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AN ASSESSMENT OF THE PERIODICAL SUCCESS OF THE EU ETS PHASE III FROM TWO PERSPECTIVES: THE MARKET EFFICIENCY AND THE FIRM-LEVEL CONSEQUENCE

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Abstract

This study proposed two criteria to assess the periodical success of the EU Emission Trading Scheme (EU ETS) Phase III: the market efficiency and the economic consequences of the EU ETS on the firm level. First, the carbon allowance spot market and the futures market are investigated to test the market efficiency. The empirical results derived from the Augmented Dickey-Fuller test, the Phillips–Perron test, the Lo & MacKinlay Variance Ratio test, and the Autoregressive Integrated Moving Average model (ARIMA) approach provide significant evidence that the carbon market is satisfied with the weak-form market efficiency. Second, a sample covering 125 companies from 4 sectors and listed in 13 countries are employed to test the effect of the EU ETS allowance price on the regulated stock market returns. This study finds that the carbon price returns have a positive relationship with the regulated firm's stock returns under the EU ETS phase III by employing the multifactor two-way fixed effect models. The findings of this study could benefit the regulated entities to make their abatement decisions, the stakeholder to diversify their carbon risks, and the policymaker to adjust their carbon regulations to meet the emission reduction target in a cost-efficient approach successfully.

Keywords: EU ETS, Carbon Market, Decarbonization, Market Efficiency, Stock Returns

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1. Introduction

The Kyoto Protocol raised the international responsibility for mitigating climate change in 1997. To meet the obligation under the Kyoto Protocol, the EU Emission Trading Scheme (EU ETS) was first proposed in 2003 (Ellerman & Buchner, 2020). This scheme is followed one of the three mechanisms which proposed by the Kyoto Protocol to alleviate the overall cost of emission reduction, the other two is Joint Implementation and Clean Development Mechanism (Krishnamurti & Hoque, 2011). The EU Emission Trading Scheme was successfully set up and start its trail and learning phase in 2005. After that, the carbon market has become the prominent political instrument to deal with climate change caused by sharply increasing carbon dioxide emissions (Calel & Dechezleprêtre, 2016). In its 17-year history, the EU ETS has experienced phase I (2005 - 2007), phase II (2008 - 2012), phase III (2013 - 2020), and now is in phase IV (2021 - 2030). Nowadays, the EU ETS, the first international emissions trading system, is the most promising policy instrument and regarded as the cornerstone of the European carbon policy. With the carbon emission reduction process approaching the 2050 carbon-neutral deadline, the role of the EU ETS in meeting the reduction target has become more and more important. Therefore, the periodical success of the EU ETS has drawn considerable of attention.

The criteria to assess the success of the EU ETS is a multidiscipline hotspot and should be located in multiple dimensions. The climatologists are interested in the role of the emission trading system in reducing carbon emissions (Klemetsen et al., 2020; Schaefer, 2019). While economists have drawn their attention on evaluating the characteristics of this ongoing market-based instrument, such as market efficiency (Daskalakis, 2013; Khediri & Charfeddine, 2015; Meraz et al. 2021; Montagnoli & De Vries, 2010; Niblock & Harrison, 2013); and the economic consequences of the policy instrument brought to the firms, for example, the stock market performance (da Silva et al., 2016; García et al. 2021; Harasheh & Amaduzzi, 2019).

Different from the command-and-control method which internalizing the cost on the emitting entities by implementing performance standards and technology mandates (Lamperti et al., 2020), the main advantage of the cap-and-trade system the EU ETS is the ability to achieve the emissions target in a cost-efficient approach. It is because that the latter enables the regulated entities reduce their carbon emission in a more flexible way (Mirzaee & Jafari, 2021). From an economic perspective, the flexibility means that the regulated firms have the rights to choose to invest in decarbonization project only if the benefits exceed their carbon cost (Daskalakis et al., 2011). He further illustrated that the carbon abatement decisions can be considered as a financial budget decision and the cost under the EU ETS is either the innovation expenses or the cost of purchasing the emission permits. Specifically, the underlying intuitions are as follows: the regulated companies tend to cut or delay investing their funds in decarbonization innovation when the EU emission allowance (EUAs) is cheap; and to invest in decarbonization innovation heavily or alter their business-in-normal operation to surrender to the emission target if the price of the EUAs is high. That illustrated that, similar to other markets, the price of the EUAs under the EU ETS is the crucial component in the decarbonization-decision processes (Daskalakis, 2013). Therefore, whether the EUAs price can truly reflect the marginal abatement costs of the company becomes a concern of economists and policymakers

The first criteria, that is the market efficiency, to assess the EU ETS is derived the above-mentioned concern. According to Fama's (1970) Efficient Market Hypothesis (EMH), the price could reflect all available information if the market is efficient. Based on this hypothesis, the carbon market, as a market-based political instrument employed to achieve decarbonization, is expected to transfer information to regulated entities fairly and efficiently. So that, the regulated entities can make their carbon-reducing decisions rely on the EUAs price. In other word, the inaccurate expectation of carbon cost that caused by mispriced EUAs would mislead regulated companies' carbon-reducing investment decisions and misallocation of resources (Niblock, 2011). The investigation on the market efficiency has been continuously focused since the establishment of the EU ETS. There was no significantly economic evidence support the market efficiency in the 'trial and learning' phase I (Daskalakis & Markellos, 2008; Seifert et al., 2008). However, Montagnoli and de Vries (2010) indicated that the EU ETS phase II exhibited the first positive sign that the market is efficient. Furthermore, Lee et al. (2020) pointed out that the carbon market shown increasing efficiency through phase I to phase III. This study would like to continue study in the market efficiency of the EU ETS based on the comprehensive phase III EUAs price data.

The second criterion to assess the periodical success of the EU ETS is the economic consequences brought by the carbon market. Huang & Zhou (2019) indicated the consequences might happen on the regional level. They pointed out that the emission trading system may provide incentives for regulated firms to produce out of the current region, shifting their emission outside to evade the cost caused by the policy. This concern about carbon leakage risk is addressed by one of the provisions of the EU ETS phase IV. It stated that the sectors with highest risk of moving their production outside of the EU will be allocated emission allowance for 100% free.

Regardless of the regional level consequences, this study draws attention on the firm level. Oestreich & Tsiakas (2015) illustrated the intuition of the firm level consequence is that too loose carbon emission policy, represented by too much free allocation of emission allowances and low carbon prices, may offer a ‘carbon premium’ to companies’ stock prices. In another way, companies are exposed to relatively higher carbon risks under a stringent policy. However, previous literature indicated ambiguous results regarding the relationship between the carbon price and the regulated firm’s stock market return. Some researchers found a negative relationship (da Silva et al., 2016; Moreno & da Silva, 2016), while some have different suggestions (García et al., 2021; Harasheh & Amaduzzi, 2019). The divergence here may derive from the firm-level emission level difference and the heterogeneity in each phase. This study would like to contribute to this literature gap by conducting a multi-sector investigation including phase III data and controlling the different emission levels.

Along with existing research, this study also focuses on above-mentioned two criteria and proposes two research questions respectively: first, whether the carbon market under the EU ETS phase III is efficient; second, to what extent could the carbon price affect the regulated firm's stock performance under the EU ETS phase III. This study preferred to test the market efficiency first since the outcome of the second question may be more reliable if the carbon market is efficient.

