Chapter 3

On bond returns in a time of climate change

3.1 Introduction

Climate change is attributed to two different causes: natural climate variability — natural internal processes or external forcings — and human activity that alters the composition of the atmosphere (Intergovernmental Panel on Climate Change, 2014; United Nations, 1992). The consensus of actively publishing climate scientists on anthropogenic global warming is in the 90%-100% range (Cook et al., 2016). The breaking point of human contribution to climate change is usually identified with the industrial revolution since economic development is strictly correlated to energy consumption (Energy Information Administration, 2017; Stern, 2007): the burning of fossil fuels has increased the concentration of atmospheric carbon dioxide (CO_2), the most prominent forcing factor, from 280 parts per million (ppm) in preindustrial times to approximately 400 ppm (Wagner & Weitzman, 2016).

The literature has established a dichotomy of climate change risks. The first category has been labeled "climate risk" (Carney, 2015): changes in extreme climate phenomena — e.g. temperature extremes, high sea levels extremes, precipitation extremes (Intergovernmental Panel on Climate Change, 2014) —, are likely to cause serious damages to agriculture, coastal zones, human health, and affect growth (Dell, Jones, & Olken, 2014; Pycroft, Abrell, & Ciscar, 2016), productivity (Graff Zivin & Neidell, 2014; Hallegatte, Fay, Bangalore, Kane, & Bonzanigo, 2015), the value of financial assets and insurance claims. The second category, labeled "transition risk" or "carbon risk", makes reference to the cost of the adjustment towards a low-carbon economy (Caldecott & McDaniels, 2014). Low-carbon transition risk is a multi-faceted concept that includes all drivers of risk linked to the decarbonisation of the economy: a) pollution reducing market-based instruments (a carbon price: a carbon tax, an auction price, or a secondary market price), b) command and control induced technological shifts aimed at a reduction of CO_2 emissions, e.g. stranded assets or assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities (Caldecott et al., 2016), and c) market risk, i.e. market demands for low carbon products (Zhou et al., 2016).

The impact of a particular market-based instrument, the European Union Emission Trading System (EU-ETS), upon financial values has already been addressed by the literature; nevertheless, efforts pertain primarily to stocks, leaving the bonds field out of the picture. The objective of this paper is to assess the impact of the 2003/87/CE directive, upon which the EU-ETS is based, on European bond returns.

Literature on the interconnection between carbon pricing and bond values is scant. Mansanet-Bataller and Pardo (2008) look at the effect of including European Union Allowances (EUAs) in diversified portfolios made up of stocks, bonds, and commodities (Brent and Natural Gas) finding that including phase I and phase II EUAs actually improves the investment opportunity set for market practitioners that have initially invested in traditional assets like stocks and bonds. Koch (2014) studies price linkages between EUAs and market fundamentals and how they vary over time. The correlation between EUAs and a set of assets like oil, gas, coal, electricity, but also stocks and bonds, is analysed in order to explain the variations of price linkages; results show that carbon and financial markets are not segmented: high expected market volatility shifts carbon-stock correlation significantly upwards and carbon-bond correlation significantly downwards. Chevallier (2009) examines the relationship between carbon future returns and changes in macroeconomic conditions, finding that macroeconomic variables such as equity dividend yields, the junk bond premium, the U.S. Treasury bill yields, and the excess return on a globally diversified portfolio of commodities are only loosely related to carbon futures returns. While this scarce body of work aims at finding the determinants of a carbon price, the study of the inverse causal relationship has, to my best knowledge, never been undertaken.

In order to detect the impact of low-carbon policy — the 2003/87/CE directive which initiated EU-ETS — upon the bond returns of European firms, a Fama and French (1993) framework, for the first time, is employed. Along with the two bond market factors proposed by Fama and French (1993), TERM and DEF, an EU-ETS participation factor is added: GMC. Supplementing classical factors with an environmental factor has already been done in research carried out on the stock market (Görgen et al., 2017; Oestreich and Tsiakas, 2015; Ravina and Kaffel, 2019). However, some differences in the construction of the environmental factor remain. In this sense, the factor construction closer to the one presented here is found in Ravina and Kaffel (2019). The rationale behind the GMC factor is the following: if we want to measure the impact of the 2003/87/CE directive with a factor, one possibility is to take all firms regulated by the policy, perform carbon accounting for each firm, construct two portfolios, i.e. a high-carbon portfolio and a low-carbon portfolio, and then take the differences of the value-weight returns. Unfortunately, this operation wouldn't permit us to uncover the real green (or carbon) premium because the firms that take part in the EU-ETS are all high-carbon firms. This means that, when we build the two portfolios, the low-carbon portfolio would contain a set of firms which are only slightly less polluting than firms in the other portfolio. The resulting environmental factor would be biased, i.e. negligible in terms of magnitude. In order to cope with the fact that the EU-ETS covers only high-carbon sectors, an alternative is to construct the environmental factor by means of two portfolios, a portfolio composed of EU-ETS liable firms (which I call "carbon" portfolio) and a portfolio composed of EU-ETS exempt firms (which I call "green" portfolio). In this context, while $TERM$ proxies for the common risk in bond returns related to unexpected changes in interest rates and DEF mimics the risk factor in returns related to shifts in economic conditions that change the likelihood of default, GMC (Green minus Carbon) is meant to mimic the risk factor in returns related to low-carbon policy, the 2003/87/CE directive in this case. The new component, the GMC factor, is obtained by subtracting the weekly value-weight carbon bond portfolio returns from the weekly value-weight green bond portfolio returns from the beginning of Phase

II (2008) of EU-ETS. The carbon bond portfolio is composed of 25 firms regulated by the 2003/87/CE directive and the green bond portfolio is composed of 25 firms exempted by the 2003/87/CE directive upon which the EU-ETS is based.

This paper makes the following contributions. Firstly, it is the first time that a factor model is employed to assess the sensitivity of bond returns to low-carbon policy. The sensitivity of bond portfolio returns to the *GMC* factor has been found to be positive in the case of green portfolios and negative in the case of carbon portfolios. Most importantly, slopes on *GMC* are highly statistically significant. Secondly, the average value of *GMC* itself is positive: finding a positive *GMC* means that in Europe, in the 2008-2018 time-span, there is no carbon premium as some of the literature asserts, but rather a green premium. Such a green premium confirms that the EU-ETS has a positive effect in the financing of the low-carbon transition: the beginning of phase II of EU-ETS — the start date of the study — coincides with both capital outflows from EU-ETS liable firms and capital inflows to EU-ETS exempt firms. Thirdly, evidence is found that the addition of an environmental factor improves the performance of the Fama and French two factor model for bonds, at least in Europe from 2008 onwards. Fourthly, since the literature has recently proposed stress testing, a technique developed for testing the stability of an entity, as an evaluation framework for climate change risks (Bank of England Prudential Regulation Authority, 2015; Fay et al., 2015; Schoenmaker and van Tilburg, 2016; Zenghelis and Stern, 2016), I follow the recent carbon stress test trend and put forward a stress test that is able to indicate the impact of a hypothetical EU-ETS average price upon bond returns. The results show the effects of a plausible, but more severe, average EU-ETS price on both carbon firms and green firms.

The paper is structured in the following way: Section 2 presents the EU-ETS; Section 3 introduces the model; Section 4 puts forward the data; Section 5 provides the empirical results; Section 6 presents the diagnostics; Section 7 exhibits the carbon stress test; Section 8 concludes.

