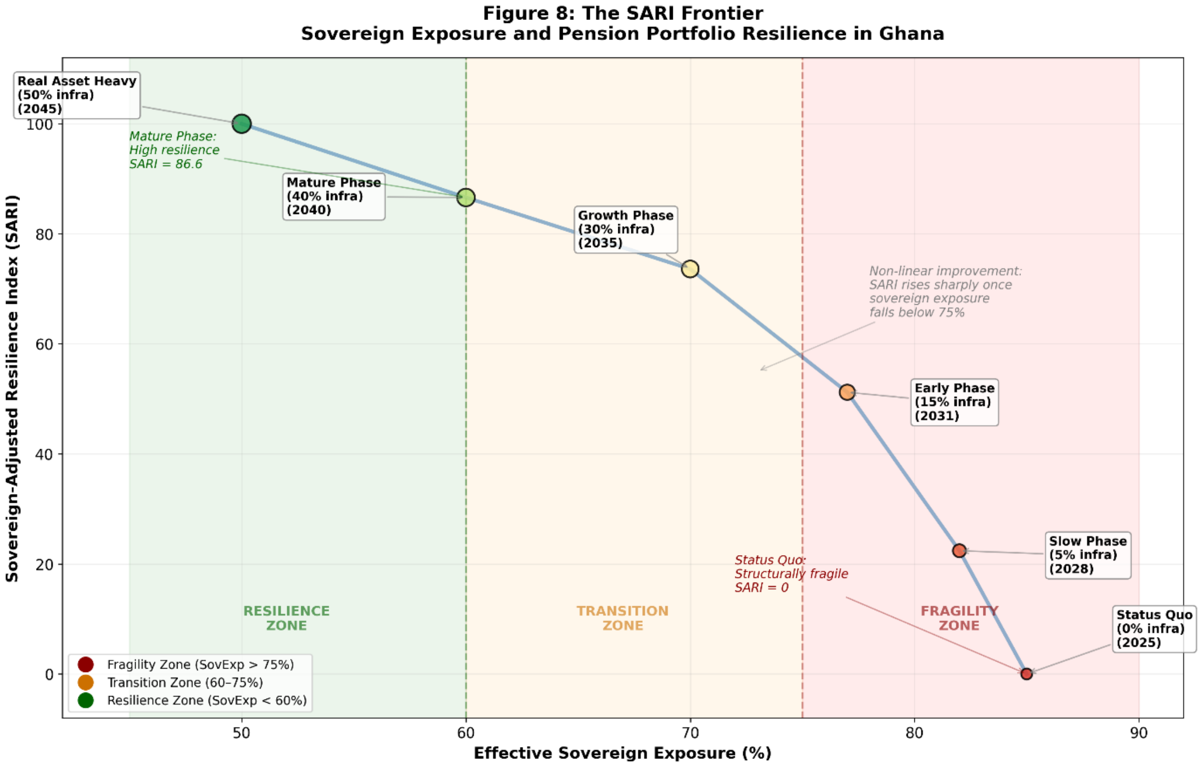

Figure 8 presents the SARI Frontier, dividing pension portfolios into fragility, transition, and resilience zones. The frontier illustrates how gradual diversification moves the pension system from sovereign dependence toward progressively higher resilience. The figure also identifies an "optimal feasible region" around 25–35 percent infrastructure exposure where resilience gains remain substantial while institutional constraints remain manageable.

