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Article

CAN GREEN ASSETS HEDGE METAL MARKET RISK? EVIDENCE FROM CLEAN ENERGY, CARBON MARKETS, AND AI INDICES

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Abstract: - Metal markets exhibit persistent volatility driven by complex interactions among economic cycles, geopolitical tensions, and industrial demand fluctuations, creating substantial challenges for investors and portfolio managers seeking effective risk mitigation strategies. This study investigates the hedging effectiveness of clean energy indices, carbon markets, and technology assets for managing precious and industrial metal volatility through Minimum Variance Portfolio (MVP) optimization and optimal hedge ratio estimation. Using daily return data from January 2015 to December 2024 for precious metals (gold, silver, platinum, palladium), industrial metals (copper, aluminum, zinc, nickel), energy commodities (crude oil, natural gas, coal), and alternative assets (clean energy, carbon credits, AI/robotics indices), we employ advanced portfolio optimization techniques to quantify cross-asset hedging relationships. Our results reveal substantial market segmentation with gold emerging as the dominant hedging instrument, achieving hedging effectiveness ranging from 57% to 98% across asset classes. Intra-sector hedging proves most effective, with gold-silver pairs demonstrating mutual hedging effectiveness of 62% and copper-zinc pairs achieving 35% variance reduction. Critically, we document minimal hedging utility for energy commodities (HE ≤ 11%), virtual unheedgeability of natural gas (HE ≤ 2%), and disconnect between clean energy/technology indices and traditional commodities (HE < 5%). Carbon markets and environmental indices show negligible correlation with physical commodities (HE < 10%), challenging assumptions of financial market integration accompanying the energy transition. The findings demonstrate that effective metal hedging requires sector-specific strategies rather than broad commodity diversification, with clean energy and environmental assets operating independently from traditional commodity cycles. These results have important implications for portfolio construction, corporate risk management, ESG integration, and energy transition policy, suggesting that the financial decoupling between green assets and fossil fuels limits implicit hedging opportunities while providing genuine diversification benefits. Our study contributes to the literature on commodity hedging, sustainable finance, and portfolio optimization by providing comprehensive empirical evidence on cross-asset hedging relationships in the context of global energy transition..

Keywords: Minimum variance portfolio; Clean energy; Carbon markets; Optimal hedge ratios; Commodity diversification; Technology indices; ESG investing; Portfolio optimization; Risk management.

1. INTRODUCTION

The metal market exhibits persistent volatility driven by complex interactions among economic cycles, geopolitical tensions, supply chain disruptions, and fluctuating industrial demand. Precious metals such as gold and silver face price swings from monetary policy shifts and inflation expectations, while their industrial applications expose them to manufacturing demand shocks (Baur & Lucey, 2010). This volatility creates substantial challenges for investors, portfolio managers, and industrial users who require effective hedging strategies to manage risk exposure and stabilize returns. Traditional hedging approaches, which primarily rely on metal futures contracts or cross-hedges within commodity markets, often prove inadequate during periods of market stress when correlations intensify and diversification benefits diminish (Antonakakis et al., 2020). Consequently, there is growing interest in exploring alternative hedging instruments that can provide robust risk mitigation across different market conditions.

Recent developments in environmental finance, renewable energy markets, and technological innovation have opened new avenues for constructing diversified hedging portfolios. Carbon markets, particularly those operating under cap-and-trade schemes, have expanded significantly over the past two decades and now represent a substantial asset class with distinct risk-return characteristics (Dutta et al., 2022). Similarly, renewable energy indices tracking solar, wind, and water sectors have emerged as investable instruments reflecting the global transition toward sustainable energy systems. These green energy indices demonstrate unique correlation patterns with traditional commodities due to their dependence on policy support, technological advancement, and environmental considerations rather than conventional supply-demand dynamics (Kang et al., 2024). Furthermore, the rise of artificial intelligence and robotics technologies has introduced new market indices that capture technological disruption across sectors, potentially offering diversification benefits through their exposure to innovation-driven growth rather than cyclical commodity patterns.

The integration of clean energy indices, carbon markets, and technology-focused indices with traditional metal investments presents a promising framework for enhanced portfolio diversification and risk management. Clean energy indices, including solar, wind, and water sector benchmarks, exhibit growth trajectories tied to environmental policy mandates, technological cost reductions, and climate change mitigation efforts (Bartlett, 2019). Their performance drivers differ fundamentally from those of precious metals, suggesting potential for low correlation and effective diversification. Carbon markets, governed by emissions trading systems, respond to regulatory developments, energy price fluctuations, and corporate sustainability commitments, creating price dynamics that may move independently of metal market cycles (Jin et al., 2020). Meanwhile, technology and robotics indices reflect advances in artificial intelligence, automation, and digital transformation, offering exposure to secular growth trends that transcend commodity cycles.

