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EXECUTIVE SUMMARY OF THE THESIS

Hedging Carbon Price Risk in Carbon-Intensive Sectors: Evidence from EU ETS-Regulated and Non-EU ETS-Regulated Firms

Tesi Magistrale in Management Engineering - Ingegneria Gestionale

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1. Introduction

The European Union (EU) aims to achieve its climate targets while preserving the competitiveness of its industries. The EU ETS is the main policy instrument used to achieve this objective and covers approximately 40% of the EU's greenhouse gas emissions [1]. Over the last decade, the EU ETS has undergone several reforms that strengthened the carbon price signal. From the beginning of 2018 to 2022, EU allowance (EUA) prices increased from below €10 per tonne to above €90 [3]. The increase in EUA prices was influenced by regulatory reforms and market developments, including the Market Stability Reserve (MSR), the strengthened Linear Reduction Factor of Phase IV, the *Fit for 55* package, and the 2022 European energy crisis [4, 5, 3]. As EUA prices increased, carbon price risk became an important financial risk factor for European firms operating in carbon-intensive sectors. Evidence shows that carbon policy shocks affect the valuation of carbon-intensive European firms [9] and the volatility transmission between EUA futures and sector equity indices increases during economic stress periods [10, 11]. However, there is still limited evidence on whether these relationships differ between EU ETS-regulated and non-EU ETS-regulated firms within and across sectors and how they evolve across different regulatory and macroeconomic regimes.

This thesis analyzes the dynamic hedging relationships between European sectoral equity portfolios and carbon and energy commodity futures. The analysis focuses on the differences between EU ETS-regulated and non-EU ETS-regulated equity portfolios within and across sectors and how these relationships change across different regulatory and macroeconomic regimes over the 2013-2026 period. The resulting hedge ratios, hedging effectiveness measures, and optimal portfolio weights are evaluated for the full sample and across six sub-periods, while risk-adjusted portfolio performance measures are used to compare different hedging strategies.

2. Literature Review

The literature examining the EU ETS has largely focused on three related areas: the determinants of carbon prices, the transmission of carbon-market shocks to financial markets, and the role of carbon assets in portfolio risk management. First, the literature shows that EUA prices are influenced by both energy-market conditions and regulatory developments. On the energy side, fuel-switching decisions have been identified as an important driver of carbon prices [19, 20, 21]. In addition, carbon prices are shaped by regulatory reforms, as well as by expectations about future climate policy and the availability of emission allowances [4, 5].

Second, as the EU ETS has developed, its interaction with financial markets has become increasingly relevant. Previous studies highlight that carbon policy shocks directly influence the valuation of carbon-intensive firms, as their stock prices respond more strongly to changes in EUA prices [9]. Research also finds that links between carbon, energy, and equity markets change over time and become stronger during periods of economic stress [10, 11]. Especially during the COVID-19 pandemic and the 2022 European energy crisis, volatility spread more strongly across carbon, energy, and financial markets [10, 11, 12]. In addition to crisis periods, the EU ETS has undergone important regulatory changes, including the introduction of the MSR and the Carbon Border Adjustment Mechanism

(CBAM). The MSR was introduced to strengthen the carbon price signal within the EU ETS by adjusting the EUA supply, and the CBAM expanded the scope of European carbon regulation to selected imported goods [2, 14]. Together with major economic events, these developments suggest that the transmission of carbon-market shocks may differ across market regimes.

Third, previous studies indicate that the impact of carbon costs is not uniform across industries. While electricity firms are often able to pass a large share of carbon costs on to consumers, this is generally more difficult for manufacturing firms because of trade exposure, production constraints, and differences in abatement flexibility [6, 7, 8]. As a result, carbon-price risk may affect firms differently across industries and across different regulatory and macroeconomic environments. This indicates that both sectoral characteristics and market conditions should be taken into account when evaluating hedging relationships.

2.1. Identified Gaps

The existing literature provides important evidence on the interaction between carbon, energy, and equity markets. However, most studies focus either on broad market indices or on individual sectors without distinguishing between EU ETS-regulated and non-EU ETS-regulated firms [9, 13]. As a result, it remains unclear whether firms subject to EU ETS compliance obligations exhibit different hedging relationships from non-EU ETS-regulated firms.

In addition, existing studies usually apply the same set of hedging assets across sectors despite their differences in production structures, energy inputs, and exposure to carbon costs [22]. Consequently, existing evidence provides only limited insight into how the relevance of different hedging assets varies across sectors.