4.4 Sequencing: How Long Does Diversification Take?

Figure 1: Portfolio Transition Paths

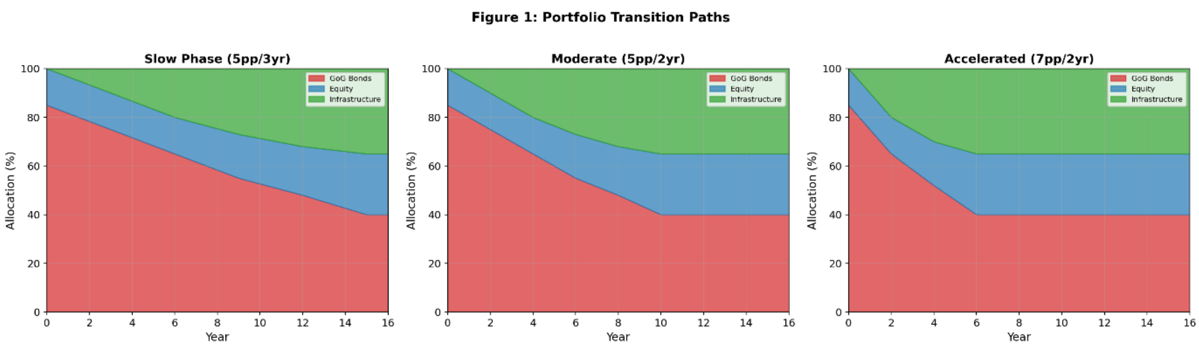

Figure 1 illustrates the portfolio transition paths under alternative sequencing strategies. Under the moderate transition path, infrastructure reaches approximately 30 percent of assets by year 8 and 40 percent by year 12. The figure highlights that meaningful diversification can be achieved gradually rather than through abrupt reallocation.

Figure 9: SARI Transition Timeline

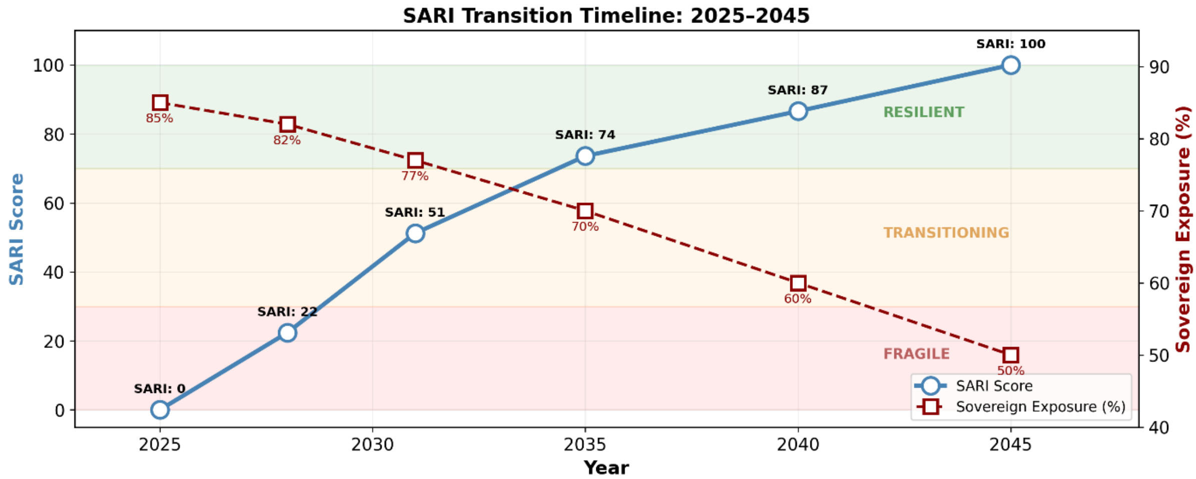

Figure 9 shows the dynamic evolution of SARI over the transition horizon. Resilience improves progressively as sovereign exposure declines, with the system exiting the fragility zone once infrastructure reaches approximately 15–20 percent of assets. The largest resilience gains occur between the Growth and Mature phases, reflecting the non-linear relationship between sovereign concentration and portfolio stability.