3.2 The 2003/87/CE directive

The 2003/87/CE directive is at the origin of the European Union Emission Trading System (EU-ETS). The EU-ETS is a market based instrument, launched as a pilot project in 2005, whose objective is to reduce greenhouse gases (GHG) emissions in all European Union (EU) countries as well as Iceland, Lichtenstein and Norway. The three-year (2005-2007) pilot project, phase I, has been followed by a four-year (2008-2012) phase II and a seven-year (2013-2020) phase III. In 2020, at the end of phase III, emissions covered by the EU-ETS, around 45% of the EU's GHG, are expected to be 21% lower than at the start of the pilot project (2005). From the beginning of phase III, the EU-ETS covers more than 11,000 installations consisting of power and heat generation, oil refineries, commercial aviation, and production of steel, iron, aluminium, metals, cement, lime, glass, ceramics, pulp, paper, cardboard, acids and bulk organic chemicals (European Commission, 2015).

The EU-ETS is a cap and trade system: the European Commission has put a cap on EU-wide GHG emissions which has been progressively reduced. When a firm belongs to one of the participating sectors, it is required to cover its emissions with emission allowances (EUAs) which are delivered on the primary market, i.e they are either auctioned or distributed free of charge. Subsequently, in the secondary-market, EUAs trading enables firms that eventually run short of allowances to purchase additional units. Environmental economics often suggests that market-based instruments, such as the EU-ETS, permit to cut emissions in a more cost efficient and flexible way than command and control regulation, as the latter tends to prescribe the same level of activity to all firms affected by the regulation (Demirel and Kesidou, 2011; Engel, Pagiola, & Wunder, 2008). Economic theory clearly indicates that, for any given level of emission abatement, if the firm's marginal cost of abatement is higher than the market's carbon price, then the efficient choice for the firm is to not abate but purchase allowances in a cap and trade scheme. Conversely, for any given level of emission abatement, when the polluting firm faces a marginal abatement cost lower than the market's carbon price, the efficient choice for the firm is to reduce emissions and sell their permits under a cap and trade scheme (Winebrake, Farrell, & Bernstein, 1995).

One of the identified issues with the EU-ETS has historically been low EUAs prices, which have generally been attributed to an imbalance of supply and demand. While the European commission has tried to address the surplus of EUAs with auction backload in phase III and with the market stability reserve (MSR), which began operations in 2019, research has delivered empirical results on the economic implications of EU-ETS. Some early studies found that the EU-ETS has a negative impact on productivity and profits of firms, while the effect on labour and investment are insignificant (Commins, Lyons, Schiffbauer, & Tol, 2011), while some others found that the EU-ETS effect on firm performance, in terms of profitability, is negligible (Jaraite-Kažukauske and Di Maria, 2016; Zhang and Wei, 2010). Another branch of research found that the EU-ETS positively affected firms' material costs and revenue, at least in the power sector (Chan, Li, & Zhang, 2013) and positively affected turnover, markup, investment intensity and labour productivity (Marin, Marino, & Pellegrin, 2017).

The impact of the EU-ETS upon financial values has also been addressed by the literature. Also in this case, results are contradictory. In the stock market, results can be divided in two categories. A first group of papers finds that the implementation of a carbon price leads to a positive effect on the financing of the low-carbon transition, i.e. capital inflows to low-carbon firms and capital outflows from high-carbon firms (Brouwers, Schoubben, Van Hulle, & Van Uytbergen, 2016; Jong, Couwenberg & Woerdman, 2014; Tian, Akimov, Roca, & Wong, 2015). A second body of work has found that such effect is not straight-froward and it actually depends on the EU-ETS phase (Moreno and Pereira da Silva, 2016; Oestreich and Tsiakas, 2015; Zhu, Tang, Peng, & Yu, 2018). Performing a similar exercise for bonds, which to the best of my knowledge has never been carried out, is the scope of this paper.

3.3 The model

To explain variation in bond returns, it is critical to distinguish systematic risks from specific risks. Systematic risks have a general impact on the returns of most securities, while specific risks influence securities individually and have a negligible effect on diversified portfolios (Litterman and Scheinkman, 1991). Theoretically, a two-factor model for bond returns can be justified by an Intertemporal Capital Asset Pricing Model (ICAPM) setting: $TERM$ and DEF are candidate hedging portfolios which proxy for underlying term and default risks in the economy. In such a setting, the factor loadings — the betas — with respect to these two factors can be considered appropriate measures of systematic risk (Gebhardt, Hvidkjaer, & Swaminathan, 2005). The Fama and French (1993) two factor model for bonds is based on the following time-series regression:

$$R_{i,t} - R_{F,t} = \alpha_i + m_i TERM_t + d_i DEF_t + e_{i,t} \tag{3.1}$$

In this equation, $R_{i,t}$ is the value-weight return for bond or bond portfolio i for period t and $R_{F,t}$ is the risk-free rate. $TERM_t$ proxies for the risk factor related to unexpected changes in interest rates. It is calculated as the difference between the returns on a value-weight long-term government bond portfolio and the one-month Treasury bill rate measured at the end of the previous month. In this framework, the T-bill rate is the proxy for the general level of expected returns on bonds, which means that $TERM$ indicates what is the difference, due to changes in interest rates, between long-term bond returns and expected returns on bonds. DEF_t is the risk factor in bond returns meant to proxy shifts in economic conditions that change the likelihood of default of a firm. It is calculated as the difference between the returns on a market portfolio of long-term corporate bonds and the returns on a portfolio of long-term government bonds. DEF provides the premium for taking a supplementary (default) risk and investing in a corporate bond rather than in a government one. $e_{i,t}$ is a zero-mean residual. If the coefficients of the time-series regression — m_i, d_i — completely capture variation in bonds expected returns, then the intercept, α_i, is indistinguishable from zero.

An environmental extension of equation (1) amounts to affirm that a systematic risk is missing from the framework: there is at least another common factor that affects bond returns. This systematic risk, entailed by low-carbon policy, plays a role in the explanation of bonds excess returns. Is it legitimate to think of low-carbon policy as a source of systematic risk? A risk is systematic when it cannot be completely eliminated, but only reduced. As an example, the risk arising from a shift in interest rates can be reduced with duration hedging or default risk can be reduced by constructing high-rating portfolios. The IPCC Special Report (2018) states that, in order not to exceed a global warming of 1.5°C above pre-industrial levels, global net anthropogenic CO_2 emissions should decline by about 45% from 2010 levels by 2030, reaching carbon neutrality — net zero global CO_2 emissions — by 2050. Carbon neutrality is a global objective that requires a global instrument: low-carbon policy. In other words, low-carbon policy is a systematic risk source because it is the answer to the global warming phenomenon. However, as for every systematic risk, low-carbon policy risk cannot be eliminated but only reduced: it can be reduced by investing in low-carbon emissions firms.

In order to measure the impact of the 2003/87/CE directive, i.e low-carbon policy, with a factor, one possibility is to take all firms regulated by the policy, perform carbon accounting for each firm, construct two portfolios, i.e. a high-carbon portfolio and a low-carbon portfolio, and then take the differences of the value-weight returns. However, this practice turns out to be problematic in a EU-ETS context: from its inception to the present, the EU-ETS has covered only a fraction of European firms and these happen to be all high-carbon firms, implying that if we were to construct the environmental factor by partitioning current EU-ETS firms into a high-carbon portfolio and a low-carbon portfolio, such a factor would be biased, i.e. negligible in terms of magnitude. In order to cope with the fact that the EU-ETS covers only high-carbon sectors, an alternative is to construct the environmental factor by means of two portfolios, a portfolio composed of EU-ETS liable firms (which I call "carbon" portfolio) and a portfolio composed of EU-ETS exempt firms (which I call "green" portfolio). I call this systematic risk factor *GMC*: green minus carbon. The *GMC* factor is obtained by subtracting the weekly value-weight EU-ETS liable bond portfolio returns (25 firms) from the weekly value-weight EU-ETS exempt bond portfolio returns (25 firms) from the beginning of Phase II (2008) of EU-ETS until 2018.