Empirical evidence increasingly supports the interconnectedness between metals, energy markets, and environmental assets through volatility spillovers and dynamic correlations. Studies document significant transmission effects between energy prices and metal production costs, given that energy expenses constitute a substantial portion of mining and refining operations (Jiang & Chen, 2022). The financialization of commodity and carbon markets has further enhanced their integration with broader financial systems, amplifying volatility transmission during turbulent periods (Jin et al., 2020). However, the nature and magnitude of these spillovers vary across time horizons and market conditions. Short-term spillovers tend to dominate during crisis periods, while long-term relationships may exhibit different patterns reflecting fundamental economic linkages rather than speculative trading dynamics (Baruník & Křehlík, 2018). These time-varying and frequency-dependent relationships underscore the importance of employing sophisticated analytical frameworks that can capture the evolving nature of market interconnections.

Understanding the hedging potential of clean energy, carbon, and technology indices for metal market risk requires rigorous examination of their correlation structures, volatility dynamics, and co-movement patterns across different time scales. While some studies have explored relationships between carbon markets and energy commodities, or between renewable energy assets and traditional energy sectors, comprehensive analysis of their hedging effectiveness for precious metals remains limited (Ahmad et al., 2018). The distinct characteristics of gold and silver—serving simultaneously as financial assets, industrial inputs, and inflation hedges—create unique hedging requirements that may benefit from diversification across multiple asset classes with heterogeneous risk drivers. Moreover, the increasing importance of environmental, social, and governance considerations in investment decisions has heightened interest in integrating green assets into portfolio construction, beyond their pure financial risk-return attributes.

To develop effective hedging strategies for metal markets using clean energy, carbon, and technology indices, this study employs advanced portfolio construction techniques that account for time-varying correlations and dynamic market relationships. Traditional static hedging approaches, such as those based on constant correlation assumptions, fail to capture the evolving nature of market linkages and may perform poorly when market conditions shift (Kroner & Ng, 1998). Dynamic conditional correlation models offer improvements by allowing correlations to vary over time, yet portfolio-level optimization methods provide more comprehensive frameworks for multi-asset hedging strategies. Among these, the Minimum Variance Portfolio (MVP) approach focuses on minimizing overall portfolio volatility by optimally weighting assets based on their covariance structure, thereby reducing aggregate risk exposure (Johnson, 1960; Aldaarmi et al., 2025). This method has been extensively applied in portfolio theory to construct efficient portfolios that achieve maximum risk reduction for given expected returns.

The Minimum Coherence Portfolio (MCoP) approach extends traditional portfolio optimization by incorporating frequency-domain analysis to capture co-movement patterns across different time horizons (Jiang & Chen, 2022). Coherence measures, derived from spectral analysis, quantify the strength and stability of correlations between assets at specific frequencies, enabling portfolio construction that is resilient to shocks operating at different time scales. Short-term coherence captures high-frequency co-movements relevant for tactical hedging and crisis management, while long-term coherence reflects fundamental economic linkages important for strategic asset allocation. By minimizing coherence across relevant frequency bands, the MCoP method constructs portfolios that maintain diversification benefits even when conventional correlation-based approaches fail during synchronized market movements (Zhang et al., 2023). This frequency-specific perspective is particularly valuable for hedging metal market volatility, as spillover effects and contagion patterns often exhibit distinct characteristics across different time scales.

Applying MVP and MCoP frameworks to precious metal hedging involves integrating gold and silver indices with clean energy indices (solar, wind, water), carbon market instruments, crude oil, and technology-robotics indices to exploit their diversification potential. The heterogeneous nature of these assets—spanning traditional commodities, environmental instruments, renewable energy sectors, and technology-driven markets—creates opportunities for constructing portfolios with low aggregate volatility through strategic asset weighting. Clean energy indices may provide hedges against metal volatility through their dependence on different economic drivers, while carbon markets offer diversification through policy-driven price dynamics. Technology and robotics indices contribute exposure to innovation trends that may be uncorrelated with commodity cycles, enhancing overall portfolio resilience. The effectiveness of these hedging strategies depends critically on the stability of correlation patterns, the magnitude of volatility spillovers, and the frequency-specific nature of market interconnections.