Finally, even though the time-varying relationships between carbon, energy, and financial markets have been analyzed in the literature, the impacts of important developments such as the introduction of the MSR, the 2022 European energy crisis, and the CBAM Transitional period are rarely examined together within a single framework. Examining these periods together provides a more complete view of how hedging relationships evolve.

2.2. Research Question Definition

Given the previous considerations, this thesis addresses the following research question:

Do EU ETS-regulated and non-EU ETS-regulated firms within carbon-intensive sectors exhibit systematically different dynamic hedging relationships with EUA futures and sector-relevant energy commodities, and how do these differences vary across sectors and market regimes?

3. Data

The sample period spans from 1 January 2013 to 30 April 2026, covering Phase III of the EU ETS and the first years of Phase IV as well as the COVID-19 pandemic, the 2022 European energy crisis, the subsequent normalization period, and the CBAM transitional period. All return series are daily log returns expressed in euros.

3.1. Sector Portfolios

Sector portfolios are constructed from selected 2-digit NACE industries. Sector selection is based on three criteria: the sector's Scope 1 CO_2-equivalent emissions share, the direct coverage of its core activities under Annex I of the EU ETS Directive, and the availability of a sufficient number of listed EU ETS-regulated and non-EU ETS-regulated firms for portfolio construction. Four sectors are selected for the analysis that satisfy all the criteria: Electricity, Gas, Steam and Air Conditioning Supply (NACE 35), Manufacture of Basic Metals (NACE 24), Manufacture of Other Non-Metallic Mineral Products (NACE 23), and Manufacture of Chemicals and Chemical Products (NACE 20). Based on the emissions dataset used in this study, these sectors account for 68.01% of the aggregate Scope 1 CO_2-equivalent emissions across the NACE 2-digit industries considered for sector selection.

Firms within each sector are classified as EU ETS-regulated or non-EU ETS-regulated based on installation-level EU ETS coverage. This classification results in eight sector portfolios, one for each sector and regulatory-status combination. Sector indices are constructed using a monthly rebalanced equal-weighted approach, where all active firms receive equal weights at the beginning of each month and weights evolve with the relative stock-price performance of firms until the next rebalancing date.

3.2. Hedging Assets

Five hedging instruments are included in the analysis, namely EUA futures, TTF natural gas futures, Brent crude oil futures, Rotterdam coal futures, and gold. The asset combinations for each sector are selected based on the sectors' main carbon cost exposures, energy inputs, and production characteristics. EUA is paired with every sector since it is the main carbon-related risk factor studied in this thesis. Natural gas is also included for all sectors due to its importance in European energy markets and industrial production. Oil is paired with the Electricity and Chemicals sectors as developments in oil markets are relevant for electricity generation costs and petrochemical value chains. Coal is paired with Basic Metals and Non-Metallic Minerals due to its role in metal production and mineral-processing activities. Gold has no direct connection to the production activities of the selected sectors and is therefore included as a placebo asset to validate the empirical results [15]. This asset-selection framework results in thirty-two sector-asset pairs.

3.3. Sub-Periods

To assess the effects of regulatory and market changes, the full sample is divided into six sub-periods. First, the Phase III Low Price period (Jan 2013-Dec 2018) covers the years before the MSR framework, when EUA prices remained low. After that, the Post-MSR period (Jan 2019-Feb 2020) is analyzed, where the MSR framework was introduced, and the EUA prices increased sharply [4, 2]. The COVID-19 period (Mar-Dec 2020) covers the sharp decline in economic activity and the disruption of financial and commodity markets caused by the pandemic [12]. The Phase IV High Price period (Jan 2021-Dec 2022) represents an exceptionally high carbon and energy price window during the Fit for 55 package and the 2022 European energy crisis [5, 2]. The Phase IV Normalization (Jan-Sep 2023) is a relatively stable period between the energy crisis and the introduction of CBAM. Finally, the CBAM Transitional period (Oct 2023-Apr 2026) begins with the introduction of mandatory emissions reporting requirements for importers of cement, iron and steel, aluminum, fertilizers, electricity, and hydrogen and extends into the beginning of the CBAM Definitive Phase, under which importers are required to comply financially from January 2026 onwards [2, 14].

