The Asset-Pricing Implications of Carbon Risk in Korea

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Abstract

This study examines the relationship between carbon risk and stock returns in Korea. We find that a firm's carbon intensity is a significant determinant of its cross-sectional stock returns. Stocks with high exposure to carbon risk exhibit higher average returns. The abnormal return associated with carbon risk is statistically significant and cannot be explained by the Fama-French three- or five-factor models. Furthermore, this phenomenon is more evident among stocks with high foreign ownership. Finally, the carbon factor commands a significantly positive risk premium for firms with carbon emission information, suggesting that carbon risk is an important risk factor.

Keywords: Carbon risk, Empirical asset pricing, Fama-Macbeth regression, GMM

JEL Classification: G11, G12, G18, Q54

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1. Introduction

Climate change issues have gained prominence in many areas, including policymakers, private sector businesses, and academia, as anthropogenic global warming has gained global consensus. According to the United Nations (U.N.), more than 130 countries have committed to achieving net zero emissions by 2050, more than 1,000 companies have set science-based targets in line with net zero, and over 500 financial institutions have joined the race to zero.[1] Given this increasing awareness of climate risk, a growing number of studies have also begun to evaluate how climate risks affect asset prices (Giglio, Kelly, and Stroebel, 2021). The empirical evidence, however, varies widely across countries, time, and asset classes, making a comprehensive understanding of the impact of climate risks on asset prices challenging (Bolton and Kacperczyk, 2020, 2021; Oestreich and Tsiakas, 2015; Pastor, Stambaugh, and Taylor, 2022). Furthermore, most studies focus on major markets, such as the US and the EU, and studies on emerging markets are limited. This study attempts to fill this void in the literature by examining how carbon risks affect the cross-section of Korean stock returns from 2011 to 2021.

We are certainly not the first to study the carbon risk premium in equity markets. Our study, however, provides several novel insights into the relationship between carbon risk and cross-sectional stock returns, particularly in the context of an emerging market. First, existing studies on the price of climate risk mostly focus on the US and other developed markets, in which the awareness of investors and their attention to climate change and sustainability issues is relatively stronger than in emerging markets like Korea. Additionally, Korea relies heavily on energy-intensive industries,[2] which contribute to the nation's economic growth, but at the same time cause the economy to be more

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[1] For example, the Net Zero Asset Owner Coalition, a group of institutional investors committed to transitioning their investment portfolios to net zero emissions by 2050, grew from 12 members with US2.4 trillion in asset under management (AUM) to 74 members with US$10.6 trillion in AUM over the recent three years from September 2019 and July 2022.

[2] In 2020, Korea was the 10th largest energy consumer in the world (BP, 2021). The leading industries, such as electronics, petrochemicals, automobiles, shipbuilding, and steel, are energy-intensive and export-oriented.

susceptible to climate transition risks than countries with less energy-intensive industry structures.[3] Therefore, based on the distinctive social and economic features of Korea and prior evidence that country-level characteristics significantly affect the carbon risk premium (Bolton and Kacperczyk, 2021), it is not clear whether existing findings based on other developed markets are applicable in Korea, necessitating the need for additional investigation on this issue. Second, the two distinctive features of the Korean data have advantages for carbon risk analysis. Korean firms whose annual greenhouse gas emissions exceed a certain level specified by regulations are mandated to disclose their carbon emissions.[4] Hence, the data itself are less vulnerable to the selection bias that prior studies have faced using data based on voluntary disclosures. In addition, the number of shares owned by foreign investors for each stock is provided by the Korean Exchange. Using foreign ownership information, we can evaluate the impact of foreign investors, who tend to have higher levels of attentiveness to environmental issues than domestic investors, on the carbon risk premium.[5]

In this study, we provide multiple empirical evaluations on the carbon risks as a determinant of cross-sectional stock returns in Korea. First, to examine whether a company's exposure to carbon risk is associated with cross-sectional stock returns, we run a Fama and MacBeth (1973) regression of excess stock returns on carbon intensity, measured as firms' total emissions scaled by either sales ($CO_2/Sales$) or assets ($CO_2/Assets$). We control for other firm characteristics known to be related to excess returns,

[3] Here, climate transitional risks refer to risks that occur in the transition process toward low-carbon economy, such as advances in climate policy, shifts in consumer preferences, changes in social norms, and technological innovation in renewable energy.

[4] If a firm's greenhouse gas emissions exceed the limits set for total threshold (50,000 tons of CO_2eq) or facility threshold (15,000 tons of CO_2eq), firms are required to report the relevant information (Article 29 of the Framework Act on Low Carbon, Green Growth). As of 2022, two countries have mandatory reporting requirements, and the other is Australia.

[5] According to the Korea Financial supervisory Service, as of 2021, 76 percentage of foreign investors in Korean listed companies are classified into institutional investors and a half of these foreign institutional investors are from the US or European countries with high levels of public attention paid to sustainability and environmental issues. Relatedly, previous studies show that foreign institutional investors play an important role in driving environmental and social performance of emerging market firms that they invested in (Aggarwal, Erel, Ferreira, and Matos, 2011; Dyck, Lins, Roth, and Wagner, 2019; Oh, Chang, and Martynov, 2011)

such as beta, size, book-to-market ratio, investment, and operating profitability. Both measures of carbon intensity show a significant positive association with cross-sectional stock returns in the presence of five firm characteristics.

We further conduct a portfolio-sort analysis. First, we construct a factor-mimicking portfolio related to carbon risk by taking a long-short position on the portfolios of individual stocks sorted based on their exposure to carbon risk. In particular, we sort stocks into three groups (low 30%, medium 40%, and high 30%) based on the measure of carbon intensity and construct equally weighted portfolios.[6] Thereafter, we compute the difference in portfolio returns between the high- and low-carbon risk exposure groups. This factor-mimicking portfolio, or carbon factor, represents a common source of risk exposure to carbon risk using a portfolio of assets. For the constructed portfolios, we estimate abnormal returns or alphas using asset pricing models (CAPM, Fama-French three- and five-factor models). We find that alphas monotonically increase from the low to high carbon risk exposure groups. The monthly returns of the zero-investment portfolios that long the high and short the low carbon risk exposure groups range between 0.70% and 0.83%. This magnitude is highly significant both economically and statistically. In addition, the statistical significance of the abnormal returns in all model specifications suggests that carbon risk is reflected in stock returns.

To further explore the mechanisms influencing the carbon risk premium in Korean stocks, we consider foreign ownership as a possible source of variation in the pricing of carbon risk. This analysis is particularly important for emerging markets such as Korea, because most foreign investors are from countries with higher levels of attentiveness to climate issues and are familiar with stricter climate

[6] To ensure robustness of the results, we also measure portfolio returns weighted by the previous month gross returns and find that results remain qualitatively the same in the analysis of equal-weighted portfolio returns. On the other hand, value-weighted portfolio returns may not be appropriate in our case. In 2020, about 300 listed firms reported carbon emissions information, and their market capitalization is 55.5% of total market capitalization of Korea. The top 10 emission reporting firms explain 39.7% of total market capitalization and 71.5% of emission reporting firms' market capitalization. This implies that value-weighted portfolio returns can be significantly affected by the returns of a few large firms. The results of our robustness checks are available upon request.

policies relative to Korea. In addition, a foreign ownership factor itself is proposed as one of the determinants of excess stock returns in Korea. Foreign investors own a significant portion of the stocks (as of the end of 2021, foreign investors own 29.5% of the total stock market capitalization) and stocks with high foreign ownership tend to have lower returns on average (Jung, Lee, and Park, 2009). Hence, it is worthwhile to examine the changes on the main results when including foreign ownership in the analysis.

A priori, foreign ownership can amplify or mitigate the results we have found regarding the carbon risk premium. If foreign investors have a higher awareness and attention towards environmental issues and demand higher compensation for bearing carbon risk than domestic investors, we expect a higher carbon risk premium among stocks with high foreign ownership. In contrast, as is the case of the omitted variable bias, if the carbon risk premium is initially attributable to their low foreign ownership, then the positive premium for carbon risk will become much smaller or insignificant once we include the foreign ownership effect in the analysis. Therefore, whether and how the foreign ownership factor affects the carbon risk premium is an empirical question.