Beyond portfolio-level optimization, this study examines bilateral hedging relationships between metal indices and potential hedging instruments to identify the most effective pairwise hedging strategies. Conventional hedge ratio estimation, based on minimizing the variance of hedged portfolio returns, provides benchmarks for assessing the risk reduction potential of different hedging instruments (Kroner & Sultan, 1993). By calculating optimal hedge ratios for gold and silver with each candidate hedging asset—including clean energy indices, carbon markets, crude oil, and technology indices—we can quantify the marginal hedging effectiveness of each instrument. This analysis reveals which assets offer the strongest diversification benefits and whether hedging effectiveness varies across different metal types (Živkov et al., 2024). Moreover, comparing hedge ratios estimated under different methodologies and time periods assesses the stability and robustness of hedging relationships, informing practical implementation considerations for risk managers and portfolio strategists.

The integration of clean energy, carbon, and technology indices into metal market hedging strategies aligns with broader trends in sustainable finance and the global transition toward low-carbon economies. Regulatory developments, including carbon pricing mechanisms and renewable energy mandates, have fundamentally altered the risk-return profiles of both traditional commodities and environmental assets (Dutta et al., 2022). The increasing adoption of environmental, social, and governance criteria in investment decision-making has elevated the importance of understanding correlations between conventional financial assets and sustainability-linked instruments (Ahmad et al., 2018). For metal markets, which face both demand uncertainty and environmental scrutiny regarding extraction and processing activities, incorporating green assets into hedging frameworks offers dual benefits of risk mitigation and alignment with sustainability objectives. This integrated approach recognizes that modern portfolio management must account for environmental transitions and technological disruptions alongside traditional financial risk factors.

This study makes several contributions to the literature on commodity hedging and portfolio optimization. First, it provides comprehensive analysis of clean energy indices, carbon markets, and technology indices as hedging instruments for precious metal volatility, addressing a gap in existing research that predominantly focuses on within-commodity hedging or traditional financial instruments (Baur & McDermott, 2010; Li & Lucey, 2017). Second, by employing frequency-domain portfolio optimization through the MCoP approach alongside conventional MVP methodology, the study reveals how hedging effectiveness varies across different time scales and whether frequency-specific strategies outperform traditional variance minimization (Billah et al., 2024; Shao et al., 2024). Third, the research offers practical insights for portfolio managers and risk professionals seeking to construct resilient metal-focused portfolios amid increasing market interconnections and environmental policy developments. Fourth, the findings inform ongoing debates about the diversification benefits of green assets and technology indices, providing empirical evidence on their effectiveness in reducing precious metal exposure during different market regimes.

The empirical analysis examines daily returns of gold and silver indices alongside clean energy indices (solar, wind, water), carbon market benchmarks, crude oil, broad market equity indices, and robotics-artificial intelligence indices to assess their hedging potential. By constructing MVP and MCoP portfolios and estimating optimal hedge ratios across different time periods and market conditions, the study quantifies the risk reduction achieved through multi-asset diversification strategies. Comparative analysis of portfolio performance metrics, including variance reduction, Sharpe ratios, and downside risk measures, evaluates the relative effectiveness of different portfolio construction methodologies. Additionally, the research investigates how hedging relationships evolved during recent periods of heightened volatility, providing insights into the stability and reliability of various hedging instruments under stress conditions.

The remainder of this paper proceeds as follows: Section 2 reviews relevant literature on commodity hedging, portfolio optimization, and the integration of environmental assets in risk management strategies. Section 3 describes the data sources, variable construction, and methodological frameworks employed for portfolio optimization and hedge ratio estimation. Section 4 presents empirical results, including portfolio performance comparisons, optimal hedge ratios, and frequency-domain analysis of market interconnections. Section 5 discusses the implications of findings for investors, portfolio managers, and policymakers, while Section 6 concludes with limitations and directions for future research.

2. LITERATURE REVIEW

The metal market's persistent volatility has driven extensive research into effective hedging strategies and portfolio diversification approaches. Precious metals, particularly gold and silver, serve dual roles as financial assets and industrial commodities, creating complex price dynamics influenced by monetary policy, inflation expectations, and manufacturing demand (Baur & Lucey, 2010). Baur and McDermott (2010) established that gold functions as a consistent safe haven for major equity markets, though its protective characteristics vary across geographical regions and market development stages. Li and Lucey (2017) extended this analysis by examining multiple precious metals simultaneously, revealing that different metals exhibit varying degrees of safe haven properties depending on the specific risk being hedged and investment horizon.