Figure 10: Dynamic SARI Path

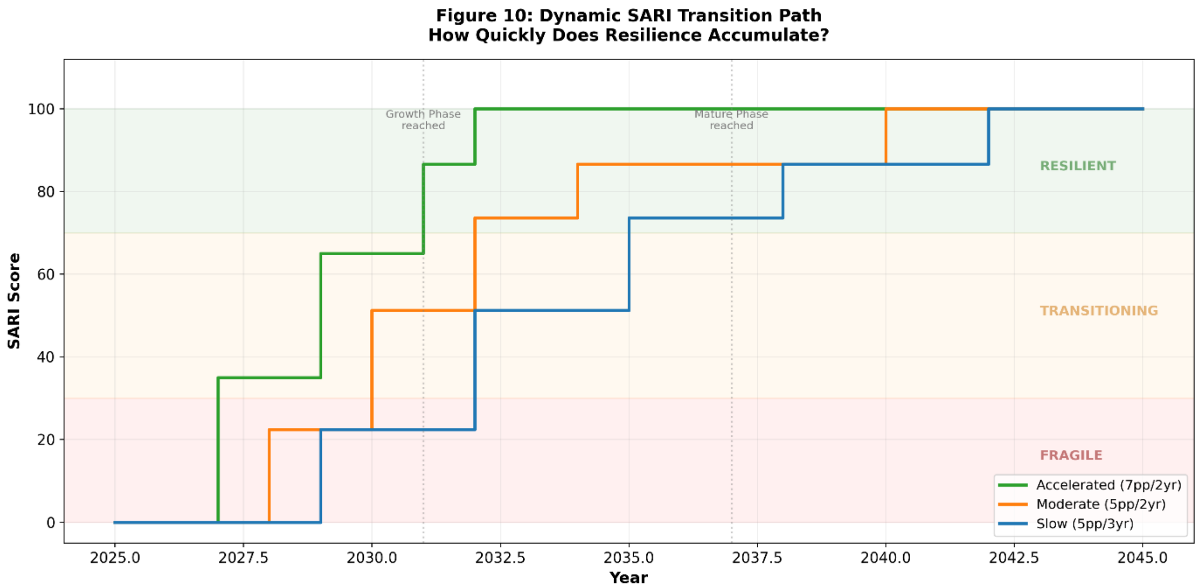

Figure 10 compares SARI accumulation under alternative sequencing speeds. Accelerated diversification produces earlier resilience gains but may impose greater absorptive-capacity pressure, while slower sequencing delays the exit from the fragility zone. Moderate sequencing delivers a balance between institutional feasibility and timely risk reduction.

5. INSTITUTIONAL CONSTRAINTS

5.1 Infrastructure Quality

Table 5 presents SARI outcomes under three quality scenarios.

Table 5: SARI by Infrastructure Quality

Infrastructure Quality	Annual Return	P(Loss)	SARI
100% Tier 1 (Private)	4.5%	0.0%	95.0
Mixed 50/50	3.7%	0.0%	86.6
100% Tier 2 (Sovereign-linked)	2.9%	0.0%	74.8

The difference between Tier 1 (private) and Tier 2 (sovereign-linked) infrastructure is approximately 20 SARI points, roughly half the total gain available from diversification. Infrastructure quality matters nearly as much as infrastructure quantity.