We find that foreign ownership strengthens the positive relationship between carbon risk and stock returns. It is demonstrated by the division of stocks into two sets of portfolios: one set of portfolios with high foreign ownership and another set of portfolios with low foreign ownership. Through Fama-Macbeth regression analysis, we find that carbon-intensity variables have positive and statistically significant coefficients only among stocks with high ownership stakes of foreign investors. In addition, we find that the monthly return of long-short portfolios based on *CO_2/Sales* with high foreign ownership is 0.88%, which is statistically significant and larger in economic magnitude than the monthly return of long-short portfolio based solely on *CO_2/Sales*. In contrast, the return of long-short portfolios with low foreign ownership is 0.58%, and abnormal returns do not exhibit a monotonic relationship with carbon risk for portfolios with low foreign ownership. Collectively, the carbon risk premium is more pronounced in groups of portfolios with high ownership stakes of foreign investors, suggesting that foreign investors demand a higher risk premium for bearing carbon risk. This result is also consistent with a recent finding that global institutional investors are increasingly concerned about climate and environmental issues (Kruger, Sautner, and Starks, 2020; Bolton and Kacperczyk, 2020, 2021; Ilhan, Krueger, Sautner, and Starks, 2021).

Lastly, we estimate the risk premium for the carbon factors using widely adopted tests of asset pricing models, the optimal generalized method of moments (GMM) estimation of the linear factor model, and the Fama-MacBeth two-stage regression of portfolio excess returns on their factor loadings. As test assets, we use decile portfolios sorted based on the measures of a firm's carbon intensity. We add the carbon factors to the Fama-French three- and five-factor models and find that the carbon factor commands a significantly positive risk premium. In other words, carbon factors capture the additional return variations of decile portfolios sorted on the measures of carbon intensity, even in the presence of conventional risk factors, indicating that investors price carbon risk and demand compensation for holding such stocks. Additionally, the use of nine portfolios double-sorted by foreign ownership and carbon intensity as test assets leads to a significant positive risk premium for both the single and double-sorted carbon factors, i.e., the long-short portfolio based only on carbon intensity and the long-short portfolio based on both carbon intensity and foreign ownership.

A prior study that is most related to the current study is the analysis conducted by Bolton and Kacperczyk (2022), who provide evidence on the pricing of climate change risks (more precisely, low-carbon transition risks) by analyzing the stock prices of companies with different levels of exposure to carbon risk. Their main interest is to examine whether stock returns reflect variations in the level of carbon emissions across firms and how the carbon premium is influenced by country characteristics such as social, political, and energy factors. However, they take a characteristics-based approach, which is not based on a factor-based asset pricing model, and thus does not address the existence of an alpha, as we show in this paper. Another related study to ours is Görgen, Jacob, Nerlinger, Riordan, Rohleder, and Wilkens (2020), who investigate the relationship between carbon risk and equity prices within a factor-based asset pricing framework. They find that carbon risk explains the systematic variation in returns. However, they do not find a carbon risk premium in the global market, which contrasts with our finding that a carbon risk premium exists among Korean stocks.

Our results contribute to the rapidly growing literature on the asset-pricing implications of climate change. Several studies suggest that climate risk is negatively associated with asset prices. For instance, Chava (2014) finds that investors demand significantly higher stock returns for firms with environmental concerns such as hazardous waste and climate change concerns. Similarly, Ilhan, Sautner, and Vilkov (2021) find that the cost of option protection against downside tail risks increases with firm-level carbon intensity, and for carbon-intensive firms, where the cost of protection against downside tail risk increases with public's attention to climate change. Choi, Gao, and Jiang (2020) show that stocks of carbon-intensive firms underperform those of low-carbon firms in abnormally warm weather, as investors revise their projections about climate risk upward and sell stocks of carbon-intensive firms in such abnormal weather. Regarding the physical risk of climate change, Alok, Kumar, and Wermers (2020) find that fund managers underweight stocks located in disaster zones following disasters, such as hurricanes and tornadoes, suggesting that investors care about climate risk. Similarly, Huynh and Xia (2021) find that investors sell stocks of a firm exposed to physical climate risk when natural disasters strike. On the other hand, Hong, Li, and Xu (2019) document that the stock prices of listed food companies in thirty-one countries did not efficiently reflect their countries' risk of droughts, suggesting that stock markets underestimated climate risks.[7]

The remainder of this paper is organized as follows. Section 2 describes the data and the

[7] Aside, several studies examine the impact of climate change on real estate and bond markets, other than the stock market. Bernstein, Gustafson, and Lewis (2019) find that residential properties exposed to sea level rise sold seven percent less than equivalent but unexposed properties. Goldsmith-Pinkham, Gustafson, Lewis, and Schwert (2021) found that municipal bond markets, particularly long-maturity bond markets, began pricing the uncertainty of future sea level rise. In contrast, Murfin and Spiegel (2020) and Baudauf, Garlappi, and Yannelis (2020) find that property prices are generally insensitive to climate risks.

relationship between the cross-sectional stock returns and carbon emissions through Fama-MacBeth regressions and portfolio-sort analyses. In Section 3, we conduct additional analyses of the foreign ownership factor. Section 4 estimates the risk premium for carbon risk factor portfolios by using various estimation methods. Finally, Section 5 concludes the paper.

2. The relationship between carbon risk and cross-sectional stock returns

2.1. Data and sample

Our sample comprises the common stocks listed on the Korea Exchange from July 2012 to December 2021. To be included in the sample, a firm must be a non-financial firm with available CO_2 emissions information and a positive book value of equity. Following Fama and French (1993, 2015), we assume that firms' accounting data for the previous fiscal year is publicly available by the end of June. Stock market data and accounting data are collected from the FnGuide database and corporate carbon emissions data are obtained from the National Greenhouse Gas Management System (NGMS). As a measure of a company's total emissions, we use the sum of Scope 1 and Scope 2 emissions, but do not include Scope 3 emissions.[8] Scope 1 and Scope 2 are essentially manageable by a company, whereas Scope 3 emissions are generated from activities beyond a company's direct control; it is also challenging to reliably measure Scope 3 emissions compared to Scope 1 and Scope 2 emissions.

Panel A of Figure I shows the number of firms with carbon emissions information in our sample from 2011 to 2020. During this period, 11.4% of the sample firms (259 of 2,270 non-financial firms), on average, report their carbon emissions to NGMS. We observe that the number of firms that disclose

[8] A company's greenhouse gas emissions are generally classified into three scopes: Scope 1 emissions are direct emissions occurred from sources that a company owns or directly controls; Scope 2 emissions are indirect emissions occurred in the process of using electricity, heat, or steam that a company purchases; and Scope 3 emissions are indirect emissions from a company's value chain, employee commuting, and business trip that a company is indirectly responsible for.

their carbon emissions consistently increased from 174 in 2011 to 309 in 2020. In addition, Panel B indicates that carbon emission information is reported mainly in carbon-intensive sectors. In 2020, most of the firms that disclose their carbon emissions are in the materials (22.3%), chemical (11.0%), and hardware (6.1%) industries, whose emissions account for approximately 78.4% of the total emissions disclosed that year.

<u>Figure I about here</u>

The variables used in the analysis are as follows. The Excess Return (R_i^e) is the monthly stock return net of the risk-free interest rate. As a proxy for the risk-free interest rate, we use 91-day CD (certificate of deposit) rate. We use two carbon emissions variables: the ratio of carbon emissions to sales and assets ($CO_2/Sales$, $CO_2/Assets$). *Beta* is the CAPM beta calculated over a one-year period, using daily stock returns. Size (*ME*) is market capitalization in million KRW. The book-to-market ratio (*B/M*) is book equity divided by the market value of equity. *Investment* is measured as the change in total assets from year t-2 to year t-1 divided by total assets in year t-2. Operating profitability (*OP*) is the ratio of revenue minus the cost of goods sold, selling, general, and administrative expenses, and interest expenses to book equity. *Foreign* is the ratio of the ownership share of foreign investors to total outstanding shares.