4. Methodology

4.1. Bivariate DCC-GARCH Framework

The dynamic relationship between each sector portfolio and hedging asset is estimated using the bivariate Dynamic Conditional Correlation (DCC)-GARCH model of Engle (2002) [16] with Student-t innovations. The conditional variance of each return series $r_{i,t}$ is modeled through a GARCH(1,1) specification

$$h_{i,t} = \omega_i + \alpha_i \varepsilon_{i,t-1}^2 + \beta_i h_{i,t-1}, \tag{1}$$

where α_i captures the impact of recent shocks and β_i measures volatility persistence. The standardized residuals $z_t = (z_{s,t}, z_{a,t})'$ are used in the DCC stage, where the time-varying conditional correlation process is given by

$$Q_t = (1 - a - b)\bar{Q} + a\, z_{t-1} z_{t-1}' + b\, Q_{t-1}, \tag{2}$$

with $R_t = \mathrm{diag}(Q_t)^{-1/2}\, Q_t\, \mathrm{diag}(Q_t)^{-1/2}$. The Student-$t$ distribution is used to account for the heavy tails observed in the return series. The two-stage estimation procedure makes it possible to estimate the model consistently across all thirty-two sector-asset pairs.

4.2. Hedge Ratios, Optimal Weights, and Hedging Effectiveness

The dynamic minimum-variance hedge ratio (HR) indicates the size of the position that should be taken in the hedging asset relative to the sector portfolio in order to minimize portfolio variance. It is defined as the conditional covariance between sector and asset returns divided by the conditional variance of the hedging asset:

$$HR_t = \frac{h_{sa,t}}{h_{a,t}}. \tag{3}$$

The HR-based hedging effectiveness follows the variance-reduction criterion of Ederington (1979) [18]:

$$\mathrm{HE}_{\mathrm{HR}} = 1 - \frac{\mathrm{Var}(r_{s,t} - HR_t r_{a,t})}{\mathrm{Var}(r_{s,t})}. \tag{4}$$

The optimal portfolio weight proposed by Kroner and Ng (1998) [17] indicates the weight assigned to the sector portfolio in the minimum-variance portfolio formed with the hedging asset.

$$w_{s,t} = \frac{h_{a,t} - h_{sa,t}}{h_{s,t} + h_{a,t} - 2h_{sa,t}}, \tag{5}$$

where $w_{s,t}$ is restricted to the interval $[0, 1]$.

The corresponding minimum-variance portfolio return at time t is

$$r_{\mathrm{OW},t} = w_{s,t}\, r_{s,t} + (1 - w_{s,t})\, r_{a,t}, \tag{6}$$

and the OW-based hedging effectiveness is given by

$$\mathrm{HE}_{\mathrm{OW}} = 1 - \frac{\mathrm{Var}(r_{\mathrm{OW},t})}{\mathrm{Var}(r_{s,t})}. \tag{7}$$

While $\mathrm{HE}_{\mathrm{HR}}$ measures the variance reduction obtained from the dynamic hedge-ratio strategy, $\mathrm{HE}_{\mathrm{OW}}$ measures the variance reduction obtained from the long-only minimum-variance portfolio. As the two measures are based on different portfolio constructions, they may lead to different conclusions regarding hedging performance.

4.3. Sub-Period Analysis

For the sub-period analysis, the DCC-GARCH model is estimated once using the full sample, and the resulting time-varying conditional moments are then analyzed separately for each sub-period. This avoids re-estimating the DCC model on relatively short samples, where the correlation parameters can be difficult to estimate accurately.

4.4. Portfolio Performance and Robustness Methods

The realized performance of the dynamic hedged portfolio $r_{H,t} = r_{s,t} - HR_t r_{a,t}$ is evaluated using risk and performance measures. Annualized Sharpe and Sortino ratios are used to compare returns relative to risk, annualized volatility measures the overall variability of portfolio returns, and the one-day 95% historical Value-at-Risk and cumulative maximum drawdown focus on potential losses. In addition to standard variance- and tail-risk measures, the analysis also examines the Omega ratio of Keating and Shadwick (2002) [23], which compares gains and losses relative to a zero-return threshold, and the Pain Index and Pain Ratio of Bacon (2008) [24], which capture the average drawdown depth over the sample period.