The phase III data was mentioned several times above as a novelty. First, the over-allocation problem is largely eliminated since the auction process of carbon emission allocation is widely employed in Phase III. Second, with the policy's gradual improvement through phases, the steadily growing number of regulated economic entities, and the continuously updated trading mechanism, the carbon market is moving towards maturity (Ibikunle et al., 2016; Tian et al., 2016) Therefore, this study expects that the emission allowances trading under the phase III could provide robust and reliable insight.

This paper is trying to contribute from two perspectives. First, testing the efficient market hypothesis (EMH) under the EU ETS phase III using both spot market price and future market price data. This would like to provide indication to the regulated firm that whether the carbon prices are reliable as reference when they are making abatement decisions. In addition, this also could benefit other stakeholder who are investing in carbon market to diversify their carbon risks. Second, trying to figure out the relationship between carbon market return and the regulated firm’s stock return, and further investigating the mediator effect of carbon emission intensity on relationship between carbon market return and the regulated firm’s stock return. This could reveal the economic insight for regulated companies to conduct decarbonization process and benefit the investors who are willing to diversify their portfolio. Third, adding evidence to the literature which interested in the relationship between stock market return and commodity market return by using a commodity control variable package including market returns of oil, natural gas, coal and electricity in the regression. Fourth, providing helpful information to policymakers to adjust their carbon regulations to meet the emission reduction target in a cost-efficient approach successfully.

This paper will be structured as follows. The next section will discuss the theoretical mechanism section, the hypotheses with regard to the research questions are developed in this section based on theoretical background and with helping of previous literatures. The third section presents the research design and provides an overview of method of research, including the discussion of data and variables. The fourth and fifth part of this study present the statistic results and an elaborate discussion, followed by the last conclusion and limitation section.

2. Theoretical Mechanism

In this section, the theoretical background is discussed first. Then, the previous literature are illustrated, and followed by the hypotheses.

2.1 Achievements and Criticisms in Each Phases of the EU ETS

At the beginning of this section, the descriptions and overviewed achievements and criticisms of each phase of the EU ETS is shown in the table 1.

TABLE 1: OVERVIEW OF THE EU ETS IN SEPARATE PHASES

	Phase I	**Phase II**	**Phase III**
Period	2005-2007	2008-2012	2013-2020
Main Feature	- Trail and learning period	- First commitment period of the Kyoto Protocol	- Considerable changes compared with Phase I and II
Achievements	- Put a price on carbon emission - Created a free trade market across the EU - Established the infrastructure - Covered power generator and energy-intensive industries	- The proportion of free allocation decreased to 90% of phase I - Auctions were introduced - The emission caps were set lower than phase I	- Auction replaced the free allocation as the main method to allocating emission allowances - A EU-wide emission cap replaced the national caps

		- Aviation sector was brought in the scheme	
Criticisms	- Too loose caps - Free allocation induced over allocated	- Still criticized for overallocation	- The cap should be tighter in order to increase the pace of emission reduction

2.2 Weak-Form Efficiency Market

Whether the prices in the carbon market are following the random walk behavior is the main key point to test the carbon market efficiency (Niblock, 2011). The random walk hypothesis (RWH) was proposed by Malkiel (1989). Specifically, this hypothesis assumes that the subsequent price changes present a random departure from previous prices. The underlying mechanism behind this random walk characteristic is that all the information is immediately reflected in the price, which is associated with the efficient market hypothesis.

The efficiency market hypothesis (EMH) was first formulated by Fama (1970). He first defined the term 'efficient' as 'a market in which prices always fully reflect available information.' Then, he proposed three different efficiency forms that differ in the set of 'available information' which are the weak form efficiency, semi-strong form efficiency, and strong form efficiency. The 'available information' set refers to historical prices under the weak form efficiency market, indicating that the past information is already contained in the prices. Semi-strong form efficiency assumes that all the public information is reflected in today's prices, while strong form efficiency assumes that all information in the market, whether public or private, is calculated in the current prices.

The association between EMH and RWH provides scholars a practical way to test the efficiency of the market. However, the market efficiency can only be tested empirically and could be recognised as efficient if the test results surpass the statistical critical value (Niblock, 2011).

2.3 Literature Review on the Carbon Market Efficiency

The assessment of the function of the EU emission trading scheme has been focused by economists back to its establishment (Daskalakis & Markellos, 2008; Seifert et al., 2008). Daskalakis & Markellos (2008) conducted research on the EU ETS phase I and they found the emission allowance return are serially predictable in both spot and future markets. They concluded that there is no significantly economic evidence indicated that the carbon market followed the weak form of efficiency. In contrast, Seifert et al. (2008) indicated that the CO2 market of the EU was relatively efficient by conducting autocorrelation analysis on emission allowance returns. They believed that the autocorrelation of carbon market returns in the EU was behaving similarly like the matured US SO2 market return. Therefore, their findings suggested that the EU ETS was informationally efficient compared with other environmental markets. With regarding to phase II of the EU ETS, the investigation on the carbon market efficiency became more abundant (Daskalakis, 2013; Ibikunle et al., 2016; Montagnoli and de Vries, 2010; Niblock and Harrison, 2013). By employing the idea that the weak form of efficiency could be tested by the random walk hypothesis, Montagnoli and de Vries (2010) conducted adjusted variance ratio test and found that carbon market in phase I was inefficient, which consistent with Daskalakis & Markellos (2008). Moreover, they also indicated that there existed restoring of market efficiency at the beginning of phase II and the EU ETS presented the first sign towards maturation. Daskalakis' (2013) further research based on phase II future market data also provided significant evidence to confirm Montagnoli and de Vries' (2010) conclusion that the EU ETS phase II was moving to efficiency and maturity. In line with these, Ibikunle et al. (2016) shown that emission allowance prices in phase II moved towards random walk benchmark and the carbon market efficiency was continuously improving. Furthermore, Niblock and Harrison (2013) tested the carbon market efficiency in two specific periods in phase II which is global financial crisis and European sovereign debt crisis respectively. They conducted the random walk tests and found the price return shown limited predictabilities and non-predictable in these two periods. They also implemented the trading rule profitability method and compared the return with buy-and-hold strategy. The results shown that no abnormal return could be gained which indicated that the carbon market in phase II satisfied the weak form market efficiency. The investigation on carbon market efficiency cannot appear its comprehensive blueprint if the phase III data are not included in the sample. Sattarhoff & Gronwald (2018) proposed an intermittency coefficient method to measure the market efficiency. By comprising phase III data, they draw the conclusion that the EU emission trading scheme became more efficient over time. Moreover, Lee et al. (2020) also pointed out that the EU carbon market exhibited increasing efficiency through phase I to phase III alongside with the maturity of the EU ETS. They concluded that phase III displayed highest information efficiency under the market deficient measure. This study expects consistent conclusion with previous literature although under different statistical testing. Therefore, the hypothesis 1 could be made as:

The carbon market under the EU ETS phase III is weak-form efficient.

2.4 Porter Hypothesis and Cash Flow Hypothesis

Two theories that indicated seemingly controversial relationships between carbon price and stock return are discussed in this section, namely the Porter hypothesis and the cash flow hypothesis. The positive relationship between carbon price and stock return is supported by the Porter hypothesis. Porter (1991) suggested that severe environmental regulation could positively influence the firm's performance through stimulating innovations. He suggested the underlying mechanism is that innovation could increase the firm's competitiveness in the long run. Particularly, the role of environmental regulation in this mechanism is a promoter to help the companies to overcome the innovation barriers, such as behavioral barriers and organizational barriers. Likewise, this 'promoter' role of environmental regulation is also supported by Hicks (1963). He presented that 'a change in the relative prices of the factors of production is itself a spur to the invention'. In this case, the increasing carbon emission cost bore by the regulated companies implicitly represent the higher productive factor. Thus, induced innovations are coupled with increasing carbon emission price. Consequently, the increasing carbon emission allowance price would relate to a higher stock return according to Porter hypothesis.