Is there a EU-ETS participation effect in average bond returns? Table 1 shows the summary statistics for the two classical term-structure bond factors and the *GMC* factor (Panel A), correlations between the three factors (Panel B) and the average weekly value-weight excess returns for four bond portfolios formed from sorts on EU-ETS participation and rating (Panel C). Panel C displays a rating effect: average return falls from low-grade bonds to high-grade bonds. This holds both in the case of carbon bonds and in the case of green bonds. Furthermore, Panel C clearly displays the EU-ETS participation effect: the green portfolio systematically outperforms its carbon counterpart at each rating level.

TABLE 3.1: Summary statistics for weekly dependent and explanatory percent returns; July 2008 to June 2018, 521 weeks.

Panel A: Explanatory returns						
Name	Mean	Std dev.	*t(mean)*	ACF(1)	ACF(2)	ACF(12)
CB	0.14	0.61	5.12	0.00	0.10	-0.04
GP	0.15	0.73	4.57	0.03	0.08	-0.04
CP	0.13	0.53	5.38	-0.04	0.11	-0.04
LTG	0.09	0.55	3.83	-0.08	0.08	0.05
RF	0.01	0.02	8.68	0.98	0.96	0.72
DEF	0.04	0.52	1.87	0.13	0.14	-0.05
TERM	0.08	0.54	3.55	-0.09	0.07	0.05
GMC	0.02	0.35	1.38	0.04	-0.01	-0.05
Panel B: Correlations between factors						
	DEF	TERM	GMC			
DEF	1	-0.31	0.20			
TERM	-0.31	1	0.38			
GMC	0.20	0.38	1			
Panel C: Dependent variables						
Name	Mean	Std dev.	*t(mean)*	ACF(1)	ACF(2)	ACF(12)
Green/HG	0.12	0.69	4.11	0.05	0.09	-0.04
Green/LG	0.15	0.87	3.93	0.05	0.10	-0.03
Carbon/HG	0.11	0.54	4.56	-0.06	0.04	-0.01
Carbon/LG	0.13	0.78	3.71	0.04	0.12	-0.09

CB is the value-weight corporate bond portfolio weekly percent return (50 bonds). GP is the value-weight green bond portfolio weekly percent return (25 bonds). CP is the value-weight carbon bond portfolio weekly percent return (25 bonds). LTG is the value-weight European long-term government bond portfolio weekly percent return (7 bonds). RF is the 1-week Euribor rate. DEF is $CB - LTG$. $TERM$ is $LTG - RF$. GMC is $GP - CP$. The four bond portfolios used as dependent variables in the excess return regressions are formed from sorts of the 50 European corporate bonds on EU-ETS participation and rating. The Green/HG portfolio is composed of EU-ETS exempt (green) firms which have a rating higher than or equal to A3 (by Moody's). The Green/LG portfolio is composed of EU-ETS exempt (green) firms which have a rating lower than A3. The Carbon/HG portfolio is composed of EU-ETS liable (carbon) firms which have a rating higher than or equal to A3. The Carbon/LG portfolio is composed of EU-ETS liable (carbon) firms which have a rating lower than A3.

Table 1 provides an argument for testing an augmented version of the Fama and French (1993) two factor model for bonds. The environmental extension of equation (1) is, then, based on the addition of an EU-ETS participation factor, GMC. The augmented specification of the model, which I call environmentally-extended Fama and French model (EE-FF) is the following:

$$R_{i,t} - R_{F,t} = \alpha_i + m_i TERM_t + d_i DEF_t + g_i GMC_t + e_{i,t} \tag{3.2}$$

3.4 The data

The environmental extension of the Fama and French (1993) two factor model for bonds (EE-FF) aims at capturing patterns in average bond returns related to shifts in interest rates, changes of probability of default and EU-ETS participation. Both the outcome and the explanatory variables are formed by means of a portfolio composition based on a sample of 50 European corporate bonds and 7 European government bonds. The returns to be explained are weekly value-weight excess returns on four bond portfolios formed on sorts on EU-ETS participation (liable or exempt) and rating (provided by Moody's). The explanatory variables include the mimicking portfolios for the unexpected changes in interest rates, $TERM$, shifts in economic conditions that change the likelihood of default, DEF, and EU-ETS participation, GMC, factors in returns. All data is from Bloomberg.

3.4.1 Explanatory returns

As Fama and French (1993) pointed out and demonstrated, variation of bond returns are due mainly to two factors. Shifts in interest rates affect both new bond emissions, by means of the coupon, and old emissions, by means of the inverse relationship between bond prices and interest rates. The factor that mimics this mechanism, $TERM$, is constructed in the EE-FF model (2) by taking the difference between the weekly value-weight returns on a long-term government bond portfolio (LTG) and the one-week Euribor rate (RF) measured at the end of the previous week. In other words, $TERM$ tells us what is the premium for holding a bond that is affected by interest rate risk. The long-term government bond portfolio is formed by 7 European long-term government bonds: issuing countries are Belgium, Italy, the Netherlands, Spain, France, UK and Germany. The value-weight returns of the long-term government bond portfolio have been calculated for each week from July 2008 to June

2018 after adjusting for different coupon frequencies (semi-annual coupon payment frequencies have been converted to annual).

The second main factor involved in the variation of bond returns is mimicked by DEF. Shifts in economic conditions can change the likelihood of default of a debt-issuing entity: measuring this phenomenon involves taking the difference between the returns of a value-weight long-term corporate bond portfolio (CB) and the returns of a value-weight long-term government bond portfolio (LTG). In the end, DEF provides the premium for investing in a portfolio of long-term corporate bonds that is more likely to be affected by changes in economic conditions than a portfolio of long-term government bonds. The portfolio of long-term corporate bonds is formed by 50 European long-term corporate bonds whereas the long-term government bond portfolio is formed by 7 European long-term government bonds (the same government bond portfolio used in the construction of the $TERM$ factor).

GMC proxies for the risk factor in bond returns related to EU-ETS participation. GMC is constructed using a portfolio of 50 European corporate bonds (the same corporate bond portfolio used in the construction of the DEF factor), out of which 25 participate in the EU-ETS since the beginning of phase II (2008) and 25 do not participate in the EU-ETS since the beginning of phase II. A firm participates in the EU-ETS since the beginning of phase II if it belongs to one of the following sectors: power and heat generation, oil refineries, and production of coke, steel, iron, cement, glass, lime, bricks, ceramics, pulp, paper and board (European Commission, 2015). The two portfolios — the "green" portfolio (GP) and the "carbon" portfolio (CP) — have been formed from July 2008 to June 2018. These portfolios do not need to be shuffled on a yearly basis since the 50 European firms that are under examination constantly participate (or not) in the EU-ETS in the 2008-2018 time frame. Weekly value-weight bond returns have been calculated for the two portfolios for the 10-year time frame for a total of 521 weekly observations. Lastly, GMC is obtained by subtracting the weekly value-weight carbon portfolio returns from the weekly value-weight green portfolio returns.