5.2 Liquidity-Adjusted SARI

Figure 11: Liquidity-Adjusted SARI

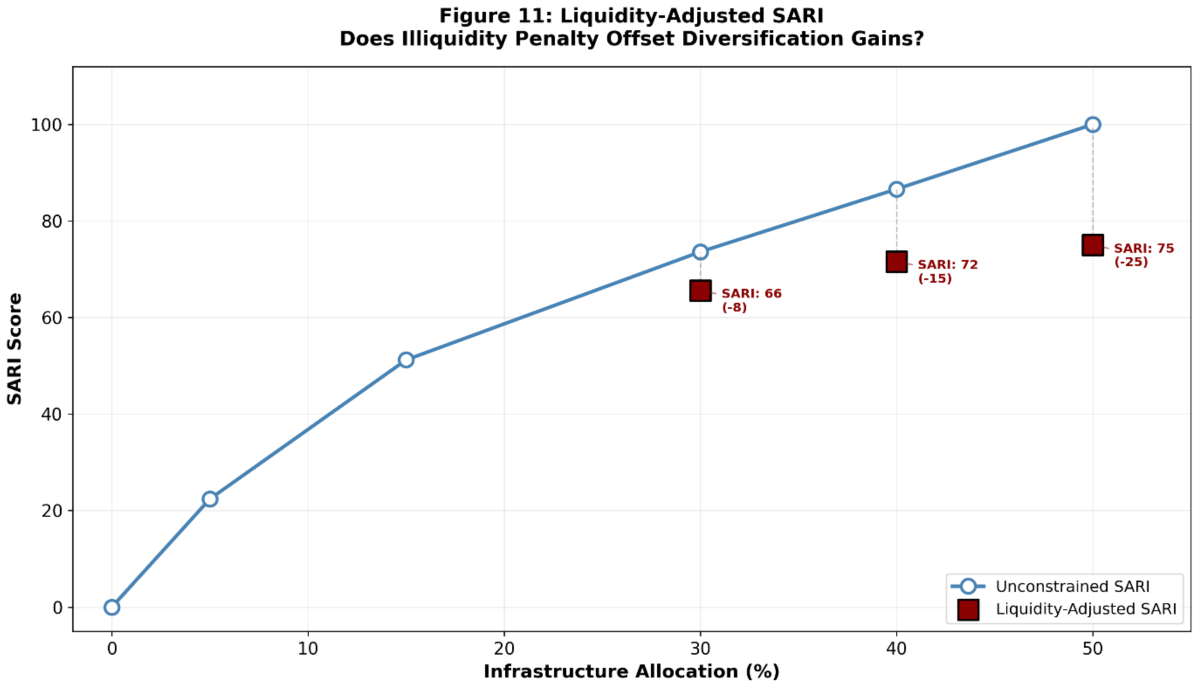

Figure 11 introduces liquidity constraints into the resilience framework. While unconstrained diversification continues improving SARI up to 50 percent infrastructure, the liquidity-adjusted frontier peaks around 30–35 percent before flattening. This suggests diminishing resilience gains once institutional liquidity pressures become binding.