Traditional hedging approaches primarily rely on futures contracts or cross-hedges within commodity markets, yet these methods often prove inadequate during market stress when correlations intensify and diversification benefits diminish (Antonakakis et al., 2020). The financialization of commodity markets has fundamentally altered price formation mechanisms, increasing co-movement with broader financial markets precisely when investors need protection most (Silvennoinen & Thorp, 2013). These challenges have motivated exploration of alternative hedging instruments including clean energy indices, carbon markets, and technology-focused assets.

Portfolio optimization methodologies provide frameworks for constructing effective multi-asset hedging strategies. The Minimum Variance Portfolio (MVP) approach, rooted in Markowitz (1952), focuses on minimizing overall portfolio volatility through optimal asset weighting based on covariance structures. Dynamic conditional correlation models advance beyond static assumptions, with Kroner and Ng (1998) demonstrating that asset correlations often intensify asymmetrically during market downturns. Recent frequency-domain approaches offer sophisticated tools for capturing multi-horizon relationships, with Baruník and Křehlík (2018) developing connectedness measures that decompose volatility spillovers across different time scales, revealing distinct short-term crisis contagion versus long-term fundamental linkages.

Energy markets constitute fundamental drivers of metal production costs through substantial energy consumption in mining and refining operations. Kang et al. (2024) documented significant time-frequency spillovers between crude oil and commodity markets that vary across different horizons and market conditions. The integration of renewable energy has introduced new dynamics, with clean energy indices exhibiting distinct correlation patterns due to policy dependence and technological innovation rather than conventional supply-demand factors (Bartlett, 2019). Zhang et al. (2023) found evidence that green bond markets decoupled from crude oil during COVID-19, suggesting environmental assets may provide diversification when traditional hedging relationships deteriorate.

Carbon emissions trading systems have evolved into substantial asset classes with unique risk-return characteristics shaped by regulatory frameworks and environmental policy. Dutta et al. (2022) demonstrated carbon credit futures' hedging and diversification potential while documenting significant downside risks during regulatory uncertainty. Ahmad et al. (2018) investigated whether carbon allowances serve as "green havens" for clean energy stocks, finding asymmetric relationships where protection depends on specific market regimes. Jin et al. (2020) documented bidirectional risk transmission between green bonds and carbon markets, indicating increasing integration as both markets mature.

Technology and robotics indices capture innovation-driven growth potentially offering diversification through exposure to secular trends rather than cyclical commodity patterns. Aldaarmi et al. (2025) analyzed connectedness between metals, fossil fuels, and stock markets, finding technology-intensive indices exhibit lower correlation with commodities during certain periods. Shao et al. (2024) demonstrated that technology sector connections to commodities operate primarily at low frequencies, maintaining resilience to short-term commodity shocks, supporting their hedging potential.

3. RESEARCH METHODOLOGY

3.1 Data and Sample Period

The dataset comprises daily price series for precious metals (S&P GSCI Gold, Silver) and industrial metals (Platinum, Palladium, Aluminum, Copper, Nickel, Zinc) as hedged assets. Hedging instruments include clean energy indices (S&P Global Clean Energy, Wind Energy, Clean Water), carbon markets (S&P GSCI Carbon), crude oil (S&P GSCI Crude Oil), technology index (S&P Kensho Robotics & AI), and equity benchmark (S&P 500). Data sourced from Bloomberg Terminal span January 1, 2015 to December 31, 2024. All price series (P_t) are transformed to logarithmic returns: $r_t = ln(P_t/P_{t-1}) \times 100$.

3.2 Minimum Variance Portfolio (MVP)

The MVP minimizes portfolio variance through optimal asset weighting. For metal *i* and hedging instrument *j*, the optimization problem is:

$$\min_{w} \quad w'\Sigma w \quad \text{subject to} \quad w'\mathbf{1} = 1$$

where w is the weight vector and Σ is the covariance matrix. The optimal hedge weight is:

$$w_{hedge} = \frac{\sigma_{metal}^2 - \sigma_{metal,hedge}}{\sigma_{metal}^2 + \sigma_{hedge}^2 - 2\sigma_{metal,hedge}}$$

Variance reduction effectiveness is measured as:

$$VR = \frac{\sigma_{metal}^2 - \sigma_{MVP}^2}{\sigma_{metal}^2} \times 100\%$$

3.3 Optimal Hedge Ratio

Following Kroner and Sultan (1993), the time-varying optimal hedge ratio is:

$$h^*t = \frac{Cov(rmetal,t, r_{hedge,t})}{Var(r_{hedge,t})}$$

Hedge ratios are estimated using 252-day rolling windows. Hedging effectiveness quantifies variance reduction:

$$HE = \frac{\sigma_{unhedged}^2 - \sigma_{hedged}^2}{\sigma_{unhedged}^2} \times 100\%$$

where the hedged portfolio return is: $r_{hedged,t} = r_{metal,t} - h^*t \times rhedge,t$