Table I presents the summary statistics for the sample. Panel A provides summary statistics of the sample with carbon emissions information (24,517 firm-month observations), and Panel B reports summary statistics for the entire sample (197,800 firm-month observations). The means of *ME* and *B/M* are much larger for firms that disclose carbon emissions. The average value of firm size with carbon emissions information is higher than the 75-percentile value for all non-financial firms. Additionally, firms with emissions information have, on average, higher foreign ownership than the entire sample. Firms that report emissions information appear to be large and value firms that are more exposed to foreign investors.

Table I about here

2.2. Fama-MacBeth cross-sectional regression

We begin by examining the effect of carbon risk on the cross-section of excess stock returns using the Fama-MacBeth (1973) cross-sectional regression approach. If carbon intensity and other firm-level characteristics help explain cross-sectional stock returns, the average slopes for these variables from the regressions should be significantly different from zero.

In line with standard asset pricing tests, we perform the Fama-MacBeth regression in two steps for the sample with carbon emissions information. First, we regress the cross-section of monthly excess stock returns on a vector of variables expected to explain returns as follows: beta (*Beta*), the log of the market value of equity (*ln(ME)*), the log of book-to-market ratio (*ln(B/M)*), investment (*Investment*), operating profitability (*OP*), and the log of two carbon intensity measures ($ln(CO_2/Sales)$, $ln(CO_2/Assets)$). The variables are winsorized at the 1% level. After running the monthly regressions, we calculate the time-series averages of the monthly regression slopes to determine the explanatory variables priced in the market.[9]

Table II shows the results of the Fama and MacBeth (1973) regressions of monthly excess stock returns on various combinations of lagged carbon intensity measures and other firm characteristics from July 2012 to December 2021. Column (1) presents the estimation results for the three firm characteristics. *ln(ME)* has a significant and negative cross-sectional relationship with excess stock returns, whereas *Beta* and *ln(B/M)* do not exhibit such relationship. We include $ln(CO_2/Sales)$ and $ln(CO_2/Assets)$ as additional independent variables in Columns (2) and (3), respectively. The average

[9] In untabulated results, we estimate the Fama-MacBeth regression by WLS using the previous month gross return as the weighting variable to minimize bias in parameter estimates when using rates of return the dependent variable as suggested by Asparouhova, Bessembinder, and Kalcheva (2013). We find that the results remain unaffected and coefficient estimates on *ln(CO2/Sales)* and *ln(CO2/Assets)* remain positive and statistically significant. The results are available upon request.

slopes of *ln*(CO_2*/Sales)* and *ln*(CO_2*/Assets)* are positive and statistically significant at the 5% level. Column (4) shows the estimation results with five firm characteristics, and columns (5) and (6) show the results with the two carbon intensity measures. As before, the average slopes of *ln*(CO_2*/Sales)* and *ln*(CO_2*/Assets)* are positive and statistically significant at the 5% level, indicating that a firm's carbon intensity can explain the cross-section of the average excess returns. The positive coefficients suggest that there is indeed a carbon risk premium for Korean stocks with high carbon intensity. *ln(ME)* and *OP* have explanatory power, whereas *beta*, *ln(B/M)*, and *investment* have no explanatory power in all specifications.

Table II about here

2.3 Portfolio sort analyses on carbon risk exposure

In the previous section, we observed that stocks with higher degrees of exposure to carbon risk exhibited higher cross-sectional excess returns on average. In this subsection, we test if carbon risk continues to retain consistent explanatory power, even when other common pricing factors are considered simultaneously.

To test this, we construct the carbon factor using the following process: Each year, we sort the stocks into three groups (low 30%, medium 40%, and high 30%) based on carbon risk measures (CO_2*/Sales* or CO_2*/Assets*). The group 'Low' contains stocks with the lowest carbon risk and group 'High' contains stocks with the highest carbon risk. We compute the monthly equal-weighted excess returns of each portfolio during the one-year period and rebalance the portfolios at the end of June each year. Then, the carbon factor is formed by taking a long position in the High portfolio and a short position in the Low portfolio. Table III reports various summary statistics for the monthly returns of the two carbon factors, along with the returns of the Fama-French five-factor portfolios. CO_2^{Sales} indicates the carbon risk factor based on CO_2*/Sales* and CO_2^{Asset} indicates the carbon risk factor based on CO_2*/Assets*. *MKT* denotes the KOSPI (Korea Composite Stock Price Index) return in excess of the risk-free rate. *SMB* (small minus big), *HML* (high minus low), *RMW* (robust minus weak), and *CMA* (conservative minus aggressive) are size, value, investment, and operating profitability factors, respectively. All returns are recorded as percentages. The two carbon factors show positive average returns during the sample period. Among all the factors, CO_2^{Sales} has the highest average return (0.83%) and t-statistics (3.55). Panel B of Table III shows the correlations among the factors used in the analysis. The correlation coefficient between the two carbon factors is 0.89. The correlation coefficients between the two carbon factors, and Fama-French five factors are relatively low and range between -0.15 and 0.47.

<u>Table III about here</u>

Figure II shows the cumulative returns of these portfolios from July 2012 to December 2021. We observe that the cumulative returns on the two carbon factors have consistently increased over time, while the CO_2^{Sales} factor has achieved relatively higher returns than the CO_2^{Asset} factor. This is surprising when compared to the cumulative returns of the Fama-French five factors fluctuating over time, as shown in Figure III.

<u>Figure II about here</u>

<u>Figure III about here</u>

We then examine whether the risk-adjusted returns, or alphas, for the portfolios based on the three asset pricing models (CAPM, the Fama-French three-factor model, and the Fama-French five-factor model) are statistically significant. Specifically, we run a simple time-series regression over the entire sample period. The regression model used is as follows:

$$R_{p,t}^{e} = \alpha_p + \beta_p' F_t + \varepsilon_{p,t} \tag{1}$$

The dependent variables are monthly excess returns ($R_{p,t}^{e}$) of portfolios sorted on the two carbon risk exposure measures (*CO_2/Sales*, *CO_2/Assets*) and the independent variables (F_t) are monthly returns of the Fama-French factors. The variable of interest is the regression intercept (α_p), which is the abnormal return or alpha of the portfolio. If carbon intensity is associated with abnormal returns, the intercept should differ significantly from zero.

Table IV reports the average excess returns and alphas of the three portfolios sorted by firms' carbon risk exposures, which are estimated from the time-series regression in Equation (1). Panel A of Table IV reports the results when firms' carbon risk exposures are measured as *CO_2/Sales*. The average excess return for the Low portfolio is 0.42, which is lower than the average excess return for all sample firms with carbon emission information of 1.01 in Table I. We observe a monotonically increasing pattern in average excess returns from the Low portfolio to the High portfolio. In the last column, we report the average returns for the zero-investment portfolio, which takes a long position in the High portfolio and a short position in the Low portfolio, that is, CO_2^{Sales}. We observe that the average return of this long-short portfolio is significantly positive. The table also provides three alphas based on the CAPM, the Fama-French three-factor model, and the Fama-French five-factor model. We observe that the alphas exhibit monotonically increasing patterns with the portfolios' carbon risk exposure. The alpha for the low portfolio is negative, while the alpha for the high portfolio is positive. The spread of the alphas between the High and Low portfolios is positive and statistically significant at the 1% level in all specifications: 0.85% in the CAPM, 0.61% in the three-factor model, and 0.68% in the five-factor model.

Panel B of Table IV replicates Panel A, but the stocks are now sorted by *CO_2/Assets*. The results are basically the same as those in Panel A of Table IV, although the statistical significance decreases to some extent. As before, the average excess returns and alphas exhibit a monotonically increasing pattern across portfolios, and the average returns and alphas of the long-short portfolio (CO_2^{Assets}) are significantly positive in all specifications, showing that portfolios with higher exposure to carbon risk are associated with higher abnormal returns. In summary, we find that carbon risk is positively associated with the abnormal returns that cannot be explained by the three asset pricing models, suggesting that carbon risk deserves to be considered an anomaly or a potential risk factor.