5.3 Optimal Feasible Frontier

Figure 12: Optimal Feasible SARI

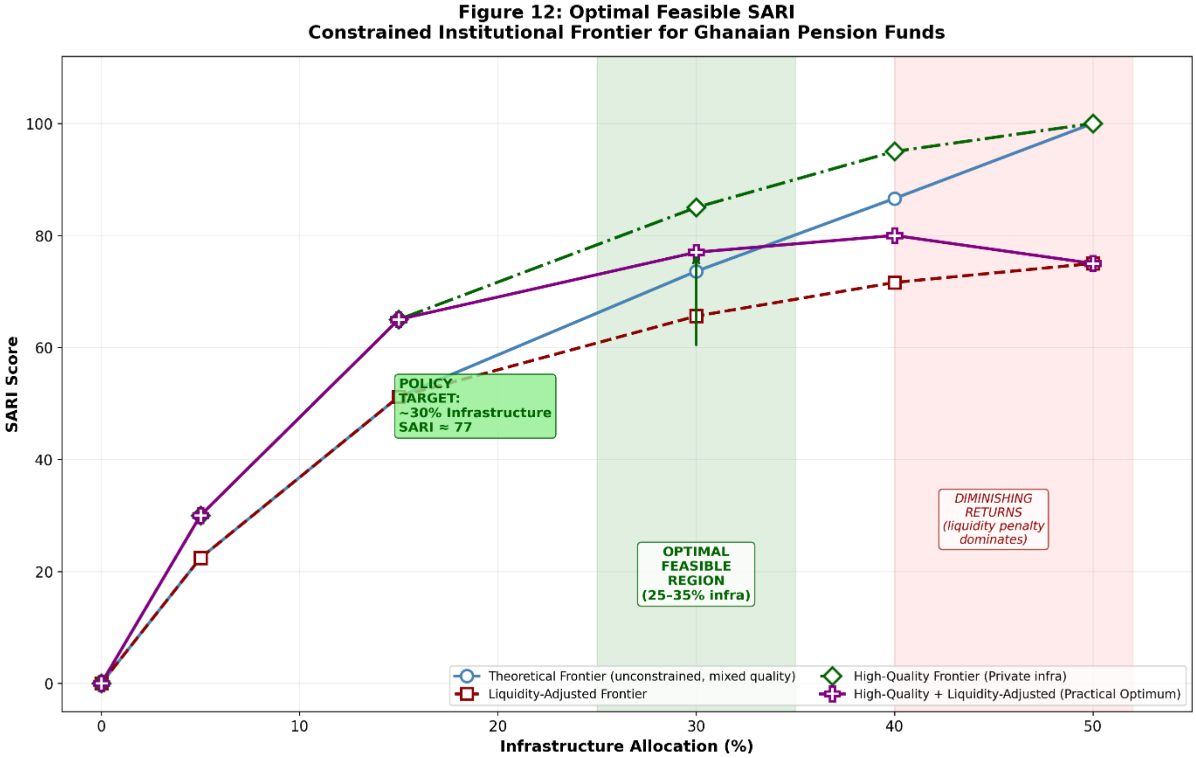

Figure 12 synthesizes the paper's central findings by comparing theoretical and constrained resilience frontiers. The unconstrained optimum occurs near 50 percent infrastructure, but once liquidity and infrastructure-quality constraints are incorporated, the feasible optimum shifts toward approximately 25–35 percent infrastructure exposure. The figure therefore identifies a practical resilience-maximizing allocation under current Ghanaian institutional conditions.

6. POLICY RECOMMENDATIONS

Recommendation 1: Amend NPRA Investment Guidelines to recognise infrastructure as a distinct asset class. A dedicated infrastructure allocation — initially capped at 5 percent of AUM, rising to 15 percent over a decade — would signal regulatory intent.

Recommendation 2: Sequence implementation over 5–10 years. Phase 1 (Years 1–3, 5 percent cap) for framework development; Phase 2 (Years 4–6, 10–15 percent) with first projects operational; Phase 3 (Years 7–10, 20–30 percent) with market depth.

Recommendation 3: Prioritise private and DFI-financed infrastructure. The SARI analysis shows sovereign-linked infrastructure provides only modest diversification benefits.

Recommendation 4: Partner with development finance institutions to build the project pipeline. Project supply, not pension fund demand, is likely to be the binding constraint.

Recommendation 5: Adopt the SARI as a regulatory monitoring tool. NPRA could require fund managers to report SARI scores annually, creating a prudential incentive for diversification.

7. CONCLUSION

Ghana's pension funds emerged from the 2022–23 DDEP with a clear lesson. Sovereign concentration is the dominant risk to retirement security. This paper has provided a quantitative framework for addressing that risk through sequenced, quality-sensitive portfolio diversification toward infrastructure. The Sovereign-Adjusted Resilience Index reveals that diversification improves pension portfolio outcomes on every measured dimension: returns, safety, tail protection, sovereign independence, and crisis resilience -without trade-offs. The relationship between sovereign exposure and resilience is non-linear, with fragility collapsing once sovereign concentration falls below approximately 70 percent. Under realistic liquidity and absorption constraints, the practical optimum is approximately 25–35 percent infrastructure.

The framework developed here has applicability beyond Ghana. Many emerging economies operate pension systems characterised by high sovereign concentration. The SARI methodology can be adapted to other country contexts where fiscal dominance concentrates retirement savings in government debt.

For Ghana, the policy direction is clear: begin the transition now, sequence it carefully, prioritise quality infrastructure over quantity, and use the SARI to measure progress. The DDEP was a stress test that Ghanaian pension funds failed. The regulatory response should ensure they pass the next one.