Panel A of table 1 displays descriptive statistics for the portfolios used as building blocks for the factors (CB, GP, CP, LTG), the risk-free rate (RF), along with the three derived risk factors in returns: $TERM$, DEF and GMC. Correlations between factors are shown in Panel B. The mean value obtained for the EU-ETS participation factor, 0.02, indicates that the EU-ETS effect is lower than the interest rate effect and the default effect: $TERM$ and DEF have means of, respectively, 0.08 and 0.04. Nevertheless, the magnitude of the GMC factor cannot be ignored. Furthermore, a positive average GMC value points to the presence of a green premium in Europe from 2008 onwards; such a green premium confirms that the EU-ETS has a positive effect — intended as capital inflows to green firms and capital outflows from carbon firms — in the financing of the low-carbon transition. In Fama and French (1993) t-statistics for $TERM$ and DEF are only 0.38 and 0.21. Table 1 displays t-statistics for $TERM$ of 3.55 and for DEF of 1.87. The t-statistic for GMC is also above 1, at 1.38. These elements, along with the scarce correlation between $TERM$, DEF and GMC pave the way for a test of the three factors as independent variables in the environmentally extended version of the Fama and French (1993) model for bonds.

3.4.2 Explained returns

In the augmented model (2), the bond returns to be explained, $R_{i,t} - R_{F,t}$, are the average excess returns of portfolios displayed in Panel C of table 1. The 4 portfolios are formed from sorts of the 50 European long-term corporate bonds on EU-ETS participation (EU-ETS liability and EU-ETS exemption) and rating (high rating and low rating). Table 2 provides descriptive statistics for the 50 European corporate bond sample.

The 25 liable (“carbon") firms have been selected by applying the following two criteria: a) belonging to the sectors that take part in the EU-ETS since the beginning of phase II (2008), and b) listing of at least one installation in the EU-ETS transaction log. Moreover, bonds issued by firms that fulfil these two criteria need to be comparable: they need to have similar issue dates, similar maturities, and a similar interest payment structure, e.g. the sample cannot contain both fixed-interest rate bonds and callable bonds. These criteria reduced reasonably the number of available bonds for the empirical exercise: around 30 bonds were found. As some of these bonds were missing pricing information, the final amount of bonds available was 25. The number of carbon firms (25) determined the number of exempted (“green") firms in the

TABLE 3.2: Descriptive statistics for the 50 European corporate bonds; Country and Sector (ICB) breakdown for Carbon and Green firms

Panel A: Country breakdown			
EU country	Green Firms	EU country	Carbon Firms
Finland	2	Czech Republic	1
France	5	Finland	3
Germany	5	France	4
Italy	4	Germany	4
Netherlands	2	Italy	4
Spain	2	Netherlands	1
UK	5	Portugal	1
		Spain	3
		UK	4
Total	25	Total	25
Panel B: ICB Sector breakdown			
Sector	Green Firms	Sector	Carbon Firms
Banks	5	Alternative Electricity	1
Broadline retailers	1	Building materials and fixtures	2
Diversified industrials	1	Conventional electricity	6
Fixed-line telecommunications	3	Gas distribution	2
Food retailers & wholesalers	3	General mining	1
Life insurance	2	Integrated Oil & Gas	5
Media agencies	2	Multiutilities	5
Mobile telecommunications	2	Paper	3
Mortgage Finance	1		
Non-equity investment services	1		
Publishing	2		
Telecommunications equipment	1		
Water	1		
Total	25	Total	25

Green Firms are EU-ETS exempt firms. Carbon firms are EU-ETS liable firms.

sample: I selected with a random procedure from the Bloomberg database 25 bonds issued by firms that fulfil the following two criteria: a) non belonging to the sectors that take part in the EU-ETS since the beginning of phase II (2008), b) no listing of firm installations in the EU-ETS transaction log. Moreover, bonds need to have, once again, similar issue dates, maturity dates and coupon payment structure. The two rating groups are formed by grouping Moody's rating codes into two categories: the high grade category includes Moody's Aaa, Aa1, Aa2, Aa3, A1, A2 and A3 codes while the low-grade category includes Moody's Baa1, Baa2, Baa3, Ba1, Ba2, Ba3, B1 and B2 codes.

The 50 securities are all "bullets" (non-callable), fixed interest rates bonds with similar issue dates (Q3 2008) and time to maturity (Q2 2018). This set of features, particularly hard to find in a single bond, explain the size of the data set. In order to overcome this relative difficulty, weekly returns have been preferred over monthly returns. The reason for the choice of the lower bound (2008) is that phase I of EU-ETS (2005-2007) has been a 3-year pilot phase of “learning by doing" to prepare for phase II, when the EU-ETS started to function effectively in order for the EU to meet its Kyoto targets. Furthermore, in Phase I (2005-2007) almost all allowances were given to businesses for free and the cap was largely based on estimates, as there was no reliable emission data available (European Commission, 2015). This resulted in a total amount of allowances issued superior to exceeded emissions that led, in 2007, to the fall of the price of allowances to zero. The upper bound of the time period (2018) is given by the need to compare bonds with similar maturities. As bond maturities are standardised, one of the typical time-to-maturity tranches is 10 years, a 2008 issue date implies a 2018 maturity date.

3.5 Results

The Fama and French (FF) two factor model (1) and the environmental extension (EE-FF) of the two factor model (2) have been run for each of the four dependent variables — four EU-ETS/Ratings portfolios — for a total of eight time-series regressions. The slopes and the R^2 values are direct evidence that $TERM$, DEF and GMC proxy for risk factors in bond returns.

3.5.1 Common variation in returns

The results of the four FF regressions and of the four EE-FF regressions are displayed in Table 3. If used as explanatory variables in the time-series regressions, $TERM$, DEF, and GMC capture common variation in bond returns. The four bond portfolios produce slopes on $TERM$ in between 17 standard errors from zero (Carbon/LG) and 55 standard errors from zero (Green/HG) when the FF model is run and in between 27 standard errors from zero (Carbon/LG) and 60 standard errors from zero (Green/HG) when the EE-FF model is employed. Slopes on $TERM$ are economically significant as well: they are in the 0.81 (Carbon/LG) - 1.38 (Green/LG) range when the FF model is run and in the 0.90 (Green/HG) - 1.20 (Green/LG) range when the EE-FF model is run. Within the two EU-ETS participation subgroups, slopes of

TABLE 3.3: Regressions for 4 value-weight portfolios formed from sorts on EU-ETS participation and Rating; July 2008 - June 2018, 521 weeks.

	Green/HG	Green/LG	CarbonHG	CarbonLG
Panel A: FF model				
α	-0.01	-0.01	0.01	0.01
$t(\alpha)$	-1.32	-1.48	0.36	0.54
m	1.08	1.38	0.82	0.81
$t(m)$	55.76	50.58	42.65	17.70
d	1.07	1.28	0.77	1.07
$t(d)$	48.80	41.27	34.93	20.46
R^2	0.89	0.86	0.82	0.52
Panel B: EE-FF model				
α	-0.01	-0.01	-0.01	-0.01
$t(\alpha)$	-0.36	-0.85	-0.40	-0.41
m	0.90	1.20	0.94	1.15
$t(m)$	60.59	45.16	49.06	27.54
d	0.93	1.13	0.86	1.35
$t(d)$	58.04	39.63	41.94	30.01
GMC	0.48	0.47	-0.32	-0.93
$t(GMC)$	24.85	13.50	-12.78	-17.03
R^2	0.95	0.90	0.86	0.69