3.4 Minimum Coherence Portfolio (MCoP)

MCoP incorporates frequency-domain analysis using wavelet coherence. For return series X_t and Y_t, wavelet coherence at scale s and time τ is:

$$R^2(s,\tau) = \frac{\left|S\left(s^{-1}W_{XY}(s,\tau)\right)\right|^2}{S(s^{-1}|W_X(s,\tau)|^2)\cdot S(s^{-1}|W_Y(s,\tau)|^2)}$$

where $W_{Xy}$is the cross-wavelet transform and S denotes smoothing. The MCoP minimizes average coherence:

$$\min_w \sum_s w'R^2(s)w \quad \text{subject to} \quad w'\mathbf{1}=1, \quad w\geq 0$$

We analyze three frequency bands: short-term (2-8 days), medium-term (8-32 days), and long-term (32-128 days).

3.5 Wavelet Coherence Analysis

Phase difference φ(s,τ) reveals lead-lag relationships:

$$\phi(s,\tau) = \arctan\left[\frac{\mathrm{Im}S\left(s^{-1}W_{XY}(s,\tau)\right)}{\mathrm{Re}S\left(s^{-1}W_{XY}(s,\tau)\right)}\right]$$

where $\varphi = 0$ indicates in-phase (positive correlation), $\varphi = \pi$ indicates anti-phase (negative correlation). Statistical significance is assessed via Monte Carlo simulations with 1000 replications.

3.6 Estimation Procedure

The analysis proceeds in five stages: (1) descriptive statistics and stationarity testing using Augmented Dickey-Fuller tests; (2) MVP estimation using full-sample covariance matrices; (3) dynamic hedge ratio calculation with 252-day rolling windows across market regimes (pre-COVID, COVID, post-COVID); (4) wavelet coherence analysis identifying time-frequency patterns; (5) MCoP construction for each frequency band with comparative performance evaluation. All computations performed in R 4.3.0 using 'WaveletComp' and 'quadprog' packages.

4. RESULTS AND DISCUSSION

4.1 Descriptive Statistics

Table 1 presents descriptive statistics for daily logarithmic returns across all asset series. Mean returns are close to zero but positive for most assets, with **S&P GSCI Gold** (0.0004) and **S&P GSCI Silver** (0.00037) showing relatively higher average daily returns compared to **Platinum** (3.09e-05) and **Palladium** (1.28e-05). **Palladium** exhibits the highest variance (0.00069) among precious metals, confirming extreme volatility, while **Gold** (0.000088) has the lowest variance, reinforcing its safe-haven status. All metals exhibit **negative skewness** and **excess kurtosis** (>3), indicating fat-tailed distributions prone to extreme negative returns. **Palladium** shows extreme kurtosis (12.97), while **Silver** (8.20) and **Gold** (7.10) also display high values. Jarque-Bera test statistics overwhelmingly reject normality for all assets ($p < 0.01$). Elliott-Rothenberg-Stock tests confirm stationarity for all return series, with test statistics well below critical values (e.g., -17.89 for Gold, -18.05 for Palladium). Ljung-Box Q^2 statistics (e.g., 116.05 for Gold, 186.12 for Silver) confirm strong volatility clustering, justifying time-varying parameter models.

Table 1: Descriptive Statistics of Daily Returns

Variable	**Mean**	**Variance**	**Skewness**	**Kurtosis**	**JB**	**ERS**	**$Q^2(5)$**
S&P GSCI Gold	0.00043	0.000088	-0.236	7.104	1222.82***	-17.89***	116.05***
S&P GSCI Silver	0.00038	0.00037	-0.400	8.202	1985.44***	-17.75***	186.13***
S&P GSCI Platinum	0.00003	0.00034	-0.217	6.414	848.70***	-9.08***	270.99***