Table IV about here

3. Foreign ownership and the CO2-return relationship

Thus far, we have provided evidence that stocks with high carbon risk exposure exhibit higher returns on average, and carbon risk is positively associated with the abnormal returns that are not explained by other common risk factors. In this section, we consider foreign ownership as a possible firm characteristic that could influence our results. As mentioned earlier, foreign ownership may moderate or magnify the relationship between carbon risk and stock returns. On one hand, if foreign investors are concerned about the financial costs of climate risk to a greater extent than domestic investors, they are likely to demand higher compensation for holding stocks with high carbon risk exposure. According to prior studies, foreign institutional investors tend to have a relatively high awareness of sustainability issues including climate change and are more likely to actively differentiate firms based on their emissions or environmental performance (Dyck, Lins, Roth and Wagner, 2019; Krueger, Sautner, and Starks, 2020, Bolton and Kacperczyk, 2021). Therefore, foreign ownership likely reinforces the positive relationship between carbon risk and stock returns in Korea as they demand a higher return for holding stocks with high carbon risk. On the other hand, prior studies show that foreign ownership is negatively associated with stock returns in Korea (Jung, Lee, and Park, 2009). If the high abnormal returns of carbon-intensive stocks are initially attributable to low foreign ownership, which is related to reasons other than carbon risks, then the positive relationship between carbon risk and stock returns could weaken when we additionally consider the effect of foreign ownership. Therefore, whether and how foreign ownership affects the relationship between carbon risk and stock returns is an empirical question.

To examine whether our main results on the relationship between carbon risk and stock returns are affected by foreign ownership, we repeat the Fama-Macbeth regression in Table II after splitting our sample equally into two groups based on foreign ownership. Table V reports the results of the Fama-MacBeth regressions for the group with low foreign ownership (Panel A) and the group with high foreign ownership (Panel B). We observe that the average slopes of *ln(CO_2/Sales)* and *ln(CO_2/Assets)* are insignificant for groups with low foreign ownership in Panel A. In contrast, the average slopes are positive and statistically significant at 1-5% levels for the groups with high foreign ownership in Panel B. Furthermore, the average slopes range between 0.17 and 0.22, which are higher than those for all sample firms with carbon emission information of Table II (between 0.15 and 0.16). Overall, the results in this table indicate that the relationship between carbon risk and abnormal returns is more evident among stocks with high foreign ownership. As such, foreign ownership appears to enhance the positive association between stock returns and carbon risk in Korea.

Table V about here

To further investigate the relationship between foreign ownership and carbon risk, we repeat the portfolio-sort analyses in the previous sections using the ownership stakes of foreign investors as an additional sorting criterion for portfolio construction. In June of each year, we construct double-sorted portfolios by intersecting the carbon intensity and foreign ownership stakes. Specifically, we sort the sample firms into three groups (low 30%, medium 40%, and high 30%) based on their carbon intensity (*CO_2/Sales* or *CO_2/Assets*) and independently sort firms into two groups (low 50% and high 50%) based on their foreign investors' share ownership. We then calculate the equally weighted monthly returns from July of year t to June of year t+1 and rebalance the portfolios at the end of June each year. We denote six portfolios sorted on carbon intensity and foreign ownership as L_cL_F, M_cL_F, H_cL_F, L_cH_F, M_cH_F, and H_cH_F, where subscripts C and F stand for carbon intensity and foreign ownership, and L, M, and H stand for Low, Mid, and High, respectively. The carbon factors are then calculated as the difference between the average return of the high-carbon portfolios and low-carbon portfolios, that is, $[(H_cH_F + H_cL_F)/2 - (L_cH_F + L_cL_F)/2]$. $F\&CO_2^{Sales}$ and $F\&CO_2^{Assets}$ denote these double-sorted carbon factors on $CO_2/Sales$ and $CO_2/Assets$, respectively, while controlling for the foreign ownership effect.

Table VI reports summary statistics for the monthly returns of the two single-sorted and two double-sorted carbon factors. Of the two double-sorted carbon factors, $F\&CO_2^{Sales}$ has the highest average return (0.73%) and highest t-statistic (3.17). Panel B shows that the correlation coefficients between the carbon factors are high (ranges from 0.77 and 0.92).

<u>Table VI about here</u>

Table VII shows the estimation results of the time-series regressions for these double-sorted portfolios grouped by foreign ownership and $CO_2/Sales$.[10] We observe that the relationship between stock returns and foreign ownership is highly dependent on carbon risk exposure. For the Low portfolios, the difference in excess returns between the low and high foreign ownership portfolios is 0.32. However, for the High portfolios, the difference is as small as 0.02. Hence, for stocks with high carbon risk, the negative association between stock returns and foreign ownership is small or negligible. In Panel A, for portfolios with low foreign ownership, average excess returns and alphas do not exhibit monotonic relations with carbon emissions in all specifications. In contrast, in Panel B, for portfolios with high foreign ownership, both average excess returns and alphas exhibit positive and significant relationships with carbon emissions in all specifications. The dispersion of average returns between the High and Low Portfolios in Panel B is 0.88% per month, which is statistically significant at the 1% level. In addition, the abnormal return of the long-short portfolio ($H_C H_F - L_C H_F$) is significantly positive in all specifications: 0.89% in the CAPM, 0.67% in the Fama-French three-factor model, and 0.77% in the Fama-French five-factor model. The alphas are larger than those of the low foreign ownership long-short portfolio ($H_C L_F - L_C L_F$) in Panel A, as well as those of the long-short portfolio (CO_2^{Sales}) sorted

[10] In untabulated results (available upon request), we perform the same analysis for the factor portfolios sorted on $CO_2/Assets$ and find that the results remain unchanged although statistical significance decreases slightly.

on $CO_2/Sales$ alone in Table IV. Overall, this extends our previous results in Table IV by showing that the abnormal returns related to carbon risk become more pronounced when combined with high foreign ownership. As such, foreign investors' influence appears to play an important role in explaining the carbon risk premium in Korea.

<u>Table VII about here</u>

4. Estimating the carbon risk premium

In the previous sections, we showed that carbon intensity is positively associated with abnormal returns that cannot be explained by conventional risk factors. We also provided evidence that this positive association is driven mostly by stocks with high foreign ownership. In this section, we estimate the risk premium associated with this carbon risk by employing two widely used tests of asset pricing models: the optimal GMM estimation of the linear factor model and the Fama-MacBeth regression of portfolio excess returns on betas.[11] The expected return beta expression of a factor-pricing model is given by

$$E\left[R^{e}_{p,t}\right] = \beta'\lambda \tag{2}$$

$R^{e}_{p,t}$ are the monthly excess returns of portfolio p at time t and λ is the risk premium of the factors. As test assets, we use decile portfolios sorted by carbon intensity, $CO_2/Sales$. If the carbon risk factors capture the additional return variations of decile portfolios sorted on the measures of carbon intensity in the presence of other common risk factors, such as the Fama-French five factors, this result can be used as supporting evidence that the carbon factor is an important pricing factor for stocks with carbon emissions information.

[11] For the details of these estimation methods, refer to Cochrane (2005).

Table VIII presents the optimal GMM estimates of the factor risk premiums for alternative model specifications. Hansen's (1982) J statistics (p-values in parentheses) for the test of overidentifying restrictions are provided for all specifications. Columns (1) and (4) present the results obtained using the Fama-French three- and five-factor models. The risk premiums for *SMB* and *RMW* are significant, whereas those for the other factors are not. This suggests that *SMB* and *RMW* help explain the cross-section of the decile portfolios. Columns (2) and (5) of Table VIII add CO_2^{Sales}, a carbon factor based on $CO_2/Sales$. The risk premium for CO_2^{Sales} is positive and significant at the 1% level. The risk premium estimates range between 0.77 and 0.78, which is very close to the average return of 0.83 for CO_2^{Sales}. The risk premium for *RMW* is no longer significant when we add a carbon factor. When using CO_2^{Assets}, the risk premium continues to be positive and significant at the 1% level, as Columns (3) and (6) show. Meanwhile, the other factors, except for *SMB*, have insignificant risk premiums in all specifications that include carbon factors. Overall, the results suggest that investors demand higher returns to hold stocks with greater exposure to carbon risk (i.e., stocks with positive betas for the carbon risk factor). Finally, the J statistics for the test of over-identifying restrictions indicate that none of the models are rejected.