To check whether the results are driven by the specifications of the modeling assumptions, the baseline model is re-estimated using an AR(1) mean equation, which accounts for possible return autocorrelation, and a GJR-GARCH(1,1) variance specification that allows volatility to respond differently to positive and negative shocks. In addition, the analysis is repeated using two alternative portfolio-construction approaches: a stable equal-weighted and a yearly rebalanced market-capitalization-weighted index. The stable equal-weighted index construction keeps both the firms and their weights fixed throughout the sample period, while the yearly rebalanced market-capitalization-weighted index is rebalanced annually based on firms' market capitalizations. These alternative specifications show the effects of the index construction method on the results.

5. Empirical Results

The hedging relationships between sector portfolios and carbon and energy assets depend on sector characteristics, market conditions, and exposure to EU ETS regulation.

The performance of the hedging assets depends on sector characteristics. EUA futures provide the highest HE_{HR} for the Basic Metals and Non-Metallic Minerals sectors, with values of 0.06 and 0.07, respectively. In these sectors, production activities are carbon intensive and firms have more limited capacity to pass carbon costs on to customers [6, 8]. Consequently, equity returns in these sectors are more closely linked to movements in EUA prices. In contrast, Brent crude oil is the most effective hedging asset for Electricity and Chemicals sectors, with HE_{HR} values of 0.08 and 0.10. The relationship between sector returns and oil prices is stronger in these sectors than in the other sectors in the sample. Natural gas has relatively low HE_{HR} in the full sample, but its HE_{HR} increases during the 2022 European energy crisis, especially for the Chemicals and Non-Metallic Minerals portfolios. Coal and gold have very low HE_{HR} throughout the sample.

EU ETS-regulated portfolios require larger EUA hedge positions than non-EU ETS-regulated portfolios. Across all sectors, EUA HRs are consistently higher for the EU ETS-regulated portfolios. The largest difference is observed in Basic Metals, where the average HR is 0.11 for the EU ETS-regulated portfolio compared with 0.06 for the non-EU ETS-regulated portfolio. Differences in HE_{HR} are generally smaller, particularly in the manufacturing sectors, which demonstrates that the non-EU ETS-regulated firms are indirectly affected by the developments in the carbon market.

Looking at the sub-periods, the results differ substantially across market regimes. Compared with the other sub-periods, EUA HE_{HR} increases significantly during the COVID-19 period. For example, the HE_{HR} of the Non-Metallic Minerals EU ETS-regulated portfolio increases from 0.05 in the Post-MSR period to 0.25 during COVID-19, which is the highest value in the sample. In this period HRs also increase with respect to other periods but the increase in HE_{HR} values is larger, making EUA futures a more effective hedging asset during this period. A different picture appears during the Phase IV High Price period. For several manufacturing sectors, natural gas becomes a more effective hedge and the HR changes from positive to negative. This is consistent with the sharp increase in gas prices during this period and their growing importance for industrial production costs. For the Chemicals sector, Brent crude oil also remains a strong hedge throughout most of this period. Additionally, the time-varying analysis shows that EUA HE_{HR} also rose during 2016-2017, before the MSR became operational, suggesting that hedging relationships can adjust to expected regulatory changes even before their implementation. Furthermore, during the CBAM Transitional period, EUA HE_{HR} increases again for Basic Metals, Non-Metallic Minerals, and Chemicals, as HE_{HR} values rise from near-zero levels in the Phase IV Normalization period to between 0.01 and 0.05 in most cases.

Portfolio performance generally improves for the sector-asset combinations with higher HE_{HR} values. The largest improvements are observed for the oil hedges in the Electricity and Chemicals sectors. For example, hedging the Electricity EU ETS-regulated portfolio with Brent crude oil increases the Sharpe ratio from 0.33 to 0.39 and reduces the maximum drawdown from 0.39 to 0.32. A similar improvement is observed for the Chemicals EU ETS-regulated portfolio as the Sharpe ratio increases from 0.02 to 0.06 when it is hedged with oil. However, lower volatility does not always coincide with a higher Sharpe ratio. The Basic Metals EU ETS-regulated portfolio hedged with EUA shows this as the volatility is lowered from 0.272 to 0.264, but the Sharpe ratio also decreases from 0.13 to 0.08. The same Basic Metals EU ETS-regulated portfolio paired with EUA also worsens drawdown-based metrics, with the Pain Index rising from 0.244 to 0.313, while the TTF natural gas hedge improves both variance and Pain metrics for the same portfolio. Across the sample, the Electricity EU ETS-regulated portfolio paired with oil is the only one that improves HE_{HR}, Sharpe, Omega, and Pain measures simultaneously. The robustness analysis produces very similar results under alternative model specifications and portfolio-construction methods.