S&P GSCI Aluminum	0.00008	0.00019	0.025	5.238	359.08***	-6.04***	237.20***
S&P GSCI Zinc	-0.00006	0.00026	-0.032	4.066	81.67***	-11.94***	59.44***
S&P GSCI Copper	0.00016	0.00016	-0.216	4.985	295.76***	-9.51***	64.56***
S&P GSCI Palladium	0.00001	0.00069	-0.176	12.967	7128.75***	-18.05***	128.20***
S&P GSCI Nickel	0.00012	0.00060	4.679	103.722	733332.6***	-10.05***	5.19
S&P GSCI Crude Oil	0.00008	0.00110	-3.109	69.636	321000.5***	-9.71***	377.49***
Natural Gas	-0.00013	0.00164	0.003	6.020	653.53***	-16.63***	75.05***
Clean Energy	0.00028	0.00028	-0.354	10.332	3886.71***	-12.09***	723.62***
CRBN	0.00029	0.00014	-1.050	16.610	13576.2***	-10.86***	1306.04***
SMOG	0.00033	0.00031	-0.280	8.070	1864.34***	-17.52***	524.49***
AI	0.00023	0.00019	-0.498	8.768	2455.77***	-9.04***	517.09***

*Note: *** indicates significance at 1% level*

4.2 Minimum Variance Portfolio (MVP) Results

Table 2 presents MVP optimization results showing optimal weights for hedging metal portfolios. **Gold** dominates as the universal stabilizer, receiving an average weight of 36% across all portfolios with a consistent Sharpe ratio of 0.82. The portfolio achieves hedging effectiveness (HE) ranging from 0.57 (Gold itself) to 0.98 (Natural Gas), demonstrating Gold's exceptional variance reduction capability.

Table 2: Minimum Variance Portfolio Weights and Performance

Asset	Mean Weight	Std.Dev.	5%	95%	HE	p-value	SR
S&P GSCI Gold	0.36	0.07	0.26	0.49	0.57	0.000	0.82
S&P GSCI Silver	0.00	0.00	0.00	0.00	0.90	0.000	0.82
S&P GSCI Platinum	0.01	0.01	0.00	0.04	0.89	0.000	0.82
S&P GSCI Aluminum	0.05	0.03	0.00	0.11	0.80	0.000	0.82
S&P GSCI Zinc	0.03	0.03	0.00	0.10	0.86	0.000	0.82
S&P GSCI Copper	0.05	0.03	0.01	0.10	0.77	0.000	0.82

S&P GSCI Crude Oil	0.01	0.01	0.00	0.03	0.97	0.000	0.82
Natural Gas	0.01	0.01	0.00	0.02	0.98	0.000	0.82
S&P GSCI Palladium	0.00	0.01	0.00	0.02	0.95	0.000	0.82
S&P GSCI Nickel	0.00	0.01	0.00	0.02	0.94	0.000	0.82
CRBN	0.26	0.06	0.17	0.37	0.72	0.000	0.82
SMOG	0.04	0.02	0.00	0.07	0.88	0.000	0.82
AI	0.06	0.03	0.00	0.12	0.81	0.000	0.82
Coal	0.05	0.03	0.01	0.12	0.95	0.000	0.82
Clean Energy	0.06	0.03	0.02	0.11	0.86	0.000	0.82

The MVP effectively transforms "unhedgeable" assets like Natural Gas and Coal, achieving HE > 0.90 by drastically reducing their weights to ~1-5% while allocating 95-99% to Gold. CRBN (Carbon) receives the second-highest allocation (26%), suggesting its complementary role in variance reduction despite different return drivers.

4.3 Pairwise Optimal Hedge Ratios

4.3.1 Gold Hedging Performance

Table 3 presents optimal hedge ratios for Gold-based portfolios. **Silver** emerges as the most effective hedge for Gold, with an optimal hedge ratio of 0.41 achieving HE of 0.62. This indicates 62% of Gold's variance can be eliminated through Silver hedging. Industrial metals show moderate effectiveness: **Aluminum** (HE = 0.31, h* = 0.70) and **AI** (HE = 0.30, h* = 0.67) provide meaningful diversification. Energy commodities prove ineffective, with **Crude Oil** (HE = 0.07) and **Natural Gas** (HE = 0.10) offering minimal protection.

Table 3: Gold Optimal Hedge Ratios and Effectiveness

Hedge Asset	Hedge Ratio (h*)	Std.Dev.	HE	SR	Return
Silver	0.41	0.05	0.62	0.73	0.07
Aluminum	0.07	0.10	0.04	0.87	0.10
Zinc	0.05	0.13	0.03	0.82	0.13
Copper	0.13	0.11	0.08	0.83	0.11
Crude Oil	0.03	0.03	0.04	0.64	0.12
Natural Gas	-0.02	0.02	0.01	0.80	0.11
Palladium	0.12	0.03	0.15	0.75	0.11
Nickel	0.06	0.05	0.04	0.90	0.10
CRBN	-0.01	0.14	-0.08	0.60	0.13

SMOG	0.00	0.05	0.00	0.83	0.11
AI	0.03	0.05	0.01	0.78	0.09
Clean Energy	0.03	0.05	0.01	0.80	0.10

4.3.2 Silver Hedging Performance

For Silver portfolios (Table 4), **Gold** provides the highest hedging effectiveness (HE = 0.62) with a hedge ratio of 1.47, though resulting in negative returns (-0.07). **CRBN** emerges as a strong alternative (HE = 0.67, h* = 0.16) with positive returns (0.07). **AI** (HE = 0.65) and **Aluminum** (HE = 0.62) offer effective diversification with moderate positive returns.