Negative relationship between carbon price and the stock return of regulated firms is indicated by the cash flow hypothesis from the microeconomic perspective. It suggests that carbon pricing imposes an additional cost for regulated companies, and the rising cost would decrease the cash flow generated by the firm. As a result, the decreased cash flow would negatively influence the stock performance of regulated firm.

However, this intuition could be doubtful since there may exist a pass-through effect. Joltreau & Sommerfeld (2019) indicated that firms under the EU Emission Trading Scheme could pass the emission cost and other compliance cost onto their downstream customs. That is, transfer the increasing cost to their consumers through an increasing price of their product (Sijm er al., 2007). Therefore, the additional compliance cost would not significantly decrease the cash flow or the competitiveness of the regulated firm. In other word, the regulated firm prevent their performance from being damaged by means of passed-through approach. Therefore, the concern of cash flow hypothesis would not be a problem. If so, a higher carbon cost which could be passed through to the consumer and would not decrease the stock return of regulated firms.

2.5 Literature Review on the Firm-level Economic Consequences

Empirically, the effect of carbon pricing on the stock market return remains ambiguous. On the one hand, da Silva et al. (2016) explained that the carbon price influences the firm's stock market return through cash flows which are eroded by the additional emission allowance costs. Furthermore, they stated that the influence on the profitability would exhibit different degrees depending on the different emission intensities of the firm.

On the other hand, Moreno & da Silva (2016) found a significant positive relationship in phase II by investigating Spanish power industry. They attribute this to the over-allocation of the permit allowance in phase II. Moreover, they also indicated that the effect of EUAs is supposed to be sector-specific and period-specific. Furthermore, García et al. (2021) investigated a sample including the power sector from six EU members in phase III. They found a significantly positive long-run relationship between the EU allowance price and the stock performance. Their study proposed that the higher carbon prices linked to higher stock returns. They further indicated that their finding verified one of the purposes of the EU ETS that the most polluting companies would be removed from the emission system through carbon reduction policies. In addition, despite the linear relationship, Harasheh & Amaduzzi (2019) found that the positive and significant relevance of EUAs return on equity return may stay constant until it reaches a certain level of EUAs price, then move oppositely.

Along with the first stage of the Porter's theory that the regulator could promote the innovation, previous literature revealed a significant effect of the EU ETS on decarbonization innovation (Calel & Dechezleprêtre, 2016; Rogge, K. S., 2016; Venmans et al., 2020). Thus, this study expects the second stage of Porter hypothesis could appear. That is, the 'promoter' EU ETS regulations could induce a higher stock return. Based on the above, hypothesis 2 could be drawn as follows:

The carbon price returns have positive relationship with the regulated firm's stock returns under the EU ETS phase III.

3. Research Design

Two empirical approaches are designed to test the two hypotheses and are discussed in this section respectively. For the first hypothesis, the time series regression and non-parametric approach, including Augmented Dickey–Fuller test (ADF test), Phillips–Perron test (PP test) and Lo & MacKinlay Variance Ratio Test (VR test), are involved. To test the second hypothesis, the fixed effect regression model with panel data is involved.

3.1 Empirical Framework for Testing Hypothesis 1

In this section, the carbon market price variables, including spot market price and future market prices, which are used to test the EU ETS efficiency of hypothesis 1 are discussed first. Then, the methodologies for testing the hypothesis 1 are explained, including the underlying mechanism of the ADF test, the PP test and the VR test.

3.1.1 Carbon Market Price variables for Testing the EU ETS Efficiency

The daily closed price of EU Allowances (EUAs) is employed to test the efficiency of the carbon spot market, denoted as *EUAs*. The daily closed price of carbon futures listed in the European Climate Exchange (ECX), including ECX DEC2, ECX DEC3 and ECX DEC4 futures of the EU emission Allowances, are employed to test the efficiency of carbon future market, denoted as *DEC2*, *DEC3* and *DEC4* respectively. The European Climate Exchange (ECX) is the largest marketplace for the EU ETS trading (Mizrach & Otsubo, 2014). Investigating in both spot market and future market could provide a comprehensive insight of the carbon market since a large part of carbon transactions are taking place in the future market (Daskalakis, 2013).

3.1.2 Methodologies for Testing Hypothesis 1

The aforementioned connection between the Efficient Market Hypothesis and the Random Walk hypothesis in the section 2.2 provides an applicable angle to test the efficiency of the EU ETS. That is, testing whether a time series of price data follows the random walk. In this study, two different unit root tests are employed to test the random walk.

One of the unit root tests involved in this research is the Augmented Dickey–Fuller test (ADF test). The null hypothesis is that the price data time series contains a unit root. The general equation (1) illustrated the underlying mechanism that the how the ADF test works. Statistically, the null hypothesis of the ADF test is that the coefficient of $Price_{t-1}$, which is α, is equal to zero. While the alternative hypothesis of ADF test is that the coefficient α is not equal to zero.

$$\Delta Price_t = \alpha Price_{t-1} + \sum_{j=1}^{p} \beta_j \Delta Price_{t-j} + \delta + \gamma t + u_t \tag{1}$$

Where: $\Delta Price_t$ is the difference of price between time t and t-1

$Price_{t-1}$ is the price at time t-1

$\Delta Price_{t-j}$ is the difference of price between time t-j and t-j-1

t is the time trend

α is the coefficient of the $Price_{t-1}$

p is the lag order of the autoregressive process

β is the coefficient of the $\Delta Price_{t-j}$

δ is the constant term

γ is the coefficient of the time trend

u_t is the innovation sequence term

According to the section 3.11, four carbon price variables are involved to test the EU ETS efficiency. Therefore, four specific regression equations are derived from the equation 1. The table 2 shows these four equations for conducting ADF test.

TABLE 2: REGRESSION EQUATIONS FOR CONDUCTING ADF TEST

Equation	
(1.1)	$\Delta EUAs_t = \alpha EUAs_{t-1} + \sum_{j=1}^{p} \beta_j \Delta EUAs_{t-j} + \delta + \gamma t + u_t$
(1.2)	$\Delta DEC2_t = \alpha DEC2_{t-1} + \sum_{j=1}^{p} \beta_j \Delta DEC2_{t-j} + \delta + \gamma t + u_t$
(1.3)	$\Delta DEC3_t = \alpha DEC3_{t-1} + \sum_{j=1}^{p} \beta_j \Delta DEC3_{t-j} + \delta + \gamma t + u_t$
(1.4)	$\Delta DEC4_t = \alpha DEC4_{t-1} + \sum_{j=1}^{p} \beta_j \Delta DEC4_{t-j} + \delta + \gamma t + u_t$

The lag order of the autoregressive process, which is p in the equation 1, should be determined first before conducting the ADF test. According to Ng & Perron (1995), the process for choosing this lag length should start with the max length which was suggested by Schwert (1989). The max lag length is calculated as:

$$Lag\ length_{max} = \left[12 * \left(\frac{T}{100}\right)^{1/4}\right]$$

Then, the Ng & Perron (1995) suggested that if the absolute t-value of last lagged difference is larger than 1.6, the maximum lag length should be chosen. Otherwise, one should reduce the lag length by one and repeat the process. The selection results of the lag order for equation 1.1, 1.2, 1.3 and 1.4 are displayed at the beginning of the section 4.3.