<u>Table VIII about here</u>

Table IX presents the estimates of the Fama-MacBeth cross-sectional regression of excess returns on betas, along with the Shanken (1992) corrected t-statistics for an alternative estimation procedure. As before, we use the decile portfolios formed on $CO_2/Sales$ as test assets. The estimation results show that the risk premium for the carbon factor is significant at the 1% level for all model specifications, whereas the coefficients of the factors other than SMB are generally insignificant. Consistent with the previous GMM estimation results in Table VIII, the Fama-MacBeth regression results suggest that the carbon risk factor commands a significant positive risk premium. The results suggest that asset pricing models that include the carbon risk factor explain the return variation in decile portfolios sorted on carbon intensity measure better than common asset pricing models without it.

Table IX about here

Next, we examine whether the carbon risk premium based on carbon risk alone in Tables VIII and IX persists even after controlling for the effect of foreign ownership. We replace the previous decile test portfolios solely sorted on carbon intensity with nine (3 × 3) test portfolios, which are equally (1:1:1) sorted on their CO2/Sales and their foreign ownership, respectively. With additional carbon factors and new test assets, we replicate the optimal GMM estimation in Table VIII and the Fama-MacBeth cross-sectional regression in Table XI.

Table X presents the GMM estimates of several linear asset-pricing models with various factor combinations. We find that the risk premiums for CO_2^{Sales}, CO_2^{Assets}, and $F\&CO_2^{Sales}$ are positive and statistically significant at the 1% and 5% levels for all specifications. On the other hand, the carbon risk premium for $F\&CO_2^{Assets}$ is significant at the 1% level in column (5) but insignificant when all the Fama-French five factors are considered in column (10). In addition, none of the Fama-French five factors, except for SMB, exhibit significant risk premiums throughout all columns. Overall, the results are consistent with the previous results without the foreign ownership factor in Table VIII.

Table X about here

Table XI presents the price of risk estimated from the Fama-MacBeth regression along with the Shanken (1992) corrected t-statistics using the double-sorted portfolios as test assets. Consistent with the results in Table IX, we observe that the risk premiums for CO_2^{Sales}, CO_2^{Assets}, and $F\&CO_2^{Sales}$ are positive and statistically significant at the 1% or 5% level in all specifications, while the risk premium for $F\&CO_2^{Assets}$ is significant in column (5) at the 5% level but insignificant in Column (10). In addition, none of the Fama-French factors, except for SMB, have a significant risk premium. In summary, these results corroborate previous results that the carbon risk factor commands a positive risk premium.

Table XI about here

5. Conclusion

As climate change has become a major threat to human well-being, investor attention to and government regulations on carbon emissions have strengthened globally. However, such attention and regulations do not occur simultaneously worldwide. Some developed countries, such as the US and the EU, took the lead, while others, mostly emerging countries including Korea, have been followers. In this study, we investigated the cross-sectional relationship between corporate carbon risk exposure and stock returns in Korea using a factor-based asset-pricing approach.

We find that for the period from 2011 to 2021, corporate carbon risk is positively associated with a risk premium, suggesting that investors consider carbon risk and demand compensation for holding such stocks. Moreover, we show that the carbon risk premium is more substantial for portfolios with high foreign ownership, consistent with the view that foreign investors are relatively more concerned about climate and environmental issues and request a higher premium for bearing carbon risk. As such, the results of our study suggest that investors price carbon risk and that foreign investors play a particularly important role in emerging markets.

The results of our study also emphasize the importance of carbon information disclosure. In most countries, carbon disclosures are not yet mandatory, and thus, firms make disclosure decisions. Given that investors price carbon risk, as our study suggests, the lack of relevant information may make stock prices less efficient. Furthermore, as carbon risk affects firms' cost of capital, mandatory carbon disclosures are expected to incentivize firms to take environmentally friendly actions, which will help achieve the goal of fighting climate change.

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Table I **Summary Statistics of Firm Characteristics**

This table reports the summary statistics (average, standard deviation, 25th, 50th, and 75th percentiles) of firm characteristics. The sample consists of firms listed on the Korean Exchange between July 2012 and December 2021. Non-financial firms with CO_2 emissions information and a positive book value of equity are included in the sample. Excess return (R_i^e) is the monthly stock return net of the risk-free rate in percentage. *CO_2/Sales* and *CO_2/Assets* are the ratio of carbon emissions in tons to sales and assets, respectively, which are multiplied by ten thousand. *Beta* is the CAPM beta calculated over a one-year period, using daily stock returns. *ME* is the market capitalization (KRW million). *B/M* is book equity divided by the market value of equity. *Investment* is measured as the change in total assets from year t-2 to year t-1 divided by total assets in year t-2. *OP* is the ratio of revenue minus the cost of goods sold, selling, general, and administrative expenses, and interest expenses to book equity. *Foreign* is the share of foreign investors' ownership of the total outstanding shares.

Panel A: CO_2 sample

	Mean	SD	p25	p50	p75
R_i^e	1.01	12.50	-5.81	-0.14	6.09
CO_2/Sales	0.52	1.35	0.07	0.17	0.48
CO_2/Assets	0.34	0.67	0.06	0.14	0.36
Beta	0.83	0.40	0.53	0.81	1.11
ME	3,779	22,482	111	302	1,362
B/M	1.33	0.93	0.66	1.13	1.76
Investment	0.04	0.17	-0.02	0.03	0.08
OP	0.02	0.29	0.00	0.05	0.10
Foreign	0.12	0.15	0.02	0.06	0.16

Panel B: Full sample

	Mean	SD	p25	p50	p75
R_i^e	1.22	16.18	-6.79	-0.23	6.68
Beta	0.84	0.41	0.55	0.84	1.12
ME	805	8,147	58	113	273
B/M	0.96	0.82	0.41	0.76	1.28
Investment	0.10	0.40	-0.03	0.04	0.13
OP	-0.01	0.53	-0.02	0.04	0.10
Foreign	0.07	0.11	0.01	0.02	0.07

Table II **Fama-MacBeth Regression of Monthly Excess Returns on Firm Characteristics and Carbon Intensity**

This table reports the Fama-MacBeth (1973) regression of monthly excess stock returns on the lagged measures of firm characteristics and carbon emissions. The definitions of characteristic variables are listed in Table I. The t-statistics (in parentheses) use the Newey and West (1987) correction for heteroscedasticity and autocorrelation. The sample period is from July 2012 to December 2021. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)
Beta	0.06	0.03	0.02	0.05	0.02	0.02
	(0.14)	(0.07)	(0.05)	(0.12)	(0.05)	(0.05)
ln(ME)	-0.22***	-0.17**	-0.16**	-0.25***	-0.21**	-0.21**
	(-2.73)	(-2.15)	(-1.98)	(-3.04)	(-2.53)	(-2.53)
ln(B/M)	0.13	0.12	0.14	0.17	0.15	0.15
	(0.71)	(0.63)	(0.77)	(0.92)	(0.80)	(0.80)
Investment				-0.24	-0.33	-0.33
				(-0.33)	(-0.44)	(-0.44)
OP				2.31***	2.21**	2.21**
				(2.60)	(2.50)	(2.50)
ln(CO_2/Sales)		0.16**			0.15**	
		(2.44)			(2.28)	
ln(CO_2/Assets)			0.16**			0.15**
			(2.22)			(2.28)

Table III **Summary Statistics of Factor Portfolios**

This table reports the average, standard deviation, t-statistics, and correlation for the monthly returns of the two carbon factors and the Fama-French five factors. All returns are recorded as percentages. MKT denotes the Korea Composite Stock Price Index (KOSPI) return in excess of the risk-free rate (91-day CD yield). SMB (small minus big), HML (high minus low), RMW (robust minus weak), and CMA (conservative minus aggressive) are the size, value, investment, and operating profitability factors, respectively. All firms listed on the Korea Exchange are sorted at the end of June of each year using the KOSPI breakpoints. CO_2^{Sales} denotes a long-short portfolio based on CO2/Sales. CO_2^{Asset} denotes a long-short portfolio based on CO2/Assets. The sample period is from July 2012 to December 2021.