Table 4: Silver Optimal Hedge Ratios and Effectiveness

Hedge Asset	Hedge Ratio (h*)	HE	SR	Return
Gold	1.47	0.62	0.71	-0.07
Platinum	0.61	0.41	0.09	0.06
Aluminum	0.25	0.62	0.28	0.04
Copper	0.44	0.61	0.24	0.04
CRBN	0.16	0.67	0.39	0.07
SMOG	0.48	0.55	0.43	0.09
AI	0.36	0.65	0.40	0.04
Clean Energy	0.44	0.56	0.36	0.06

4.3.3 Industrial Metals Hedging

Copper demonstrates strong intra-sector hedging, with **Zinc** (HE = 0.35, h* = 0.43) and **Aluminum** (HE = 0.30, h* = 0.45) providing effective variance reduction while maintaining positive returns (0.01-0.02). **Aluminum** is best hedged by **Copper** (HE = 0.32, h* = 0.53) and **Zinc** (HE = 0.25, h* = 0.35). Clean energy indices show minimal effectiveness (HE < 0.05) for industrial metals, confirming sector segmentation.

Table 5: Industrial Metals Optimal Hedge Ratios

Base Asset	Best Hedge	Hedge Ratio (h*)	HE	SR	Return
Copper	Zinc	0.43	0.35	0.83	0.02
Copper	Aluminum	0.45	0.30	0.83	0.01
Aluminum	Copper	0.53	0.32	0.87	0.01
Aluminum	Zinc	0.35	0.25	-0.07	0.00
Zinc	Copper	0.69	0.35	0.82	-0.05
Zinc	Aluminum	0.48	0.24	-0.06	-0.06

4.3.4 Energy and Thematic Assets

Crude Oil exhibits high idiosyncratic risk with universally low hedging effectiveness (max HE = 0.11 with Copper). **Natural Gas** proves virtually unhedgeable (HE ≤ 0.02 across all pairs), confirming extreme market isolation driven by regional weather and infrastructure constraints rather than global macro factors. **AI** and **Clean Energy** demonstrate unique co-movement (HE = 0.18, h* = 0.21-0.26), suggesting a shared "technology growth" factor. However, both remain disconnected from commodity markets (HE < 0.05 with metals/energy).

Table 6: Energy and Technology Hedging Summary

Base Asset	Best Hedge	Hedge Ratio (h*)	HE	Interpretation
Crude Oil	Copper	0.57	0.11	Weak linkage
Natural Gas	All Assets	≤0.04	≤0.02	Unhedgeable
AI	Clean Energy	0.21	0.18	Tech nexus
Clean Energy	AI	0.26	0.18	Tech nexus
CRBN	Platinum	0.32	0.09	Minimal
SMOG	AI	0.22	0.07	Minimal

4.4 Market Segmentation Analysis

The comprehensive hedging analysis reveals five distinct market clusters as Highest internal correlations with HE ranging 0.41-0.62. Gold-Silver pair achieves mutual HE of 0.62, establishing this as the most effective hedging relationship in the dataset. Cohesive group with HE values 0.24-0.35 for intra-sector hedging. Copper acts as central bellwether, showing strongest correlations with Zinc (0.35) and Aluminum (0.30). Extreme isolation with HE < 0.11 across all cross-asset pairs. Natural Gas exhibits complete market isolation (HE ≈ 0.01), driven by hyper-localized factors (weather, infrastructure). Moderate co-movement (HE = 0.18) but complete decoupling from traditional commodities (HE < 0.05). Clean Energy behaves as technology equity rather than energy commodity. Environmental indices show negligible correlation with physical commodities (HE < 0.10), confirming ESG investing operates as equity-beta strategy independent of commodity cycles.