The second methodology to test the market efficiency of hypothesis 1 is the Phillips–Perron Test (PP test). The null hypothesis of the PP test is that it has a unit root. Different from the ADF test which employed the lag term, the Phillips–Perron (1988) uses Newey–West standard errors to account for serial correlation. The general regression equation for the PP test is as equation 2:

$$Price_t = c + \beta t + \gamma Price_{t-1} + u_t \qquad (2)$$

Where: $Price_t$ is the price at time t

$Price_{t-1}$ is the price at time t-1

t is the time trend

c is the constant term

β is the coefficient of the time trend

γ is the coefficient of the $Price_{t-1}$

u_t is the innovation sequence term

The specific regression equations regarding to the four different carbon price variables could be derived from the equation 2. The table 3 displays the four regression equations for the PP test.

TABLE 3: REGRESSION EQUATIONS FOR CONDUCTING PP TEST

Equation	
(2.1)	$EUAs_t = c + \beta t + \gamma EUAs_{t-1} + u_t$

(2.2) $DEC2_t = c + \beta t + \gamma DEC2_{t-1} + u_t$

(2.3) $DEC3_t = c + \beta t + \gamma DEC3_{t-1} + u_t$

(2.4) $DEC4_t = c + \beta t + \gamma DEC4_{t-1} + u_t$

Lo & MacKinlay Variance Ratio Test, which is a non-parametric approach used to test the random walk, are conducted thirdly. Lo and Mackinlay (1988) first proposed this variance ratio test and illustrated the underlying mechanism as: if the time series variable follows a random walk, the variance should change the same in each equally spaced interval. In other words, the variance changed in k periods of time should be k multiply the variance changed in 1 period if the time series variable follows a random walk (Zhang et al., 2020). Therefore, the variance ratio should significantly equal to one if the data series follows a random walk. The null hypothesis of the Lo & MacKinlay Variance Ratio test is that the variance ratio of k-period return equals to 1 (Charles & Darné, 2009). Statistically, the formular to calculate the variance ratio could be expressed as:

$$VR(k) = \frac{\widehat{\sigma^2}(k)}{\widehat{\sigma^2}(1) * k}$$

Where: VR(k) is the variance ratio of k-period return

$\widehat{\sigma^2}(k)$ is the estimation variance of k-period return

$\widehat{\sigma^2}(1)$ is the estimation variance of 1-period return

3.2 Empirical Framework for Testing Hypothesis 2

In this section, variables and methodologies regard to hypothesis 2 are discussed. Two regression models are employed to test the relationship between the carbon price returns and the regulated firms' stock returns in hypothesis 2. Both models use the daily stock returns of the regulated firm as the dependent variable. However, model 1 employs the daily EU Allowance returns as the independent variable. Moreover, model 2 added an interaction term based on model 1 to investigate the mediator effect of the carbon emission intensity on the relationship between the carbon price returns and the regulated firms' stock returns.

3.2.1 Dependent Variable

The daily stock return of the regulated firm is employed as the dependent variable for testing the hypothesis 2. It is derived from the closed price by using the continuous return formula, which is $stock\_return_t = \ln(price_t / price_{t-1})$. It provides a more accurate result of return than the discrete method, which is $r_t = (price_t – price_{t-1}) / price_{t-1}$. It deserves to mention that the return could be treated as the first difference of the log form of price and this could help to fix the non-stationary problem of the carbon price data. This method is also used when dealing with the non-stationarity of the independent variables.

3.2.2 Independent Variable

The daily EU Allowance (EUAs) return is employed as the independent variable. It is calculated from the log form of the closed price of EUAs spot market by using the same continuous return formula as the dependent variable.

An interaction term generated from the product of the return of EUAs and the carbon intensity is employed as an independent variable in model 2. In this study, the firm's carbon intensity is defined as the total amount of annual emission of CO_2 divided by the revenue. Therefore, a higher value of carbon intensity indicated that the company would emit relatively large amount of CO_2 when generating one unit of revenue. The dummy variable carbon intensity recognized the top 10 percent companies in the dataset with highest carbon intensity with the value equal to 1 and 0 otherwise. Under this mechanism, the interaction term represents the moderator effect of carbon intensity on the relationship between the carbon price returns and the regulated firms' stock returns.

3.2.3 Control Variables

To deal with the omitted variable bias in order to obtain more accurate relationship between dependent and independent variables, several control variables are also introduced.

Factors in Capital Asset Pricing Model (CAPM), including risk-free rate and market return, are introduced as two control variables. CAPM is widely involved as a guide theory in the investigation of stock returns. Tian et al. (2016) also employed these two variables in their research which focus on the relationship between stock returns and the carbon market returns.

Return of commodities, including variables such as return of the oil, return of the electricity, and the return of the coal, are also employed as control variables. The underlying rationale of using this commodity-variables package could be stated in two perspectives. On the one hand, the cash flow hypothesis (Fisher, 1930) believed that higher commodities' price may increase the cost burden of most firms, hence, reducing the future cash flows. Therefore, commodities' price negatively influences the stock return. In line with this theory, Smyth & Narayan (2018) also concluded that high commodities' price sometimes indicated a higher inflation rate and interest rate, which will depress the discounted cash flow and thus decrease the stock returns. On the other hands, Iyke & Ho (2021) illustrated that the investors have always seen the commodity market as a haven to diversify their portfolio of equity market. Therefore, the commodity return may have a negative relationship with stock returns.

In the interest of clarification, the definition of the variables used for testing the hypothesis 2 are shown in the table 4. The symbols are the representations of variables employed in the regression equation.

TABLE 4: DEFINITION OF THE VARIABLES

Symbol	Definition
stock_return	Dependent variable, the daily stock return of the regulated firm
eua_return	Independent variable, the daily EU Allowance (EUAs) return
carbon_intensity	Dummy variable equals to 1 if the firm's carbon intensity belongs to the highest 10 percent and equals to 0 otherwise
eua_carbon	Product of EU Allowance return and carbon intensity
risk_free	The risk-free rate

market_return	The daily return of the market portfolio
oil_return	The daily return of the oil
electricity_return	The daily return of the electricity
coal_return	The daily return of the coal

3.2.4 Methodologies for Testing Hypothesis 2

The multifactor two-way fixed effect model controlled with heteroskedasticity and serial correlation robustness is used to test the hypothesis 2. In model 1, the stock return of the regulated firm is the dependent variable, and the EUAs return is the independent variable. In model 2, the aforementioned interaction term is added. Furthermore, the control variables including the risk-free rate, the return of market portfolio, the return of oil, the return of electricity, and the return of the coal are employed in both models. The table 5 shows the regression equations of the model 1 and 2.

TABLE 5: REGRESSION MODELS

Model	Equations
1	$stock\_return_{i,t} = \beta_0 + \beta_1 * eua\_return_{i,t} + \beta_2 * risk\_free_{i,t} + \beta_3 * market\_return_{i,t}$ $+ \beta_4 * electricity\_return_{i,t} + \beta_5 * oil\_return_{i,t} + \beta_6 * coal\_return_{i,t} + \varepsilon_{i,t}$
2	$stock\_return_{i,t} = \beta_0 + \beta_1 * eua\_return_{i,t} + \beta_2 * risk\_free_{i,t} + \beta_3 * market\_return_{i,t}$ $+ \beta_4 * electricity\_return_{i,t} + \beta_5 * oil\_return_{i,t} + \beta_6 * coal\_return_{i,t}$ $+ \beta_7 * carbon\_intensity_{i,t} + \beta 8 * eua\_carbon_{i,t} + \varepsilon_{i,t}$

3.3 Sample and Data

In order to provides reliability of this study, the collection process of data is presented at the beginning of this section, following with the description of the sample used in this study.