At the end of December of each year, bonds are allocated to two EU-ETS participation groups: EU-ETS exempt (Green firms) and EU-ETS liable (Carbon firms). Bonds are then allocated to two rating groups: High-grade (HG) if the bond is rated A3 or higher (notation provided by Moody's) and Low-grade (LG) if the bond is rated lower than A3. The intersections of the two sorts produce 4 EU-ETS/Rating portfolios. The dependent variables in the regressions are the weekly excess returns on the 4 EU-ETS/Rating portfolios. The independent variables in the regressions are the interest rate factor, $TERM$, the default factor, DEF and the EU-ETS participation factor, GMC. Panel A shows the intercepts, coefficients, t-values, and the adjusted R^2 value for the regressions of the 4 dependent variables on $TERM$ and DEF (FF model). Panel B shows the intercepts, coefficients, t-values, and the adjusted R^2 value for the regressions of the 4 dependent variables on $TERM$, DEF, and GMC (EE-FF model).

low-grade portfolios are always higher than (or equal) the slopes of high-grade portfolios. The nature of the $TERM$ factor and interest rate expectations explain why the sensitivity of bonds expected returns to the $TERM$ factor drops from low-grade bond portfolios to high-grade bond portfolios, which is a phenomenon found also in Fama and French (1993) or in Lin, Wang, & Wu (2011). $TERM$, calculated as the difference between the weekly long-term government bond return and the one-week Euribor rate measured at the end of the previous week, represents the premium for investing in a bond which is exposed to interest rate fluctuations. Even though duration is on average lower for low-grade bonds than for high-grade bonds when the time to maturity is similar, the higher sensitivity of low-grade bonds to $TERM$ is explained by the ex-ante interest rates: when interest rates are expected to rise, low duration bonds become more attractive than high-duration bonds which are more affected by interest rate risk.

The slopes on DEF are in between 20 standard errors from 0 (Carbon/LG) and 48 standard errors from 0 (Green/HG) when the FF model is run, while they are in between 30 standard errors from 0 (Carbon/LG) and 58 standard errors from 0 (Green/HG) when the EE-FF model is run. The DEF slopes are in the 0.77 (Carbon/HG) - 1.28 (Green/LG) range when the FF model is run and in the 0.86 (Carbon/HG) - 1.35 (Carbon/LG) range when the EE-FF model is employed. Again, within the two EU-ETS participation subgroups, slopes of low-grade portfolios are always bigger than slopes of high-grade portfolios, which is consistent with previous literature (Acharya, Amihud, & Bharath, 2013; Gebhardt, Hvidkjaer, & Swaminathan, 2005). DEF is the risk factor in bond returns meant to proxy for shifts in economic conditions that change the likelihood of default of a firm. In other terms, it provides the premium for taking a supplementary (default) risk and investing in a corporate bond rather than in a government bond. Declining coefficients from low-grade bonds to high-grade bonds follow this risk-return logic.

GMC slopes are all at least 12 standard errors from zero (Carbon/HG). The second less statistically significant GMC slope is 13 standard errors from zero (Green/LG). All other slopes are more than 17 standard errors from 0. In terms of economic significance, one would expect slopes on GMC to be positive, i.e. GMC positively contributes to bonds excess average returns, when the dependent variable is EU-ETS exempt, and negative, i.e. GMC negatively contributes to bonds excess average returns, when the dependent variable is EU-ETS liable. Indeed, this is the case and slopes on GMC are positive when the dependent variables are green portfolios and negative when the dependent variables are carbon portfolios: green portfolios have slopes in between 0.47 (Green/LG) and 0.48 (Green/HG) and carbon portfolios have slopes in between -0.32 (Carbon/HG) and -0.93 (Carbon/LG). Slopes on GMC are exactly the same when the dependent variable is a green portfolio, which is consistent with the basic intuition that if a firm is EU-ETS exempt then the EU-ETS participation effect is the same for both high-grade firms and low-grade firms. On the other hand, if a firm is EU-ETS liable, slopes on GMC vary: low-grade firms have stronger negative exposure to GMC to reflect the fact that a firm with weaker fundamentals, i.e. a low-grade firm, is expected to cope less well with a more stringent low-carbon policy than a firm with stronger fundamentals, i.e. a high-grade firm. It is not surprising, then, to find a higher spread in *GMC* slopes between the Green/LG portfolio and the Carbon/LG portfolio than between the Green/HG portfolio and the Carbon/HG portfolio.

3.5.2 Sub-period analysis

Phase III of EU-ETS (2013-2020) has been described as a considerable step forward with respect to phase II (2008-2012) in terms of environmental goals. For example, a single EU-wide cap on emissions has replaced the previous system of national caps and auctioning has replaced free allocation as the default method for allocating allowances. We can check if the market agrees with the view that Phase III has been more stringent than Phase II by breaking down the time-period of analysis into two sub-periods and verifying if the sensitivity of the left hand-side portfolios to the EU-ETS participation factor varies between the two phases. Table 4 displays the results of the regression of the four dependent variables on two (FF model) and three factors (EE-FF model) for the two sub-periods. The phase III sub-period ends, in this exercise, in Q2 2018 with the end of the dataset.

Table 4 clearly confirms the results of table 3. On the other hand, there is no evidence that phase III of EU-ETS has been perceived as more stringent than phase II by the market: statistical significance is almost unchanged between carbon portfolios, while decreasing for the Green/HG portfolio and increasing for the Green/LG portfolio. Nevertheless, all coefficients on *GMC* are at least 8 standard errors from zero. Also, in terms of economic significance, the differences between the two phases are minimal. The spread between the EU-ETS exempt firms and the EU-ETS liable firms has not increased between phase II and phase III but it is actually slightly smaller (1.12 in phase II and 0.95 in phase III).

3.5.3 Model performance

As Fama and French (2015) suggest — based on Merton (1973) — the essential indicators of the effectiveness of an asset-pricing model are indistinguishable from zero

TABLE 3.4: Regressions for 4 value-weight portfolios formed from sorts on Rating and EU-ETS participation for Phase II of EU-ETS (2008-2012) and Phase III of EU-ETS (2013-2018); July 2008 - June 2018, 521 weeks.

Panel A: FF model								
	Phase II				Phase III			
	Green/HG	Green/LG	Carbon/HG	Carbon/LG	Green/HG	Green/LG	Carbon/HG	Carbon/LG
α	-0.01	-0.01	0.01	0.01	-0.01	-0.01	-0.01	0.01
$t(\alpha)$	-0.03	-1.33	0.74	0.11	-3.07	-0.70	-0.75	3.78
m	1.07	1.38	0.82	0.84	1.11	1.27	0.86	0.73
$t(m)$	38.85	33.81	31.33	12.04	27.24	31.93	17.22	16.09
d	1.08	1.26	0.76	1.15	1.06	1.35	0.80	0.70
$t(d)$	32.52	25.89	24.32	13.75	35.73	46.92	22.02	21.14
R^2	0.89	0.86	0.83	0.51	0.88	0.92	0.74	0.72