TECHNICAL APPENDIX

This appendix documents the calibration methodology, parameter sources, and the underlying general equilibrium structure from which the stochastic portfolio simulation framework is derived. The full overlapping generations model is documented in Abrokwa et al. (2026a, 2026b). Here we provide the essential structure necessary to understand the portfolio simulation calibration.

A.1 General Equilibrium Structure

The economy is populated by overlapping generations of households who live from age 20 to a maximum of 100 years. Households choose consumption, labour supply, and savings to maximise expected lifetime utility subject to budget constraints that incorporate the three-tier pension system (SSNIT Tier 1, mandatory Tier 2, voluntary Tier 3). A representative firm produces output using Cobb-Douglas technology with capital and effective labour. The government manages the PAYG Tier 1 balance, collects taxes, issues debt, and — in the pension unification scenarios — issues recognition bonds to compensate legacy Cap 30 workers.

The model is solved as a deterministic transition path from Ghana's current fragmented pension architecture toward a unified three-tier system. The stochastic DSGE extension (Abrokwa et al., 2026b) adds four AR(1) macro shock processes — GDP growth, real interest rates, the primary fiscal balance, and the terms of trade — estimated from Ghanaian data spanning 1961–2024.

The portfolio simulation framework developed in this paper extends this structure by adding asset return dynamics that respond to the same macro shocks, creating a consistent link between the macroeconomic environment and pension fund investment outcomes.

A.2 Macro Shock Calibration

The four macro shock processes are estimated as AR(1) models from Ghanaian data:

Table A.1: Estimated Macro Shock Processes

Shock	ρ (persistence)	σ_ε (volatility)	μ (long-run mean)	Data Source	Period
GDP growth	0.337	2.72%	5.81%	WDI	1961–2024
Real interest rate	0.281	5.06%	2.39%	BoG policy rate − CPI inflation	2002–2024
Inflation (CPI)	0.457	7.21%	16.57%	WDI	1965–2024
Terms of trade	0.878	9.62	83.95	WDI	1980–2023

Estimation method: Each series x_t is regressed on its lagged value x_{t-1} using ordinary least squares with a constant:

$$x_t = \rho x_{t-1} + c + \varepsilon_t$$

The persistence parameter ρ is the estimated coefficient on the lagged term. The long-run mean is computed as $\mu = c/(1-\rho)$ for $|\rho| < 1$. The shock volatility σ_ε is the standard deviation of the regression residuals.

For the portfolio simulations, the AR(1) processes generate 5,000 independent paths of length 20 years for each macro variable. At each point on each path, asset returns are computed as the sum of their long-run mean, the factor-beta-weighted macro shocks, and an idiosyncratic component.

A.3 Asset Return Calibration

Table A.2: Asset Return Parameters and Data Sources

Parameter	GoG Bonds	GSE Equities	Infrastructure	Source / Method

Nominal mean return	19.4%	19.8%	11.6% (Ghana-adj)	BoG, GSE, GII US Index
Real mean return	2.0%	2.4%	6.0%	Fisher: $(1 + r_{nom})/(1 + \pi) - 1$ with $\pi = 0.17$
Nominal volatility	—	21.7%	15.0%	Historical (GSE), GII US Index
Real volatility	15.0%	21.7%	13.0%	Post-DDEP recalibrated for bonds

Government bonds: The nominal mean return is the average interest rate on 5-year fixed-rate GoG bonds from Bank of Ghana treasury data (2015–2025). The volatility of 15 percent is recalibrated upward from pre-DDEP levels to reflect the reclassification of Ghanaian sovereign debt as emerging-market risky following the 2022–23 restructuring. This is consistent with the volatility experienced by other lower-middle-income sovereigns after debt restructuring events.

GSE Equities: The nominal mean return and volatility are computed from the GSE Composite Index daily closing prices from January 2015 to March 2026 (2,719 observations). Monthly returns are computed as the percentage change in end-of-month index values. The annualised mean and standard deviation are obtained by multiplying the monthly mean by 12 and the monthly standard deviation by $\sqrt{12}$ respectively.