First, the Refinitiv database is used to collect the EU ETS data. An EU ETS covered installation dataset is employed as foothold of this study. Companies who are holding these installations are discovered based on this installation dataset.

Second, the batch search tool in Orbis database is engaged to match the companies' name and the companies' ID since only the companies' name are obtained in the first step. The ISIN number are discovered at this stage since this study aims to investigate the stock return. The sample of this study are reduced heavily at this stage since most of the regulated firm are non-listed firms.

Third, the data of stock price and carbon intensity are acquired from Refinitiv based on the ISIN number obtained from the Orbis.

Then, the EUAs price and ECX DEC2, ECX DEC3, and ECX DEC4 futures prices are all obtained from Refinitiv database; the risk-free rate is derived from the Refinitiv database by using the return of 10 years government bonds based on the countries the company listed on; the market return is derived from the Refinitiv database by using the stock exchange index based on the countries the company listed on; the price of oil (Brent crude oil spot price), the price of electricity (Germany electricity spot price), the price of natural gas (NBP actual price), the price of coal (European market history price) are all obtained from Refinitiv.

After the collection process, the sample used in this study contains 125 companies from 4 sectors classified by the Nomenclature of Economic Activities (NACE), including mining and quarrying (B), manufacturing (C), electricity, gas, steam and air conditioning supply (D), and transportation and storage (H); and from 13 countries including Austria, Belgium, Czech Republic, Germany, Denmark, Spain, Finland, France, Greece, Italy, Norway, Poland, and the United Kingdom.

The time span for all variables is from 2013 to 2020 since this study focuses on the EU ETS under Phase III. Moreover, the time period covers 2009 trading days after merging the carbon market daily data with the stock market daily data and the commodity market daily data. The detailed description of all the variables including mean, standard deviation, minimum and maximum value also display in the description statistics table 6.

4. Results

In this section, the results of descriptive statistics, Augmented Dickey–Fuller test, Phillips–Perron test, Lo & MacKinlay variance ratio test, correlation test, regression of model 1 and 2 and robustness test are discussed.

4.1 Descriptive Statistics

The mean value, standard deviation, minimum value and maximum value are shown in the table 6. The risk-free rate is negative in some time period and this study alters them into 0.

TABLE 6: DESCRIPTIVE STATISTIC

	Mean	Stand dev.	Min	Max
stock_return	0.0002036	0.0105197	-0.1167053	0.0705713
eua_return	0.000721	0.0333026	-0.4097023	0.2018661
carbon_intensity	0.4614691	0.498514	0	1
eua_carbon	-0.0000748	0.021739	-0.4104232	0.2011452
risk_free	0.013163	0.014606	0	0.1937811
market_return	0.0002741	0.0126704	-0.1692376	0.1146064
electricity_return	0.0007643	0.0165875	-0.1552052	0.1427011
oil_return	-0.0000672	0.0245005	-0.2797615	0.190774
coal_return	-0.0000659	0.0164897	-0.0993464	0.1006651
gas_return	-0.0006488	0.0422173	-0.6993778	0.4514713

4.2 Correlation

It could be seen from the first column of the table 7 that the correlation between independent variable *eua_return* and dependent variable *stock_return* is significantly positive, which provides a preliminary look of the result before conducting the regression analysis. The correlation between the variable *market_return* and the dependent variable *stock_return* is significantly strong, which is consistent with the previously mentioned CAPM theory. However, the variable *risk_free* shows insignificantly negative correlation with the dependent variable *stock_return*. When looking through the whole table, the correlation coefficients between explanatory variables are all relatively small and smaller than 0.5. It indicates that the severity of multicollinearity is low.

TABLE 7: CORRELATION MATRIX

	1	2	3	4	5	6	7	8	9
1. stock_return	1.0000								
2. eua_return	0.1605***	1.0000							
3. risk_free	-0.0023	-0.0096***	1.0000						
4. market_return	0.7702***	0.1584***	-0.0074***	1.0000					
5. electricity_return	0.4428***	0.1184***	0.0183***	0.4563 ***	1.0000				
6. oil_return	0.3019***	0.1936***	-0.0095***	0.2561***	0.0987***	1.0000			
7. coal_return	0.1010***	0.0722***	-0.0094***	0.0772***	0.0326***	0.1107***	1.0000		
8. gas_return	0.0782***	0.1390***	-0.0056***	0.0668***	0.0137***	0.0757***	0.1462***	1.0000	
9. eua_carbon	0.0837***	0.6528***	-0.0071***	0.0839***	0.0612***	0.1075***	0.0357***	0.0778 ***	1.0000

* p<0.05,** p<0.01,*** p<0.001

4.3 Augmented Dickey–Fuller Test for Hypothesis 1

The table 8 shows the statistic test results of the Augmented Dickey-Fuller (ADF) test and the detailed time series regression results of regression equation 1.1, 1.2, 1.3 and 1.4 are shown in the Appendices 1. It could be seen from Table 8 that the t-value of *EUAs* is -1.653, and the p-value is equal to 0.7710, which is higher than the critical value 0.05. Therefore, the null hypothesis of ADF test could not be rejected. The results of the ADF test show that the variable *EUAs* contains a unit root and indicate that carbon price variable *EUAs* follows a random walk. For the three carbon futures listed in the European Climate Exchange (ECX), the p-values are all higher than 0.05. That means all the null hypotheses of the ADF test could not be rejected. Therefore, the ADF tests indicate that the variables *DEC2*, *DEC3*, and *DEC4* all follow the random walk. Consequently, the hypothesis 1 should be accepted and the conclusion could be draw based on the ADF test. That is, the carbon market under the EU ETS phase III is weak-form efficient.

TABLE 8: THE RESULTS OF AUGMENTED DICKEY–FULLER TEST

	EUAs	DEC2	DEC3	DEC4
Dickey-Fuller test statistic	-1.653	-1.170	-1.177	-1.146
MacKinnon approximate p-value	0.7710	0.9165	0.9152	0.9209

* p<0.05, ** p<0.01, *** p<0.001

4.4 Phillips–Perron Test for Hypothesis 1

The table 9 shows the statistic test results of the Phillips–Perron (PP) test and the detailed time series regression results of regression equation 2.1, 2.2, 2.3 and 2.4 are shown in the Appendices 2. It could be seen from Table 9 that the rho-value of *EUAs* equals -9.489, and the t-value is equal to -2.275. The MacKinnon approximate p-value is 0.4479, which is higher than the critical value 0.05. Therefore, the null hypothesis of PP test could not be rejected. That is, the PP test indicated that the variable *EUAs* contains a unit root and follows a random walk, which is consistent with the ADF test.

In line with the *EUAs*, the p-values of the three futures listed in the European Climate Exchange are all higher than 0.05, equal to 0.8534, 0.8647, and 0.8728, respectively, indicating that the null hypotheses of PP test could not be rejected. That is, the PP test indicated that these variables contain a unit root and follow a random walk, which is consistent with the ADF test. In that case, the hypothesis 1 should be accepted. Therefore, based on the results of the Phillips–Perron test and Augmented Dickey-Fuller test, the conclusion could be made as that the carbon market under the EU ETS phase III is weak-form efficient.