Panel B: EE-FF model								
	Phase II				Phase III			
	Green/HG	Green/LG	Carbon/HG	Carbon/LG	Green/HG	Green/LG	Carbon/HG	Carbon/LG
α	0.01	-0.01	0.01	-0.01	-0.01	0.01	-0.01	0.01
$t(\alpha)$	0.90	-1.09	0.41	-0.43	-1.92	2.26	-2.26	2.71
m	0.90	1.22	0.93	1.19	0.95	1.04	1.04	0.94
$t(m)$	45.75	29.91	36.27	18.70	25.72	39.74	21.65	24.30
d	0.94	1.14	0.84	1.41	0.87	1.09	1.01	0.95
$t(d)$	43.30	25.25	29.61	19.94	28.75	50.70	25.83	29.99
GMC	0.50	0.46	-0.31	-0.98	0.40	0.56	-0.43	-0.51
$t(GMC)$	19.11	8.28	-9.01	-11.48	11.20	21.96	-9.21	-13.53
R^2	0.95	0.88	0.87	0.68	0.92	0.97	0.80	0.83

the end of December of each year, bonds are allocated to two EU-ETS participation groups: EU-ETS exempt (Green firms) and EU-ETS liable (Carbon firms). Bonds are then allocated to two rating groups: High-grade (HG) if the bond is rated A3 or higher (notation provided by Moody's) and Low-grade (LG) if the bond is rated lower than A3. The intersections of the two sorts produce four EU-ETS/Rating portfolios. The dependent variables in the regressions of Panel A and Panel B are the weekly excess returns on the 4 EU-ETS/Rating portfolios for Phase II of EU-ETS (2008-2012) and for Phase III of EU-ETS (2013-2018). The independent variables in the regressions are the interest rate factor, $TERM$, the default factor, DEF and the EU-ETS participation factor, GMC. Panel A shows the intercepts, coefficients, t-values, and the adjusted R^2 value for the regressions of the 4 dependent variables on $TERM$ and DEF (FF model). Panel B shows the intercepts, coefficients, t-values, and the adjusted R^2 value for the regressions of the 4 dependent variables on $TERM$, DEF, and GMC (EE-FF model).

intercepts: if the coefficients of the time-series regressions completely capture variation in expected returns, then the intercept, α_i, is indistinguishable from zero. The intercepts found (Table 3 and 4) with the two-factor model (FF) and its environmental extension (EE-FF) are all almost indistinguishable from zero, the lowest being -0.01 and the highest being 0.01, which is of central importance for a well-specified asset pricing model. To test the zero intercept hypothesis for combinations of portfolios and factors, I compute the Gibbons, Ross, and Shanken (1989) GRS statistic for both the FF model and the EE-FF model in the whole sample period and for the two sub-periods identified as phase II and phase III (Table 5). This operation permits us to assess how well the two factor (FF) model and the three factor (EE-FF) model explain average excess bond returns and answer the question of the improvement provided by adding the *GMC* factor to the two classical bond factors.

TABLE 3.5: GRS statistics for tests of the FF model and the EE-FF model; July 2008 - June 2018, 521 weeks.

Panel A: FF model			
	Phase II (2008-2012)	Phase III (2013-2018)	Phase II & Phase III (2008-2018)
GRS	0.66	4.32	3.31
p-value	0.623	0.002	0.011
Panel B: EE-FF model			
	Phase II (2008-2012)	Phase III (2013-2018)	Phase II & Phase III (2008-2018)
GRS	0.53	2.72	2.82
p-value	0.711	0.030	0.026

The table tests the ability of the two-factor model (FF model) and the three factor model (EE-FF model) to explain weekly excess returns on the 4 EU-ETS/Rating portfolios. Panel A shows the GRS statistic testing whether the expected values of all 4 intercept estimates are zero when the FF model is employed in Phase II of EU-ETS (2008-2012), in Phase III of EU-ETS (2013-2018) and in Phase II and Phase III (2008-2018). Panel B shows the GRS statistic testing whether the expected values of all 4 intercept estimates are zero when the EE-FF model is employed in Phase II of EU-ETS (2008-2012), in Phase III of EU-ETS (2013-2018) and in Phase II and Phase III (2008-2018).

Interestingly, in Phase II, the GRS statistic is 0.66 for the FF model and 0.53 for the EE-FF model with p-values of only, respectively, 0.62 and 0.71. This suggests that the null of zero intercepts cannot be rejected for the 4 left-hand side portfolios when the FF model and the EE-FF model are employed. On the contrary, in Phase III the GRS test rejects the hypothesis that the FF model and the EE-FF model explain the average returns on bonds. However, the GRS statistic of the FF model (4.32) is higher that the GRS statistic of the EE-FF model (2.72). If we take the whole sample period (2008-2018), the GRS test rejects the hypothesis that the FF model and the EE-FF model produce regression intercepts for the 4 bond portfolios that are all equal to zero — the GRS statistic is 3.31 for the FF model and 2.82 for the EE-FF model — but, again, the EE-FF model produces a lower GRS statistic than the FF model. Armed with statistical evidence, I conclude that it is legitimate to consider the addition of the GMC factor to the classical Fama and French bond factors in Europe, at least from 2008.

3.6 Diagnostics

The GRS statistics (Table 5) tell us that, in terms of model comparison, the EE-FF model is preferable to the FF model in Phase II, in Phase III and in the full time period 2008-2018. The robustness check for the inference that the EE-FF model explains the cross-section of expected bond returns is based upon two tests. Firstly, correlation among risk factors (Table 1) may lead to a concern about the unique information that the newly proposed EU-ETS participation factor carries. To investigate this issue, I first regress the GMC factor upon the remaining two factors, $TERM$ and DEF:

$$GMC_t = \lambda_0 + \lambda_1 TERM_t + \lambda_2 DEF_t + e_t^{GMC} \tag{3.3}$$

Once I generate the residuals from (3), I add them to the intercept and label the result as orthogonal GMC ($GMCO$). Performing this operation permits us to filter out the common information and retain only the unique information contained in GMC. Then, I repeat the 4 time-series regression of the EE-FF model (2) for the whole sample period substituting $GMCO$ for GMC; in this way, $GMCO$ — a zero-investment portfolio uncorrelated with DEF and $TERM$ — captures common variation in bond returns left by DEF and $TERM$. Results are reported in Table 6.

In the regressions, $GMCO$ keeps its significance, both in economic and statistical terms. The slopes on $GMCO$ in the EE-FF model (Table 6) are identical to the slopes on GMC in the EE-FF model (Table 3) by construction. Slopes for $TERM$ and DEF shift up for green portfolios and shift down for carbon portfolios. However, the spreads in the $TERM$ and DEF slopes for green portfolios (0.29 and 0.21) are almost identical to those of Table 3 (0.30 and 0.20), whereas the spreads for carbon portfolios (0.02 and 0.29) are lower than those in Table 3 (0.21 and 0.49). In terms of statistical significance, the EE-FF model that uses $GMCO$ as explanatory variable produces coefficients for both $TERM$ and DEF which are more statistically significant than those produced by the EE-FF model that uses GMC as explanatory variable. This is the case for six regressions out of eight, the only exception being regressions of Carbon/LG portfolios.

The second robustness test, in the spirit of Fama and French (1993), brings upon

TABLE 3.6: Regressions for four value-weight portfolios formed from sorts on Rating and EU-ETS participation; July 2008 - June 2018, 521 weeks.

	Green/HG	Green/LG	Carbon/HG	Carbon/LG
α	-0.01	-0.01	-0.01	-0.01
$t(\alpha)$	-0.36	-0.86	-0.40	-0.41
m	1.08	1.37	0.83	0.81
$t(m)$	82.52	58.77	48.89	22.09
d	1.07	1.28	0.77	1.06
$t(d)$	72.24	47.96	40.04	25.53
$GMCO$	0.48	0.47	-0.32	-0.93
$t(GMCO)$	24.85	13.50	-12.79	-17.03
R^2	0.94	0.90	0.86	0.69

At the end of December of each year, bonds are allocated to two EU-ETS participation groups: EU-ETS exempt (Green firms) and EU-ETS liable (Carbon firms). Bonds are then allocated to two rating groups: High-grade (HG) if the bond is rated A3 or higher (notation provided by Moody's) and Low-grade (LG) if the bond is rated lower than A3. The intersections of the two sorts produce 4 EU-ETS/Rating portfolios. The dependent variables in the regressions are the weekly excess returns on the 4 EU-ETS/Rating portfolios. The independent variables in the regressions are the interest rate factor, $TERM$, the default factor, DEF and the orthogonal EU-ETS participation factor, $GMCO$. $GMCO$ is the sum of the intercept and the residuals from the regression of GMC on $TERM$ and DEF. The table shows the intercepts, coefficients, t-values, and the adjusted R^2 values for the regressions of the 4 dependent variables on $TERM$, DEF and $GMCO$.