6. Conclusions

This thesis analyzes how the hedging relationships of carbon and energy assets differ across carbon-intensive sectors, between EU ETS-regulated and non-EU ETS-regulated firms, and in different market environments. The findings show that hedging effectiveness depends on the underlying sector's characteristics, regulation by the EU ETS, and the examined period. The implications of these results are discussed below for EU ETS-regulated firms, policymakers, and investors.

For EU ETS-regulated firms, the choice of the hedging asset should reflect sectoral characteristics rather than relying fully on EUA futures to hedge carbon price risk. For instance, EUA provides the greatest variance reduction for the Basic Metals and Non-Metallic Minerals sectors, while Brent crude oil is more effective for the Electricity and Chemicals sectors. However, the hedge with the greatest variance reduction is not always the most attractive choice because other aspects of portfolio performance, such as tail risk and drawdown, may lead to a different conclusion. For example, a Basic Metals firm focused on volatility reduction may prefer EUA futures, while a firm more concerned about drawdown risk may find TTF natural gas more suitable for the same portfolio. Moreover, the magnitude and, in some cases, even the direction of hedge ratios change across regimes, as illustrated by the sign reversal of the TTF natural gas hedge during the 2022 European energy crisis. Therefore, EU ETS-regulated firms should periodically reassess their hedge positions.

For policymakers, the consistently higher EUA hedge ratios for EU ETS-regulated firms suggest that the effects of carbon pricing policies extend beyond compliance requirements and are also reflected in financial markets. This is consistent with the EUA's changing role over time from a compliance instrument in the earlier phases of the EU ETS to one with a stronger financial role during Phase III and Phase IV [3]. The time-varying analysis also implies that EUA hedging relationships can respond to carbon market regulations even before their full effects are reflected in firms' operations, as observed in the rise in EUA hedging effectiveness during 2016–2017, around the period of the 2017 MSR reform agreements and before the MSR became operational in January 2019 [25]. Furthermore, the findings underline the strong interaction between carbon and energy markets, especially during the 2022 European energy crisis. This suggests that the financial impact of carbon-market reforms should be assessed together with energy market conditions, since the same reform may have different financial effects depending on energy market conditions.

For investors, firms' regulatory status is another important consideration alongside sector selection. Within the same industry, EU ETS-regulated portfolios are more closely linked to EUA price movements, whereas non-EU ETS-regulated portfolios are exposed more indirectly through energy-market spillovers. Investors seeking greater direct exposure to carbon-price movements may therefore prefer EU ETS-regulated firms within a sector, while those aiming to limit such exposure may prefer non-EU ETS-regulated firms. In addition, investors holding diversified portfolios across carbon-intensive sectors may benefit from aligning their hedging instruments with the sector composition of their portfolios, as the four sectors exhibit different hedging relationships with carbon and energy markets.

6.1. Limitations and Further Research

Several limitations should be considered when interpreting the results. The bivariate DCC-GARCH framework was chosen to allow a direct comparison of the hedging performance of individual assets. However, combinations of carbon and energy assets generally provide stronger variance reduction than the single-asset hedges.

The analysis is based only on European listed firms and may therefore not fully reflect the broader sector characteristics. In addition, the sub-period analysis requires a clear distinction of different regimes and crisis periods, but also requires sufficiently long samples for reliable estimation. This limitation is partly mitigated by estimating the DCC-GARCH model over the full sample and evaluating the resulting hedge ratios and hedge effectiveness within each sub-period.

The realized performance of the hedging strategies may differ from the results reported in this thesis since the portfolio analysis does not take the transaction costs, financing costs, or margin requirements into account. The CBAM-related results should also be reassessed as more data from the Definitive Phase become available.

These limitations also point to several directions for future research. The analysis could be extended through multivariate frameworks that allow multiple hedging assets to be considered simultaneously and provide a better understanding of spillovers between carbon, energy, and equity markets. Future studies could also examine a broader set of sustainability-related assets, including green bonds, renewable-energy equities, and carbon investment products. Finally, the CBAM-related findings should be reassessed in the future with longer samples from the Definitive Phase to assess the effects of CBAM once firms are fully exposed to its financial requirements.

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