TABLE 9: THE RESULTS OF PHILLIPS–PERRON TEST

	EUAs	DEC2	DEC3	DEC4
Phillips-Perron rho test statistic	-9.489	-4.068	-3.828	-3.647
Phillips-Perron tau test statistic	-2.275	-1.425	-1.387	-1.358
MacKinnon approximate p-value	0.4479	0.8534	0.8647	0.8728

4.5 Lo & MacKinlay Variance Ratio Test for Hypothesis 1

The statistic results of the Lo & MacKinlay variance ratio test are shown in the table 10. It could be seen from table 10 that the p-value for each span of differencing (2,5,10, 20 and 30) of *EUAs* are higher than the critical value 0.05, equals 0.7096, 0.3642, 0.4419, 0.1960, 0.1547, respectively. Thus, the null hypothesis of the Lo & MacKinlay variance ratio test could not be rejected. This means that the variance ratio of the price variable *EUAs* are significantly equal to 1. In other words, the variable *EUAs* follows a random walk, which is consistent with the ADF test and PP test. In a similar way, the z-statistic values and P-values of variables *DEC2*, *DEC3*, and *DEC4* in all spans of differencing (2,5,10, 20 and 30) all indicate that the null hypothesis of Lo & MacKinlay variance ratio test could be rejected. Thus, the variance ratio of the price variable *DEC2*, *DEC3*, and *DEC4* are significantly equal to 1 which indicate that these future price variables all follow a random walk. The results of Lo & MacKinlay variance ratio test are consistent with the ADF test and PP test.

Altogether, the conclusion of the hypothesis 1 could be draw based on the results of Augmented Dickey-Fuller test, Phillips–Perron test and Lo & MacKinlay variance ratio test. That is, the carbon market under the EU ETS phase III is weak-form efficient.

TABLE 10: THE RESULTS OF LO & MACKINLAY VARIANCE RATIO TEST

	Period/k	VR value	z-statistic	P-value
EUAs	2	1.015	0.3724	0.7096
	5	0.923	-0.9075	0.3642
	10	0.907	-0.7689	0.4419
	20	0.783	-1.2931	0.1960
	30	0.710	-1.4231	0.1547
DEC2	2	0.966	-0.8214	0.4114
	5	1.002	0.0251	0.9800
	10	0.934	-0.4745	0.6351
	20	0.874	-0.6536	0.5134
	30	0.813	-0.8038	0.4215
DEC3	2	0.969	-0.7693	0.4417
	5	1.004	0.0394	0.9686
	10	0.938	-0.4491	0.6534
	20	0.886	-0.5948	0.5520
	30	0.833	-0.7215	0.4706
DEC4	2	0.972	-0.6895	0.4905
	5	1.006	0.0683	0.9455
	10	0.939	-0.4472	0.6547
	20	0.893	-0.5602	0.5753
	30	0.848	-0.6612	0.5085

4.6 Regression Analysis Results for Hypothesis 2

It could be seen from Table 11 that the overall fitness of Model 1 is equal to 0.6185, meaning 61.85% variation of the dependent variable could be explained by the explanatory variables. The coefficient of the independent variable returns of the EUAs (*eua_return*) in

Model 1 is equal to 0.0042652, which is positive, and the p-value of the coefficient is lower than the critical value 0.001, which indicates it is significant. Therefore, the null hypothesis could be rejected with the 99.9% level of significance. Consequently, the hypothesis 2 that the carbon price returns have positive relationship with the regulated firm's stock returns under the EU ETS phase III should be accepted.

The results of control variables in Model 1 are also shown in Table 11. The control variable returns of the market portfolio (*market_return*) has the strongest power to explain the dependent variable stock returns (*stock_return*) with a coefficient equal to 0.5575665 and significant on the 99% level. The control variable risk-free rate (*risk_free*) has a significant negative relationship with the dependent variable. The control variables from the commodity package all have significantly positive relationships with the dependent variable.

Model 2 further investigates the mediator effect that the carbon intensity (*carbon_intensity*) brings on the relationship between the independent variable (*eua_return*) and the dependent variable (*stock_return*) by involving an interaction term (*eua_carbon*). It could be seen from the table 7 that the coefficient of the interaction term (*eua_carbon*) in Model 2 is significantly negative. This result indicates that carbon intensity has a moderating effect on the relationship between the independent variable (*eua_return*) and the dependent variable (*stock_return*). That is, the stock returns of firms with the highest level of emission intensity have negative relationship with the EUAs returns. Whereas the the coefficient of independent variable (*eua_return*) remains significantly positive which verifying the conclusion derived from the model 1.

Altogether, the hypothesis 2 that the carbon price returns have positive relationship with the regulated firm's stock returns under the EU ETS phase III should be accepted.

TABLE 11: REGRESSION RESULTS OF MODEL 1 AND MODEL 2

	Model (1)	Model (2)
	stock_return	stock_return

eua_return	0.0042652***	0.0057702***
	(6.81)	(6.15)
risk_free	-0.00429*	-0.00433*
	(-2.42)	(-2.48)
market_return	0.5575665***	0.5575063***
	(31.12)	(31.11)
electricity_return	0.0882724***	0.0882242***
	(12.44)	(12.44)
oil_return	0.0481685***	0.0481207***
	(20.95)	(20.97)
coal_return	0.0210708***	0.021029***
	(35.88)	(36.02)
carbon_intensity		0.0000249
		(0.94)
eua_carbon		-0.0034908**
		(-2.87)
Observation	222,184	222,184
R^2	0.6185	0.6185
Industry	Yes	Yes
Country	Yes	Yes
Time	Yes	Yes

t-statistic values in parentheses

* p<0.05, ** p<0.01, *** p<0.001

4.7 Robustness Test

In this section, the robustness tests are conducted. The ARIMA model is used to test the robustness of hypothesis 1. For hypothesis 2, there are two methods involved, one is cutting the sample size, and the other is changing one of the control variables.

4.7.1 Autoregressive Integrated Moving Average Model for Testing Hypothesis 1

The weak-form efficiency market hypothesis indicated that all historical information is already contained in the price. Specifically, the historical price could not be used to predict the future price. The Autoregressive integrated moving average model (ARIMA) could be used as a handful tool to predict (Feng et al., 2011; Khan et al., 2021; Zhu & Chevallier, 2017). Therefore, it could be used to test the hypothesis 1 by comparing the predicted value and the actual value.

The time period Jan 1, 2017 to Jan 1, 2018 is used to estimate the spot market model, and the following 20 days are used as the comparing period. The time period Jan 1, 2017 to June 30, 2019 is used to estimate the future model, and the following 20 days are used as the comparing period.

After estimating and comparing the AIC and BIC values of 18 selected models, the model ARIMA (3,1,2) for predicting the spot market return (*predicted_eua_return*) and the model ARIMA (2,1,2) for predicting the ECX DEC3 future market return (*predicted_DEC3_return*) are chosen since these two models have the smallest BIC number among others. Table 12 shows the results of ARIMA regression.