the residuals generated from the EE-FF model (2) to check that the regressions capture the variation through time in the cross section of expected returns. There is evidence that the default spread, the term spread and short-term interest rates predict bond returns: if the three factors of the EE-FF model actually capture the cross section of expected returns, the predictability of bond returns should be embodied in the explanatory returns and residuals should be unpredictable. This hypothesis is tested with the following regression:

$$e_{i,t+1} = \beta_0 + \beta_1 DFS_t + \beta_2 TS_t + \beta_3 RF_t + \eta_{i,t+1} \tag{3.4}$$

In the equation, $e_{i,t+1}$ are the time series residuals for the four bond portfolios from the EE-FF model (2). DFS_t (default spread) is the difference at the end of week t between the yield on a corporate bond portfolio and the long-term government bond yield. TS_t (term spread) is the difference at the end of week t between the long term government bond yield and the 1-week Euribor rate (RF_t). Results clearly indicate that there is no evidence that the residuals from the EE-FF time series regressions are predictable. R^2 values in the four regressions are, at most, 0.01. Out of the twelve slopes, none are statistically significant at the 0.05 level.

3.7 Stress testing bond returns

Recently, the literature has proposed stress testing, a technique developed for testing the stability of an entity, as an evaluation framework for climate change risks. In financial risk analysis a stress test is characterized by four essential features (Borio, Drehmann, & Tsatsaronis, 2014): a set of risk exposures subjected to stress, a scenario that defines the exogenous shocks that stress the exposures, a model that maps the shocks onto an outcome and a measure of such an outcome. In this context, the Bank of England Prudential Regulation Authority (2015) suggests an integration of climate change risk factors in standard stress-testing techniques, Zenghelis and Stern (2016) encourage financial corporations and fossil fuel companies to undertake stress tests to evaluate their "future viability against different carbon prices and regulations" (p. 9), Schoenmaker and van Tilburg (2016) call for, as a next step, the developing of "carbon stress tests to get a better picture of the exposure of the financial sector" (p. 7), and the World Bank has also taken this direction (Fay et al., 2015). Besides these scientific endorsements, in France the recent law n° 2015-992 (article 173) relative to the energy transition for green growth, promulgated just before the COP 21 in Paris, makes reference to climate change stress tests. The financial stress test literature, following Koliai (2016), can be split in four main categories (table 8): general presentation of the instrument in the early 2000s, portfolio stress test development, systemic stress test emergence in the wake of the 2007-2009 crisis and diagnosis of the realised exercises.

The literature, while portraying stress testing as quintessential to financial risk management (Bensoussan, Guegan, & Tapiero, 2014), describes the technique through dichotomies: top-down and bottom-up approaches, first and second round effects, sensitivity and scenario analysis, historical and hypothetical scenarios, direct and reverse stress tests. In the top-down approaches, the empirical relationship between a banking variable and an exogenous stressor is assumed at the portfolio level of

TABLE 3.7: Categorisation of stress test literature (Koliai, 2016).

Topic	Selected authors
Conceptual aspects	Berkowitz (2000); Blaschke et al. (2001); Čihàk (2007)
Portfolio stress tests	Kupiec (1998); Breuer and Krenn (1999); Bee (2001);Kim and Finger (2001); Aragonés et al. (2001); Breuer et al. (2002); Alexander and Sheedy (2008); McNeil and Smith (2012); Breuer and Csiszàr (2013)
Systemic stress tests	Boss (2008); Alessandri et al. (2009); Aikman et al. (2009); van den End (2010, 2012); Engle et al. (2014); Acharya et al. (2014)
Diagnostics	Haldane (2009); Borio and Drehmann (2009); Hirtle et al. (2009); IMF (2012); Greenlaw et al. (2012); Borio et al. (2012)

The table shows the categorisation of the stress-test literature performed by Koliai (2016) into 4 topics: conceptual aspects, portfolio stress test, systemic stress test and diagnostics.

low granularity, while in the bottom-up approach the empirical relationship is estimated at the highest possible level of granularity of a banking variable. First-round effects come from the immediate impact of the shock on the financial system, while second-round effects include "possible domino effects from the institutions that are directly affected by the shock to other intermediaries and, possibly, to market infrastructures and the entire financial system" (Quagliariello, 2009, p.33). Sensitivity testing aims at determining how changes to a single risk factor will impact the institution or the portfolio while scenario analysis studies the effect of a simultaneous move in a group of risk factors. Scenarios have been subject to requirements by the Basel Committee on Banking Supervision (2009) which demands them to be plausible but severe: historical scenarios rely on a significant market event experienced in the past, whereas a hypothetical scenario is a significant market event that has not yet happened (Committee on the Global Financial System, 2005). Direct stress tests set scenarios and derive losses, while "starting from a big loss and working backward to identify how such a loss would occur is commonly referred to among risk management professionals as reverse stress testing" (Breuer, Jandačka, Mencía, & Summer, 2012, p. 332).

The aim of the carbon stress test is to show the impact of a plausible but more severe average EU-ETS price on European bond returns. How can we get an insight into the effect of more aggressive carbon pricing on bond returns? The carbon stress test put forward leverages the *GMC* factor as it plays an intermediary role between carbon pricing and excess bond returns. GMC is meant to mimic the risk factor in returns related to low-carbon policy, the 2003/87/CE directive in this case. It follows that the GMC factor and the EU-ETS carbon price should be, in theory, positively correlated: when the EU-ETS carbon price increases, GMC should rise accordingly. Conversely, if the EU-ETS carbon price decreases, GMC should decline as well. The equation for the carbon stress test is, then, based on the sensitivity of the GMC factor to the EU-ETS carbon price, which can easily be obtained by multiplying the correlation coefficient between the EU-ETS price and the GMC factor (0.48) with the ratio of the standard deviation of the GMC factor and the standard deviation of the EU-ETS carbon price:

$$z = \rho_{gmc,ets} \left(\frac{\sigma GMC}{\sigma ETS} \right) \tag{3.5}$$

In equation (5), z is the sensitivity of the GMC factor to the EU-ETS carbon price (ETS) in the 2008-2018 time-span. $\rho_{gmc,ets}$ is the Pearson correlation coefficient between the EU-ETS price and the GMC factor, σGMC is the standard deviation of the GMC factor, σETS is the standard deviation of the EU-ETS carbon price. Evidently, z is also the slope of the regression of GMC on ETS. Assuming that such regression is a well-specified model for GMC, i.e. intercept is zero, then by simple substitution Equation (2) becomes:

$$R_{i,t} - R_{F,t} = \alpha_i + m_i TERM_t + d_i DEF_t + \rho_{gmc,ets} \left(\frac{\sigma GMC}{\sigma ETS} \right) g_i ETS_t + e_{i,t} \tag{3.6}$$

Holding all other variables constant and focusing only on the relation between the left-hand side portfolios and the EU-ETS carbon price, the carbon stress test is based on the following equation:

$$\Delta(R_{i,t} - R_{F,t}) = \rho_{gmc,ets} \left(\frac{\sigma GMC}{\sigma ETS} \right) g_i \Delta ETS_t \tag{3.7}$$

In this equation, $\Delta(R_{i,t} - R_{F,t})$ is the average hypothetical variation in excess bond returns, g_i is the sensitivity of portfolio or bond i to EU-ETS participation, and ΔETS_t is the average hypothetical EU-ETS carbon price variation. In order to understand the impact of a plausible but more severe EU-ETS average price on the bond returns under examination, the average EU-ETS carbon price (9.46 euros in the July 2008 - June 2018 time span) is stressed by 20% (low shock), 50% (medium shock), and 100% (high shock). The carbon stress test is performed at two levels: bond portfolio level and individual security level. In the first case, the bond returns under examination are the excess returns on the four value-weight bond portfolios formed from sorts on EU-ETS participation and rating. In the second case, the bond returns under examination are the excess returns of the individual bonds of the 50 corporate bond sample.