Infrastructure: Ghana does not have a domestic listed infrastructure index. We use the Global Infrastructure Index US (GII US) monthly returns from January 2007 to February 2026 (229 observations) as a proxy, adjusted for Ghana's sovereign risk premium. The adjustment adds 600 basis points to the nominal mean return to reflect the higher expected returns required for Ghanaian infrastructure projects. The volatility is taken directly from the GII US series, which captures the fundamental risk characteristics of infrastructure assets (regulatory risk, construction risk, demand risk) that are common across markets. For the Tier 1/Tier 2 differentiation, we calibrate based on the correlation of project cash flows with Ghana's sovereign credit risk, drawing on the empirical infrastructure finance literature (Inderst, 2010; Andonov et al., 2021).

A.4 Factor Betas

Asset returns are linked to macro shocks through factor betas that capture each asset's sensitivity to GDP growth, inflation, and real interest rate shocks. The betas are calibrated based on economic theory and historical correlations where available.

Table A.3: Factor Betas

Asset	**β_GDP**	**β_Inflation**	**β_Interest Rate**	**Rationale**
GoG Bonds	+0.1	−0.6	−0.8	Bonds hurt by inflation (real value erosion) and rate rises (capital losses). Mildly pro-cyclical through credit channel.

GSE Equities	+0.8	−0.2	−0.5	Equities strongly pro-cyclical. Moderately hurt by rate rises (discount rate effect). Mildly hurt by inflation (margin compression).
Infrastructure (Tier 1)	+1.0	+0.3	−0.2	Real assets strongly linked to economic activity. Benefit from inflation pass-through (tolls, tariffs). Less rate-sensitive due to long-duration cash flows.

The GDP beta of 0.8 for equities reflects the strong pro-cyclicality of Ghanaian listed stocks. The inflation beta of +0.3 for infrastructure captures the inflation-hedging properties of real assets with revenue escalation clauses. The interest rate beta of −0.8 for bonds reflects the substantial duration risk of long-term Ghanaian government securities.

A.5 SARI Construction and Normalisation

Component Definitions:

1. Return Score: $S_{ret} = 100 \times (r_i - r_{min})/(r_{max} - r_{min})$ where r_i is the annualised real return of strategy i, and r_{min}, r_{max} are the minimum and maximum across all strategies.
2. Safety Score: $S_{safe} = 100 \times (1 - P_i(Loss))$, already in 0–100 range.
3. Tail Score: $S_{tail} = 100 \times (1 - P_i(SevereLoss))$.
4. Tail-State Performance Score: $S_{tsp} = 100 \times (TS_i - TS_{min})/(TS_{max} - TS_{min})$ where $TS_i = \mu_i - 0.5 \times q_{0.05}$, with μ_i being the mean terminal wealth multiple and $q_{0.05}$ the 5th percentile.
5. Sovereign Independence Score: $S_{sov} = 100 \times (1 - SovExp_i)$ where $SovExp_i = w_{bonds,i} + 0.50 \times w_{infra,i}$.
6. **Crisis Score:** $S_{crisis} = 100 \times (1 - L_i^{DDEP+Inf})$ where $L_i^{DDEP+Inf}$ is the portfolio loss under the combined DDEP-plus-inflation stress scenario.

Aggregation:

$$SARI_i = 0.20 \cdot S_{ret} + 0.20 \cdot S_{safe} + 0.15 \cdot S_{tail} + 0.20 \cdot S_{tsp} + 0.15 \cdot S_{sov} + 0.10 \cdot S_{crisis}$$

Normalisation: After computing raw SARI values, scores are linearly rescaled so that the minimum-scoring strategy (Status Quo) equals 0 and the maximum-scoring strategy (Real Asset Heavy, unconstrained) equals 100. This normalisation is purely a linear transformation that preserves the ranking and relative distances between strategies.