Panel A: Average returns of factor portfolios

	MKT	SMB	HML	RMW	CMA	CO_2^{Sales}	CO_2^{Asset}
Mean	0.49	0.40	0.30	0.02	-0.01	0.83	0.70
SD	4.01	3.43	2.56	2.03	1.86	2.50	2.54
t-stat	1.31	1.25	1.25	0.12	-0.08	3.55	2.92

Panel B: Correlation

	MKT	SMB	HML	RMW	CMA	CO_2^{Sales}	CO_2^{Asset}
MKT	1	0.02	0.17	-0.02	0.09	-0.05	0.01
SMB		1	0.13	-0.37	0.28	0.47	0.46
HML			1	-0.11	0.42	0.14	0.13
RMW				1	-0.36	-0.15	-0.12
CMA					1	0.15	0.19
CO_2^{Sales}						1	0.89
CO_2^{Asset}							1

Table IV **Average Excess Returns and Alphas of Portfolios Sorted on Carbon Risk Measures.**

This table reports the average monthly excess returns ($R_{p,t}^{e}$) and alphas of the carbon risk factor portfolios. The alphas are from the CAPM, Fama-French three-factor model, and Fama-French five-factor model. Firms are sorted into three groups (low 30%, medium 40%, and high 30%) based on the two carbon intensity measures, CO_2/Sales and CO_2/Asset, and the equal-weighted excess returns of each portfolio are calculated. The portfolios are rebalanced annually. The carbon factors, CO_2^{Sales} and CO_2^{Asset}, are constructed using the difference in portfolio returns between the high- and low-carbon risk exposure groups. Coefficient estimates significant at the 5% level are in bold and the associated t-statistics are in parentheses. The sample period is from July 2012 to December 2021.

Panel A: CO_2/Sales (3:4:3)

	Low	Mid	High	H-L (CO_2^{Sales})
Average $R_{p,t}^{e}$	0.42	**1.14**	**1.25**	**0.83**
	(0.92)	(2.30)	(2.48)	(3.55)
CAPM Alpha	-0.11	**0.59**	**0.73**	**0.85**
	(-0.54)	(2.19)	(2.30)	(3.57)
3 Factor Alpha	**-0.45**	0.14	0.16	**0.61**
	(-2.83)	(0.80)	(0.82)	(2.83)
5 Factor Alpha	**-0.31**	0.30	**0.37**	**0.68**
	(-2.22)	(1.86)	(2.02)	(3.18)

Panel B: CO_2/Assets (3:4:3)

	Low	Mid	High	H-L (CO_2^{Asset})
Average $R_{p,t}^{e}$	0.54	**1.07**	**1.23**	**0.70**
	(1.19)	(2.15)	(2.41)	(2.92)
CAPM Alpha	0.00	0.53	**0.70**	**0.69**
	(0.02)	(1.87)	(2.23)	(2.87)
3 Factor Alpha	**-0.31**	0.04	0.15	**0.46**
	(-2.02)	(0.22)	(0.76)	(2.10)
5 Factor Alpha	-0.19	0.22	0.36	**0.54**
	(-1.38)	(1.31)	(1.90)	(2.48)

Table V **Fama-MacBeth Regressions of Monthly Excess Returns on Firm Characteristics and Carbon Intensity: Comparison between High and Low Foreign Ownership Groups**

This table reports the Fama-MacBeth (1973) regressions of monthly excess stock returns on lagged measures of firm characteristics. Panel A (Panel B) reports the regression results for the groups with the lowest 50% (highest 50%) foreign ownership. The definitions of characteristic variables are listed in Table I. The t-statistics (in parentheses) use the Newey and West (1987) correction for heteroskedasticity and autocorrelation. The sample period is from July 2012 to December 2021. ***, **, and * indicate statistical significance at the 1%, 5% and 10% levels, respectively.

Panel A: Low Foreign Ownership

	(1)	(2)	(3)	(4)	(5)	(6)
Beta	-0.27	-0.29	-0.24	-0.31	-0.34	-0.34
	(-0.52)	(-0.57)	(-0.47)	(-0.61)	(-0.67)	(-0.67)
ln(ME)	-0.51***	-0.48***	-0.45***	-0.59***	-0.57***	-0.57***
	(-3.42)	(-3.17)	(-2.94)	(-3.85)	(-3.60)	(-3.60)
ln(B/M)	0.07	0.06	0.11	0.04	0.04	0.04
	(0.32)	(0.30)	(0.54)	(0.19)	(0.18)	(0.18)
Investment				-1.20	-1.27	-1.27
				(-1.10)	(-1.16)	(-1.16)
OP				3.15***	3.21***	3.21***
				(2.63)	(2.68)	(2.68)
ln(CO_2/Sales)		0.10			0.10	
		(0.98)			(1.01)	
ln(CO_2/Assets)			0.18			0.10
			(1.42)			(1.01)

Panel B: High Foreign Ownership

	(1)	(2)	(3)	(4)	(5)	(6)
Beta	0.49	0.44	0.43	0.51	0.46	0.46
	(0.97)	(0.87)	(0.86)	(1.02)	(0.91)	(0.91)
ln(ME)	-0.16	-0.11	-0.11	-0.16	-0.12	-0.12
	(-1.63)	(-1.14)	(-1.14)	(-1.58)	(-1.20)	(-1.20)
ln(B/M)	0.12	0.07	0.09	0.19	0.13	0.13
	(0.48)	(0.27)	(0.38)	(0.73)	(0.50)	(0.50)
Investment				0.64	0.53	0.53
				(0.65)	(0.53)	(0.53)
OP				1.60	1.41	1.41
				(1.28)	(1.13)	(1.13)
ln(CO_2/Sales)		0.22***			0.19**	
		(2.60)			(2.21)	
ln(CO_2/Assets)			0.17**			0.19**
			(2.17)			(2.21)

Table VI **Summary Statistics of Carbon Factors**

This table reports the average, standard deviation, t-statistics, and correlations for the monthly returns of the four carbon factors. CO_2^{Sales} denotes a long-short portfolio based on CO_2/Sales. CO_2^{Asset} denotes a long-short portfolio based on CO_2/Assets. $F\&CO_2^{Sales}$ denotes a long-short portfolio based on CO_2/Sales and foreign ownership. $F\&CO_2^{Assets}$ denote long-short portfolios based on CO_2/Assets and foreign ownership. The sample period is from July 2012 to December 2021.

Panel A: Average returns of factor portfolios

	CO_2^{Sales}	CO_2^{Asset}	$F\&CO_2^{Sales}$	$F\&CO_2^{Asset}$
Mean	0.83	0.70	0.73	0.55
SD	2.50	2.54	2.46	2.68
t-stat	3.55	2.92	3.17	2.20

Panel B: Correlation

	CO_2^{Sales}	CO_2^{Asset}	$F\&CO_2^{Sales}$	$F\&CO_2^{Asset}$
CO_2^{Sales}	1	0.89	0.92	0.77
CO_2^{Asset}		1	0.81	0.90
$F\&CO_2^{Sales}$			1	0.83
$F\&CO_2^{Asset}$				1

Table VII **Average Excess Returns and Alphas of Portfolios Bivariate Sorted on Carbon Risk Exposure and Foreign Ownership**

This table reports the average monthly excess returns ($R^{e}_{p,t}$) and alphas of portfolios bivariate sorted on a stock's carbon risk exposure and foreign ownership. Panel A (Panel B) reports the average excess returns and alphas of the factor portfolios with the lowest 50% (highest 50%) foreign ownership, which are further sorted into three groups based on CO_2/Sales (low 30%, medium 40%, high 30%), and the equal-weighted excess returns of each portfolio are calculated. The portfolios are rebalanced annually. We denote six portfolios sorted on carbon intensity and foreign ownership as L_cL_F, M_cL_F, H_cL_F, L_cH_F, M_cH_F, and H_cH_F, where subscripts C and F stand for carbon intensity and foreign ownership, and L, M, and H stand for Low, Mid, and High, respectively. The abnormal return of the long-short portfolio with low (high) foreign ownership $H_CL_F - L_CL_F$ ($H_CH_F - L_CH_F$) is constructed using the difference in portfolio returns between the high and low carbon risk exposure groups. Coefficient estimates significant at the 5% level are in bold and the associated t-statistics are in parentheses. The sample period is from July 2012 to December 2021.