TABLE 12: THE RESULTS OF ARIMA PREDICTION MODEL

	ARIMA (3,1,2)	ARIMA (2,1,2)
	predicted_eua_return	predicted_DEC3_return
ar		
L1	-0.8706495 ***	0.3910438***
	(-16.49)	(22.06)
L2	-1.10503***	-0.977783 ***
	(-27.54)	(-103.43)

L3	-0.2234542 ***	
	(-4.28)	
ma		
L1	0.7226973***	-0.383254***
	(31.02)	(-31.20)
L2	1	1
	(.)	(.)
Observation	254	614
AIC	-1092.4	-2725.2
BIC	-1071.2	-2703.1

t-statistic values in parentheses

* p<0.05,** p<0.01,*** p<0.001

After the estimation of the models, the white noise test is conducted on the residuals. Table 13 shows the results of the white noise Q statistic value and the p-value. It could be seen that p-values of both models are higher than 0.05, which means there are white noises. These results indicate that the estimation of ARIMA (3,1,2) and ARIMA (2,1,2) models are valid.

TABLE 13: THE RESULTS OF THE WHITE NOISE TEST

	ARIMA (3,1,2)	ARIMA (2,1,2)
White noise Portmanteau (Q) statistic	16.0747	15.9625
Prob > chi2(20)	0.7120	0.7190

Then, a comparison of the predicted value and the actual value could be conducted. The two graphs below show the comparisons in the spot market and future market, respectively. These two graphs show no significant prediction power of these two models which means that the historical price could not be used to predict the future. Therefore, the hypothesis 1 that the carbon market under the EU ETS phase III is weak-form efficient should be accepted. This conclusion verifies the robustness of the results obtained by conducting the Augmented Dickey–Fuller test, Phillips–Perron test, and the Lo & MacKinlay variance ratio test.

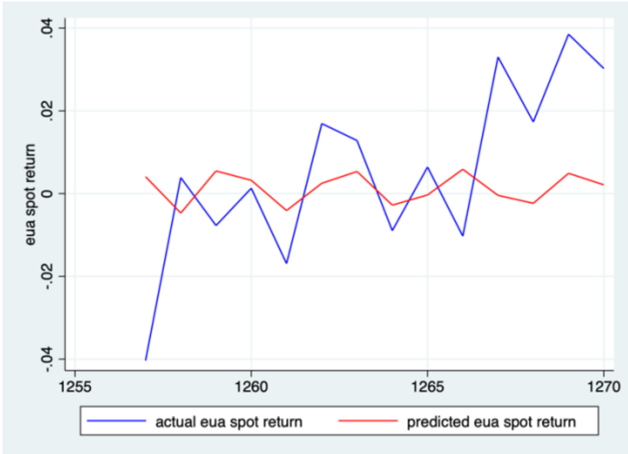

FIGURE 1: COMPARISON OF PREDICTED VALUE AND ACTUAL VALUE OF ARIMA (3,1,2) FOR SPOT MARKET

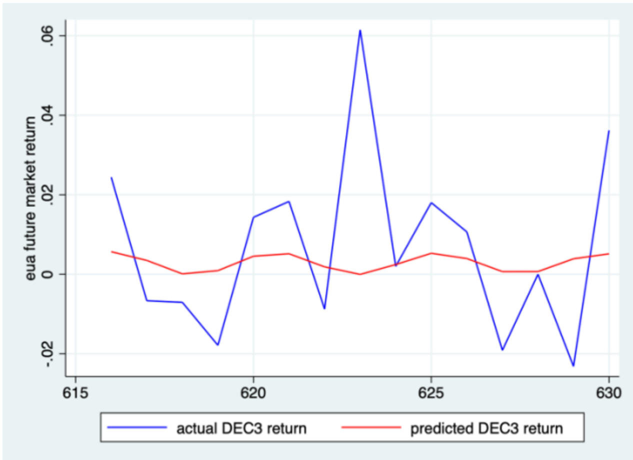

FIGURE 2: COMPARISON OF PREDICTED VALUE AND ACTUAL VALUE OF ARIMA (2,1,2) FOR FUTURE MARKET

4.7.2 Cut the Sample Size for Robustness Test of Hypothesis 2

The robustness test could be conducted by cutting the sample size. In this case, focusing on one of the sectors in the sample is a way to cut the sample size since the sample is covered several industries. The manufacture industry is chosen since it contains the most observations among others. It could be seen from table 14 that the coefficient of the independent variable, the return of EUAs (*eua_return*), is significantly positive in both models with value equals to

0.0033394 and 0.0047062, respectively. Regarding this, the hypothesis 2 that the carbon price returns have positive relationship with the regulated firm's stock returns under the EU ETS phase III should be accepted. This conclusion verifies the robustness of findings in section 4.6. In addition, all the coefficients of the independent and control variables in table 14 mirror the results shown in table 11, which further indicates the robustness.

TABLE 14: REGRESSION RESULTS OF MODEL 1 AND MODEL 2 IN MANUFACTURE INDUSTRY

	Model 1	Model 2
	stock_return	stock_return
eua_return	0.0033394***	0.0047062***
	(4.68)	(3.75)
risk_free	-0.00908**	-0.00906**
	(-3.14)	(-3.15)
market_return	0.6003374***	0.6002779***
	(45.26)	(45.22)
electricity_return	0.0698116***	0.0697733***
	(11.75)	(11.76)
oil_return	0.0474871***	0.047444***
	(21.70)	(21.74)
coal_return	0.0205227***	0.0204877***
	(28.18)	(28.42)
carbon_intensity		2.63e-06
		(0.08)
eua_carbon		-0.0030146*
		(-2.51)
Observation	129,989	129,989
R^2	0.6373	0.6373
Industry	Yes	Yes

Country	Yes	Yes
Time	Yes	Yes

t-statistic values in parentheses

* p<0.05,** p<0.01,*** p<0.001

4.7.3 Change the Control Variable for Robustness Test of Hypothesis 2

The robustness test could also be conducted by changing the control variables in the model. In this case, changing the *coal_return* to the *gas_return* since these two energy sources are always mixed use in the process of production (Wara, 2007). It could be seen from table 15 that the coefficients of the independent variable (eua_return) in both models are significantly positive. Therefore, the hypothesis 2 that the carbon price returns have positive relationship with the regulated firm's stock returns under the EU ETS phase III should be accepted. This conclusion verifies the robustness of findings in section 4.6.

TABLE 15: REGRESSION RESULTS OF MODEL 3 AND MODEL 4

	Model 3	Model 4
	stock_return	stock_return
eua_return	0.0044156***	0.0060054***
	(7.06)	(6.15)
risk_free	-0.00403*	-0.00408*
	(-2.10)	(-2.16)
market_return	0.5593002***	0.5592369***
	(31.44)	(31.43)
electricity_return	0.0894878***	0.0894369***
	(12.81)	(12.81)
oil_return	0.0485794***	0.0485288***
	(20.99)	(21.01)

gas_return	0.0055708***	0.0055485***
	(20.13)	(20.06)
carbon_intensity		0.0000273
		(0.274)
eua_carbon		-0.0037041**
		(-2.89)
Observation	228,490	228,490
R^2	0.6209	0.6210
Industry	Yes	Yes
Country	Yes	Yes
Time	Yes	Yes

t-statistic values in parentheses

* p<0.05,** p<0.01,*** p<0.001

5. Results Discussion

To refresh the memory, this section starts with restating the two hypotheses. Specifically, hypothesis 1 is that the carbon market under the EU ETS phase III is weak-form efficient and hypothesis 2 is that the carbon price returns have a positive relationship with the regulated firm's stock returns under the EU ETS phase III.