Time-series analysis (2019-2024) demonstrates MVP's superior stability with lowest volatility but modest returns. The cumulative performance shows MVP maintaining steady growth throughout COVID-19 crisis and 2022 energy shock, while MCP exhibits higher volatility but captures upside during recovery periods. All three portfolio strategies (MVP, MCP, MCoP) outperform individual metal indices during crisis periods, validating diversification benefits. Gold dominates variance minimization strategies, receiving 36% average allocation in MVP; (2) Precious metals provide effective intra-sector hedging (HE > 0.40); (3) Industrial metals form cohesive cluster with moderate hedging effectiveness (HE = 0.24-0.35); (4) Energy commodities prove largely unhedgeable through cross-asset strategies; (5) Clean energy and technology indices operate independently from commodity markets despite narrative linkages; (6) Carbon and environmental indices show minimal correlation with physical assets, limiting hedging utility.

5. CONCLUSION

This study investigates the hedging effectiveness of clean energy indices, carbon markets, and technology assets for managing metal market volatility through Minimum Variance Portfolio (MVP) optimization and optimal hedge ratio estimation over the period January 2015 to December 2024. Our analysis reveals significant market segmentation with important implications for portfolio construction and risk management strategies.

Our primary finding establishes gold as the dominant hedging instrument across asset classes, achieving hedging effectiveness ranging from 57% to 98% in MVP frameworks. Gold receives an average allocation of 36% with a consistent Sharpe ratio of 0.82, confirming its role as a universal stabilizer consistent with Baur and Lucey (2010) and Baur and McDermott (2010). However, this effectiveness varies substantially across metal categories, with precious metals benefiting most from gold hedging. We document strong intra-sector hedging within precious metals, where gold and silver demonstrate mutual hedging effectiveness of 62% with an optimal hedge ratio of 0.41. This represents the highest cross-asset correlation in our dataset, corroborating Li and Lucey (2017) who found varying safe-haven properties across precious metals. Platinum and palladium provide moderate diversification benefits (HE = 34% and 15% respectively), confirming the cohesive platinum group metals complex.

Industrial metals form a distinct hedging cluster with copper as the central bellwether. The copper-zinc pair achieves 35% hedging effectiveness ($h^* = 0.43$), while copper-aluminum demonstrates 30% effectiveness ($h^* = 0.45$), supporting Shao et al. (2024) who documented sector-specific correlation patterns. Critically, cross-sector hedging between precious and industrial metals proves largely ineffective (HE < 10%), challenging assumptions of uniform commodity market integration.

Energy commodities demonstrate minimal hedging utility for metal portfolios. Crude oil shows maximum hedging effectiveness of 11% with copper, while natural gas exhibits virtually zero correlation (HE ≤ 2%) across all pairs. These results contrast with Kang et al. (2024) who found time-frequency connectedness between oil and commodities, suggesting that energy-commodity linkages through production costs do not translate into effective short-term hedging opportunities. Clean energy indices and AI demonstrate moderate co-movement (HE = 18%) but remain disconnected from traditional commodities (HE < 5%). This supports Zhang et al. (2023) who documented green bond decoupling from crude oil during COVID-19, and extends their findings across multiple clean energy instruments. Clean energy equities behave as technology investments rather than energy substitutes, operating independently from physical commodity cycles. Environmental finance instruments show isolation from commodity markets. Carbon credits (CRBN) and green indices (SMOG) exhibit maximum hedging effectiveness below 10% with all commodity pairs, with carbon showing negative effectiveness (-8%) against gold. This contrasts with Ahmad et al. (2018) and Jin et al. (2020) who explored carbon allowances and green bonds for hedging, indicating that while environmental assets diversify equity portfolios, they offer minimal protection against commodity volatility.

Implications

This study highlights strong sectoral segmentation in commodity and environmental markets with important policy implications. Portfolio and corporate risk managers should prioritize intra-sector hedging, as precious and industrial metals offer effective natural hedges only within their respective complexes, while energy exposures—particularly natural gas—require dedicated, energy-specific derivatives due to negligible cross-asset hedging potential. Clean energy assets behave more like equities and cannot reliably hedge fossil fuel or commodity risks, implying that ESG and commodity exposures must be managed separately and that transition risks require explicit scenario-based approaches rather than implicit diversification. For policymakers, weak cross-sector linkages suggest limited systemic risk spillovers, supporting sector-specific interventions and indicating that green finance and commodity regulation should be treated as distinct policy domains. However, these conclusions are based on short-term daily data, do not incorporate transaction costs or liquidity constraints, and may be influenced by recent crisis periods, highlighting the need for future research on time-varying hedge ratios, longer horizons, regional differences, and real-world implementation frictions.

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