Panel A: Low Foreign Ownership

	Low (L_cL_F)	Mid (M_cL_F)	High (H_cL_F)	$H_CL_F - L_CL_F$
Average $R^{e}_{p,t}$	0.66	**1.32**	**1.24**	0.58
	(1.21)	(2.41)	(2.30)	(1.78)
CAPM Alpha	0.12	**0.75**	0.72	0.60
	(0.33)	(2.21)	(1.95)	(1.83)
3 Factor Alpha	-0.40	0.20	0.11	0.51
	(-1.43)	(0.91)	(0.45)	(1.51)
5 Factor Alpha	-0.25	0.41	0.30	0.55
	(-0.91)	(1.90)	(1.32)	(1.65)

Panel B: High Foreign Ownership

	Low (L_cH_F)	Mid (M_cH_F)	High (H_cH_F)	$H_CH_F - L_CH_F$
Average $R^{e}_{p,t}$	0.34	0.85	**1.22**	**0.88**
	(0.74)	(1.85)	(2.31)	(2.83)
CAPM Alpha	-0.19	0.33	**0.70**	**0.89**
	(-0.95)	(1.41)	(1.99)	(2.83)
3 Factor Alpha	**-0.47**	0.03	0.20	**0.67**
	(-2.68)	(0.13)	(0.68)	(2.14)
5 Factor Alpha	**-0.34**	0.12	0.43	**0.77**
	(-2.09)	(0.64)	(1.53)	(2.46)

Table VIII **Estimation of Carbon Risk Premium: GMM Estimation**

This table reports the coefficient estimates and associated t-statistics from the optimal Generalized Method of Moments (GMM) estimations of the alternative stochastic discount factor model specifications. The test assets are decile portfolios sorted on CO_2/Sales. Portfolios are rebalanced at the end of June each year and the equal-weighted excess returns are calculated. MKT, SMB, HML, RMW, and CMA denote market, size, value, investment, and operating profitability factors, respectively. CO_2^{Sales} denotes a long-short portfolio based on CO_2/Sales. CO_2^{Asset} denotes a long-short portfolio based on CO_2/Assets. The sample period is from July 2012 to December 2021. The J-statistic for a test of over-identifying restrictions and its associated p-values (in parentheses) are provided at the bottom. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)
MKT	-0.67	-0.05	-0.32	-0.67	-0.18	-0.02
	(-1.24)	(-0.07)	(-0.40)	(-1.07)	(-0.19)	(-0.01)
SMB	1.83***	1.30**	1.35**	1.99***	1.66**	1.43
	(4.17)	(2.39)	(2.05)	(4.25)	(2.19)	(1.24)
HML	0.85	-0.06	0.58	0.01	-0.36	-0.10
	(0.86)	(-0.04)	(0.43)	(0.01)	(-0.35)	(-0.09)
RMW				-0.74**	-0.49	-0.60
				(-2.05)	(-1.34)	(-1.27)
CMA				-0.50	0.03	-0.36
				(-0.58)	(0.03)	(-0.41)
CO_2^{Sales}		0.78***			0.77***	
		(4.30)			(4.27)	
CO_2^{Asset}			0.77***			0.72***
			(3.41)			(2.75)
J-statistic	6.25	7.95	6.96	4.26	6.76	4.90
(p-value)	(0.51)	(0.24)	(0.32)	(0.51)	(0.15)	(0.30)

Table IX **Estimation of Carbon Risk Premium: Fama-MacBeth Regression**

This table reports the risk prices estimated using the Fama-MacBeth regression along with their associated Shanken's (1992) t-statistics (in parantheses). The test assets are decile portfolios sorted on CO_2/Sales. Portfolios are rebalanced at the end of June each year and the equal-weighted excess returns are calculated. MKT, SMB, HML, RMW, and CMA denote market, size, value, investment, and operating profitability factors, respectively. CO_2^{Sales} denotes a long-short portfolio based on CO2/Sales. CO_2^{Asset} denotes a long-short portfolio based on CO2/Assets. The adjusted R^2 values from Jagannathan and Wang (1996) are presented. MAE is the average of the absolute errors. The sample period is from July 2012 to December 2021. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)
MKT	-0.16	0.29	0.43	-0.16	0.32	0.45
	(-0.31)	(0.44)	(0.59)	(-0.28)	(0.43)	(0.56)
SMB	1.98***	1.56**	1.34	2.12***	1.51*	1.29
	(2.95)	(2.15)	(1.64)	(3.42)	(1.84)	(1.33)
HML	0.11	-0.66	-0.79	-0.25	-0.73	-0.74
	(0.08)	(-0.44)	(-0.52)	(-0.25)	(-0.62)	(-0.63)
RMW				-0.48	-0.37	-0.30
				(-1.00)	(-0.72)	(-0.57)
CMA				0.60	0.33	0.09
				(0.64)	(0.35)	(0.09)
CO_2^{Sales}		0.78***			0.78***	
		(3.09)			(3.07)	
CO_2^{Asset}			0.90***			0.91***
			(2.87)			(2.86)
R^2	0.96	0.97	0.97	0.96	0.96	0.96
MAE	0.12	0.12	0.12	0.12	0.11	0.11

Table X **Estimation of Carbon Risk Premium with Consideration of Foreign Ownership: GMM Estimation**

This table reports the coefficient estimates and associated t-statistics from the optimal generalized method of moments (GMM) estimations of the alternative stochastic discount factor model specifications. The test assets are nine portfolios that are bivariate sorted by foreign ownership and CO_2/Sales. Portfolios are rebalanced in June each year and the equal-weighted returns are calculated from July of year t to May of year t+1. MKT, SMB, HML, RMW, and CMA denote market, size, value, investment, and operating profitability factors, respectively. CO_2^{Sales} denotes a long-short portfolio based on CO_2/Sales. CO_2^{Asset} denotes a long-short portfolio based on CO_2/Assets. $F\&CO_2^{Sales}$ denotes a long-short portfolio based on CO_2/Sales and foreign ownership. $F\&CO_2^{Assets}$ denote long-short portfolios based on CO_2/Assets and foreign ownership. The sample period is from July 2011 to December 2021. The J-statistic for a test of over-identifying restrictions and its associated p-values (in parentheses) are provided at the bottom. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
MKT	0.08	0.76	0.76	0.59	0.58	-0.30	0.92	0.66	0.85	0.26
	(0.14)	(1.18)	(1.12)	(1.00)	(0.87)	(-0.39)	(0.94)	(0.78)	(1.02)	(0.33)
SMB	1.11**	1.08**	1.09**	1.23**	1.30**	1.49***	0.74	0.96*	0.82*	1.17***
	(2.47)	(2.23)	(2.14)	(2.48)	(2.42)	(3.48)	(1.34)	(1.86)	(1.85)	(2.74)
HML	1.15	-1.26	-1.18	-1.20	-1.02	0.75	-0.96	-0.67	-0.68	0.31
	(1.16)	(-0.89)	(-0.82)	(-0.84)	(-0.67)	(0.88)	(-0.49)	(-0.39)	(-0.48)	(0.29)
RMW						0.09	-0.31	-0.33	-0.18	0.12
						(0.13)	(-0.35)	(-0.41)	(-0.25)	(0.18)
CMA						-0.19	-0.43	-0.24	-0.44	-0.34
						(-0.15)	(-0.32)	(-0.17)	(-0.40)	(-0.28)
CO_2^{Sales}		0.71***					0.72***			
		(3.48)					(3.60)			
CO_2^{Asset}			0.88***					0.85**		
			(3.49)					(2.28)		
$F\&CO_2^{Sales}$				0.70***					0.63***	
				(3.18)					(2.74)	
$F\&CO_2^{Asset}$					0.87***					0.49
					(2.69)					(0.98)
J-statistic	7.52	3.75	3.68	3.85	4.07	4.11	3.19	3.33	3.07	3.58
(p-value)	(0.28)	(0.59)	(0.60)	(0.57)	(0.54)	(0.39)	(0.36)	(0.34)	(0.38)	(0.31)