First, two statistic tests for time series regression, namely the Augmented Dickey-Fuller (ADF) test and the Phillips–Perron (PP) test, are conducted to test hypothesis 1. The null hypothesis of both the ADF test and the PP test is that the price data time series contains a unit root. The results indicated that the null hypothesis of both tests for all the price variables could not be rejected. Therefore, the spot market price (*EUAs*) and the European Climate Exchange (ECX) future prices (*DEC2, DEC3, and DEC4*) all follow the random walk, indicating that the carbon market under the EU ETS phase III is weak-form efficient.

Second, a non-parametric approach, the Lo & MacKinlay Variance Ratio test, is conducted to test hypothesis 1. The null hypothesis of this test is that the variance ratio of k-period return equals 1, meaning the variable follows a random walk. According to the results, the null hypothesis could not be rejected which indicates that the spot market price (*EUAs*) and the European Climate Exchange (ECX) future prices (*DEC2, DEC3, and DEC4*) all follow a random walk. Consequently, the Lo & MacKinlay variance ratio test results also indicate that the carbon market under the EU ETS phase III is weak-form efficient.

Third, the Autoregressive integrated moving average model (ARIMA) is employed to test the robustness of the abovementioned three tests. By comparing the predicted and actual values, the results of ARIMA models verify the robustness. Therefore, hypothesis 1 that the carbon market under the EU ETS phase III is weak-form efficient should be accepted with confidence.

Fourth, the multifactor two-way fixed effect model controlled with heteroskedasticity and serial correlation robustness is used to test hypothesis 2. The relationships between the independent variable (*eua_return*) and the dependent variable (*stock_return*) are significantly positive in both Model 1 and Model 2, which means that the return of the regulated stocks increases when the return of EUAs increases. Therefore, hypothesis 2 that the carbon price returns have positive relationship with the regulated firm's stock returns under the EU ETS phase III should be accepted.

Fifth, the robustness tests for hypothesis 2 are conducted by cutting the sample size and changing the control variable. The results of both methods mirrored the results of the original regression models which verified the robustness. Therefore, hypothesis 2 that the carbon price returns have a positive relationship with the regulated firm's stock returns under the EU ETS phase III should be accepted with confidence.

Sixth, an additional finding involving an interaction term in the regression provides further insight into the EU ETS. The interaction term (*eua_carbon*) shows a significantly negative relationship with the dependent variable (*stock_return*), indicating that the higher EUA price could harm the stock performance of high carbon intensity companies. In other words, the function of the EU ETS intended to 'punish' the high emission companies is appearing.

6. Conclusion and Limitations

This study proposed two criteria to assess the periodical success of the EU ETS under phase III: the market efficiency and the economic consequences of the EU ETS on the firm level. The empirical results show that the carbon market under the EU ETS phase III is satisfied with the weak-form efficiency and the stock price of the regulated firm would like to go up with the increasing price of the carbon emission allowance. The findings of this study could provide more evidence on the characteristic and the function of the EU ETS and benefit the regulated entities to make their abatement decisions, the stakeholder to diversify their carbon risks, and the policymaker to adjust their carbon regulations to meet the emission reduction target in a cost-efficient approach successfully.

However, several limitations exist in this study, which should be illustrated and shed light on future studies.

First, obtaining the firm-level data is difficult since most regulated firms under the EU ETS are not public companies. Because of this, the sample size is limited since this study chose to use the stock market performance as the representation of the economic consequence brought by the EU ETS. Therefore, further analysis could use another indicator, for instance, firm value, as a research target to assess the economic consequences.

Second, the carbon intensity, which is calculated as the total amount of annual emission of CO2 divided by the revenue, is not always obtainable since the annual emissions are not mandatorily disclosed information. Therefore, the sample size went down because this study would like to investigate the mediator effect brought by the carbon intensity.

Third, this study only focused on phase III of the EU ETS since the data for ongoing phase IV are limited. Phase IV covers the period of the Covid-19 pandemic and the conflicting period between Russia and Ukraine which could influence the decarbonization process enormously. Hence, the future study could focus on assessing the function of the market-based policy instrument, the EU ETS, in volatile environments.

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APPENDICES

APPENDICES 1: THE RESULTS OF REGRESSION OF AUGMENTED DICKEY–FULLER TEST

	Equation (1,1)	Equation (1,2)	Equation (1,3)	Equation (1,4)
	ΔEUAs	ΔDEC2	ΔDEC3	ΔDEC4
L1	-0.003496	-0.0034719	-0.003369	-0.0031881
	0.0021151	0.0029681	0.002863	0.0027809
L1D	0.0066809	-0.0314039	-0.0288148	-0.025367
	0.0224176	0.0321765	0.032206	0.0322087
L2D	-0.0703626**	0.0501251	0.0547516	0.0528219
	0.0224033	0.0321884	0.0321712	0.0321704
L3D	-0.0233976	-0.0270517	-0.0277592	-0.0293947
	0.0224453	0.0322278	0.0321622	0.0321683
L4D	0.0498031*	0.0415752	0.0411789	0.0403802
	0.022459	0.0322674	0.0321939	0.0322059
L5D	-0.0155039	-0.0684424*	-0.0651746*	-0.0642194*
	0.0224617	0.0322018	0.0322143	0.0322249
L6D	-0.0050849	-0.0686924*	-0.0635965	-0.0659488*
	0.0221527	0.0322871	0.0322942	0.0323021
L7D	0.0225297	0.018494	0.020628	0.0235617
	0.0221145	0.0323309	0.0322796	0.0322963
L8D	-0.0225093	0.0019347	0.0064545	0.0058334
	0.0221149	0.032291	0.0322869	0.0323063
L9D	0.0033579	-0.0001153	-0.0021243	-0.0047232
	0.0221114	0.0322743	0.0322642	0.0322847
L10D	0.0247979	0.0211542	0.0229449	0.0247198
	0.022104	0.0322748	0.0322129	0.0322316
L11D	-0.0081579	0.0017858	0.0047096	0.006993
	0.0220889	0.0322795	0.0321952	0.0322142

L12D	-0.0938289***	-0.0075257	-0.0097675	-0.0080474
	0.0220835	0.0322208	0.0322285	0.0322464
L13D	0.0220835	-0.0668699*	-0.0623953	-0.0608922
	0.0220714	0.0321402	0.0322268	0.0322417
L14D	0.0072424	0.0152055	0.0219416	0.0216233
	0.0220041	0.0321799	0.0322079	0.0322144
L15D	0.0114598	-0.0081568	-0.0086256	-0.0091191
	0.0219842	0.032192	0.0321645	0.0321743
L16D	-0.0368496	-0.0281062	-0.0233887	-0.0203666
	0.0218693	0.0321618	0.0321316	0.0321431
L17D	-0.0940712***	-0.0589462*	-0.0635254*	-0.0595715
	0.0218831	0.032073	0.0321189	0.0321257
L18D			-0.0105413	-0.0101234
			0.0321487	0.0321503
L19D			0.0798984*	0.0779285*
			0.0320179	0.0319498

Standard errors in parentheses

* p<0.05,** p<0.01,*** p<0.001

APPENDICES 2: THE RESULTS OF REGRESSION OF PHILLIPS–PERRON TEST

	Equation (2,1)	Equation (2,2)	Equation (2,3)	Equation (2,4)
	EUAs	DEC2	DEC3	DEC4
L1	0.9949569***	0.9957491***	0.9959968***	0.9961805***
	0.002152	0.0029164	0.0028215	0.0027475

Standard errors in parentheses

* p<0.05,** p<0.01,*** p<0.001