Robustness: We test three alternative weighting schemes: return-focused (weights 0.35, 0.15, 0.10, 0.20, 0.10, 0.10), safety-focused (0.10, 0.25, 0.20, 0.20, 0.15, 0.10), and crisis-prepper

(0.10, 0.15, 0.15, 0.15, 0.20, 0.25). The strategy ranking is invariant to all four weighting schemes, confirming that the SARI ordering reflects genuine multidimensional improvement rather than sensitivity to a specific set of weights.

A.6 Stress Test Calibration

DDEP Scenario: A one-time 30 percent haircut is applied to the government bond component of the portfolio in year 5. This is calibrated to approximate the net present value loss experienced by bondholders under Ghana's 2022–23 Domestic Debt Exchange Programme, after accounting for the special terms negotiated for pension funds (15 percent face value uplift, 5 percent cash coupon, extended maturities).

Inflation Spike Scenario: A sustained 10 percentage point increase in inflation is applied for years 5–7. This is calibrated to Ghana's experience during 2022–23, when inflation rose from approximately 13 percent to over 54 percent. The scenario captures the compound effect of inflation on nominal bond returns and cost-of-living adjustments.

Currency Crisis Scenario: A 50 percent depreciation of the Ghanaian cedi is applied in year 8, calibrated to the cumulative depreciation experienced during Ghana's 2022 exchange rate adjustment. The scenario includes pass-through effects on domestic inflation (15 percentage points), negative bond return effects (through imported inflation and policy rate responses), and positive infrastructure return effects (through foreign-currency-denominated project revenues).

Combined Scenario: The DDEP and inflation spike scenarios occur simultaneously, capturing the compound sovereign-macro stress that Ghana experienced during 2022–23.

A.7 Institutional Constraint Calibration

Liquidity Penalty: The penalty function is calibrated based on the illiquidity characteristics of private infrastructure assets and the liquidity requirements of defined-contribution pension schemes entering their decumulation phase.

Infrastructure Allocation	**Liquidity Penalty (SARI points)**	**Rationale**
0–15%	0	No material liquidity impact
15–25%	3	Mild — manageable with liquid bond and equity buffers
25–35%	8	Moderate — begins to constrain benefit payment flexibility
35–45%	15	Significant — requires committed liquidity management

>45%	25	Severe — illiquidity risk becomes a first-order concern

Absorption Capacity: The pipeline constraint caps are calibrated based on NPRA estimates of currently identifiable bankable infrastructure projects in Ghana. The "moderate pipeline" cap of 15 percent reflects the share of total pension AUM (approximately GHS 9.6 billion) that could be absorbed by projects currently at financial close or in advanced procurement. The "severe constraint" cap of 8 percent reflects projects at financial close only.

A.8 Data Sources

Data	Source	Period	Frequency
GSE Composite Index	Ghana Stock Exchange	Jan 2015 – Mar 2026	Daily
GSE Financial Index	Ghana Stock Exchange	Jan 2015 – Mar 2026	Daily
GII US Infrastructure Index	Global Infrastructure Index	Jan 2007 – Feb 2026	Monthly
IGF US Infrastructure Financials	Global Infrastructure Index	Jan 2007 – Feb 2026	Monthly
91-Day, 182-Day, 364-Day T-Bill Rates	Bank of Ghana	Jan 2015 – Feb 2026	Weekly
2YR–20YR Fixed-Rate Bond Yields	Bank of Ghana	2015–2025	Per auction
GDP Growth, Inflation, Terms of Trade	World Development Indicators	1961–2024	Annual
Monetary Policy Rate	Bank of Ghana MPC	2002–2026	Per meeting
Pension Fund Asset Allocation	NPRA Statistical Bulletin	Q1–Q4 2025	Quarterly

A.9 Reproducibility

All simulations are implemented in Python 3.14 using NumPy, pandas, and SciPy. The codebase is organised in a modular structure separating data loading, shock estimation, portfolio simulation, SARI computation, and visualisation. Random number generation uses a fixed seed (42) to ensure exact reproducibility. The complete code and processed datasets are available from the authors upon request

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