Table XI **Estimation of Carbon Risk Premium with Consideration of Foreign Ownership: Fama-MacBeth Regression**

This table reports the risk prices estimated using the Fama-MacBeth regression along with their associated Shanken's (1992) t-statistics (in parantheses). The test assets are nine portfolios that are bivariate sorted by foreign ownership and CO_2/Sales. Portfolios are rebalanced in June each year and the equal-weighted returns are calculated from July of year t to May of year t+1. *MKT*, *SMB*, *HML*, *RMW*, and *CMA* denote market, size, value, investment, and operating profitability factors, respectively. CO_2^{Sales} denotes a long-short portfolio based on CO_2/Sales. CO_2^{Asset} denotes a long-short portfolio based on CO_2/Assets. $F\&CO_2^{Sales}$ denotes a long-short portfolio based on CO_2/Sales and foreign ownership. $F\&CO_2^{Assets}$ denote long-short portfolios based on CO_2/Assets and foreign ownership. The adjusted R^2 values from Jagannathan and Wang (1996) are presented. MAE is the average of the absolute errors. The sample period is from July 2011 to December 2021. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

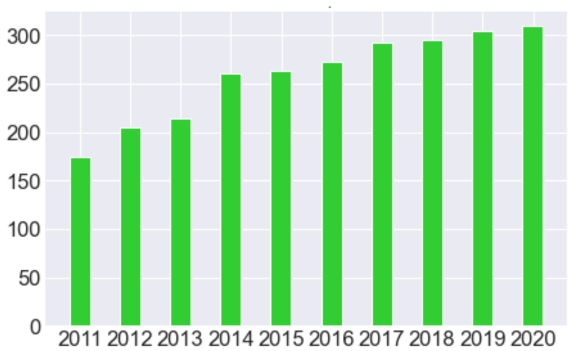
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
MKT	-0.02	0.76	0.66	0.48	0.47	-0.14	0.75	0.61	0.45	0.38
	(-0.04)	(1.16)	(1.07)	(0.74)	(0.79)	(-0.23)	(0.90)	(0.80)	(0.63)	(0.56)
SMB	0.89	1.02*	1.07*	1.17**	1.29**	1.13**	0.74	0.84	0.98*	1.08**
	(1.52)	(1.76)	(1.86)	(2.03)	(2.22)	(2.19)	(1.14)	(1.40)	(1.77)	(2.04)
HML	1.46	-1.21	-1.06	-0.53	-0.76	1.43	-0.64	-0.53	0.10	0.03
	(1.16)	(-0.74)	(-0.69)	(-0.30)	(-0.46)	(1.38)	(-0.38)	(-0.33)	(0.07)	(0.02)
RMW						0.46	0.02	-0.05	0.27	0.15
						(0.59)	(0.02)	(-0.06)	(0.32)	(0.18)
CMA						0.19	-0.17	0.09	-0.46	-0.20
						(0.14)	(-0.13)	(0.06)	(-0.35)	(-0.15)
CO_2^{Sales}		0.76***					0.75***			
		(2.81)					(2.81)			
CO_2^{Asset}			0.89***					0.88**		
			(2.95)					(2.36)		
$F\&CO_2^{Sales}$				0.58**					0.56**	
				(2.00)					(1.97)	
$F\&CO_2^{Asset}$					0.82**					0.68
					(2.03)					(1.25)
R^2	0.96	0.98	0.98	0.97	0.97	0.93	0.96	0.96	0.96	0.96
MAE	0.13	0.10	0.09	0.12	0.11	0.15	0.10	0.09	0.11	0.10

Figure I **Corporate Carbon Emissions Disclosure**

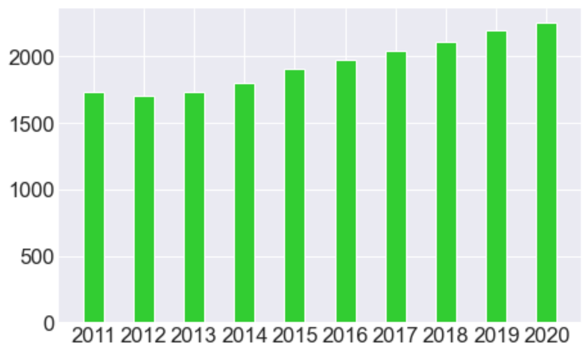
The graphs show the number of firms with carbon emissions information, the number of non-financial firms listed in the Korean stock market from 2011 to 2020 (Panel A), and the distribution of carbon emission disclosure across industries as of 2020, based on the number of firms (on the left of Panel B) or based on their carbon emissions (on the right of Panel B).

Panel A: Number of Corporate Carbon Emissions Disclosure (2011–2020)

Firms with CO2 information

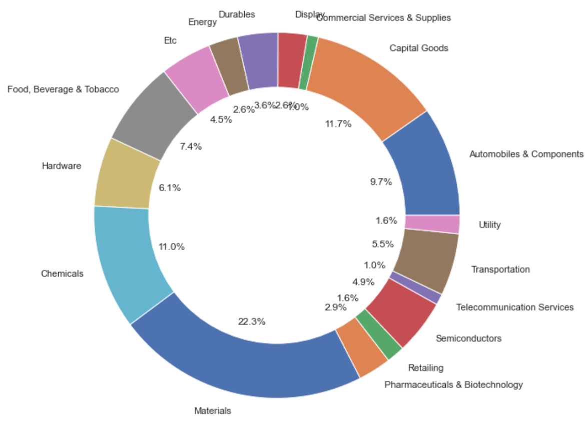


Total Sample



Panel B: Corporate Carbon Emission Disclosure across Industries (as of 2020)

Number of firms



CO_2 emissions

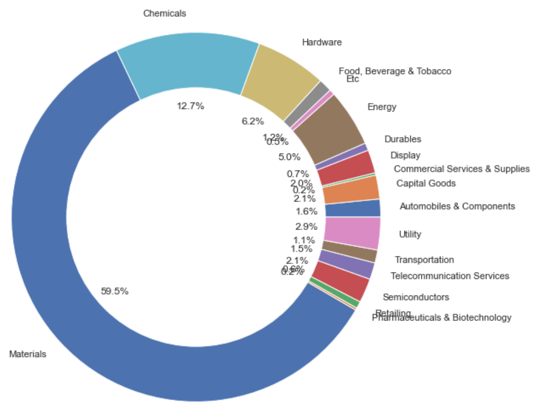


Figure II **Cumulative Returns on the carbon risk factors**

The graph shows the cumulative returns of the two long-short portfolios from July 2012 to December 2021. CO_2^{Sales} denotes a long-short portfolio formed by CO_2/Sales. CO_2^{Asset} denotes a long-short portfolio formed by CO_2/Assets.

Figure III **Cumulative Returns on Fama-French Five-Factor Portfolios**

The graph shows the cumulative returns on the Fama-French five factor portfolios from July 2012 to December 2021. MKT denotes the Korea Composite Stock Price Index (KOSPI) return in excess of the risk-free rate (91-day CD yield). SMB (small minus big), HML (high minus low), RMW (robust minus weak), and CMA (conservative minus aggressive) are the size, value, investment, and operating profitability factors, respectively.