TABLE 3.8: Carbon stress-test for four value-weight portfolios formed from sorts on EU-ETS participation and Rating and 50 individual corporate bonds; July 2008 - June 2018, 521 weeks.

Panel A: Regressions for four EU-ETS/Rating value-weight portfolios							
	Green/HG	Green/LG	Carbon/HG	Carbon/LG			
Low shock	0.02	0.02	-0.01	-0.03			
Medium shock	0.04	0.04	-0.03	-0.08			
High shock	0.08	0.08	-0.05	-0.16			
Panel B: Individual regressions for green firms							
	Mean	Std	Min	Q1	Q2	Q3	Max
Low shock	0.02	0.02	-0.01	0.00	0.01	0.03	0.06
Medium shock	0.04	0.05	-0.03	0.01	0.03	0.07	0.15
High shock	0.09	0.09	-0.06	0.02	0.07	0.15	0.30
Panel C: Individual regressions for carbon firms							
	Mean	Std	Min	Q1	Q2	Q3	Max
Low shock	-0.02	0.03	-0.09	-0.02	-0.01	-0.01	0.01
Medium shock	-0.04	0.07	-0.23	-0.04	-0.01	-0.01	0.02
High shock	-0.08	0.14	-0.46	-0.08	-0.03	-0.02	0.04

At the end of December of each year, bonds are allocated to two EU-ETS participation groups: EU-ETS exempt (Green firms) and EU-ETS liable (Carbon firms). Bonds are then allocated to two rating groups: High-grade (HG) if the bond is rated A3 or higher (notation provided by Moody's) and Low-grade (LG) if the bond is rated lower than A3. The intersections of the two sorts produce four EU-ETS/Rating portfolios. Panel A shows the results of the Carbon stress-test for the four EU-ETS/Rating bond portfolios. Panel B shows summary statistics of the Carbon stress-test carried out individually for 25 EU-ETS exempt (Green) firms. Panel C shows summary statistics of the Carbon stress-test carried out individually for 25 EU-ETS liable (Carbon) firms. In each stress-test, the average EU-ETS carbon price is stressed by 20% (low shock), 50% (medium shock), and 100% (high shock).

Table 8 (Panel A) shows the results of the carbon stress test for each of the four value-weight portfolios under the three shock scenarios: the second, third and fourth rows provide the average variation of weekly percent excess returns under the three EU-ETS carbon price scenarios. The signs of the values in Panel A reflect the signs of the slopes found for GMC in Table 3: g_i is positive, i.e. GMC positively contributes to bonds average excess returns, when the portfolio is EU-ETS exempt and g_i is negative, i.e. *GMC* negatively contributes to bonds average excess returns, when the dependent variable is EU-ETS liable. The average variation of weekly excess returns for the two Green portfolios are identical as the slopes on *GMC* found with the EE-FF model (2) are similar: 0.48 (Green/HG) and 0.47 (Green/LG). On the other hand, the average variation of weekly excess returns for the two Carbon portfolios reflects the fact that *GMC* slopes found with the EE-FF model (2) are -0.32 (Carbon/HG) and -0.93 (Carbon/LG).

Panel B and Panel C display the results of the carbon stress test carried out at individual bond level. In this case, individual *GMC* slopes have been calculated for each bond; I can report that in the Green category (25 firms) all slopes on *GMC* found by running the EE-FF model (2) for each security are positive and statistically significant at the 0.05 level besides three cases (which are negative but not statistically significant at the 0.05 level). Furthermore, all slopes on *GMC* found by running the EE-FF model (2) individually for the 25 carbon firms are negative and statistically significant at the 0.05 level with the exception of two cases (which are positive but not statistically significant at the 0.05 level).

3.8 Conclusions

This paper answers the research question of the impact of the 2003/87/CE directive which initiated EU-ETS, i.e. low-carbon policy, upon European bond returns by putting forward a risk factor in bond returns related to EU-ETS participation: *GMC*. The sensitivity of bond portfolio returns to the *GMC* factor has been found to be positive in the case of Green portfolios and negative in the case of Carbon portfolios. Most importantly, slopes on *GMC* are statistically highly significant. Ultimately, the average value of *GMC* itself is positive: finding a positive *GMC* means that in Europe, in the 2008-2018 time-span, there is no carbon premium as some of the literature asserts, but rather a green premium.

The test of the *GMC* factor has been carried out in a Fama and French (1993) framework, where bond returns are explained by means of two risk-factors in returns: *TERM* and *DEF*. It has been found that augmenting the Fama and French

(1993) model for bonds with the *GMC* factor improves the effectiveness of the model, at least with regard to Europe between 2008 and 2018. The description of average bond returns is improved when the *GMC* factor is added: the EE-FF model produces lower GRS statistics than the original FF model. This holds true in the 2008-2018 time-span and in the 2008-2012 (Phase II) and 2013-2018 (Phase III) sub-periods.

The last contribution of this paper is inspired by the recent climate change risk stress test trend. The literature has recently proposed stress testing, a technique developed for testing the stability of an entity, as an evaluation framework for climate change risks (Bank of England Prudential Regulation Authority, 2015; Fay et al., 2015; Schoenmaker and van Tilburg, 2016; Zenghelis and Stern, 2016). The carbon stress test put forward, which leverages the *GMC* factor, is able to indicate the impact of an EU-ETS average price increase upon bond returns: results show the effects of a plausible but more severe EU-ETS average price on bond portfolios formed on EU-ETS participation and rating and on individual bonds.

Three policy implications can be derived from these contributions. The first two implications are of interest to financial practitioners and the third is of interest to legislators. Firstly, the presence of a green premium in the European bond market in the years 2008-2018 is a useful asset management insight for financial practitioners. In other words, low-carbon investments can no longer be understood solely from the point of view of taking an ethical stand: nowadays, as the green premium shows, investing in low-carbon firms is a profitable exercise. Secondly, in terms of asset pricing models, the augmented version of the Fama and French (1993) model for bonds is preferable to the original one, at least in Europe since 2008. Thirdly, the low-carbon transition risk stress test put forward, by showing the average impact on bond returns of various scenarios of carbon pricing, provides useful insights to legislators in terms of the financing of low-carbon transition, i.e. increasing capital inflows towards green firms and capital outflows from carbon firms. The low-shock scenario, for example, would provide an additional boost to the low-carbon transition, without harming excessively high-carbon firms.

Chapter 4

Extreme climate events and financial values: empirical evidence from the stock market

4.1 Introduction

The literature has partitioned climate change risks in two categories. The first category has been labeled “climate risk" (Carney, 2015) and refers to the link between global warming and natural and human systems. Extreme climate phenomena like temperature extremes, high sea level extremes, and precipitation extremes (Intergovernmental Panel on Climate Change, 2014), are likely to seriously affect economic growth (Dell, Jones, & Olken, 2014; Pycroft, Abrell, & Ciscar, 2016), productivity (Graff Zivin & Neidell, 2014; Hallegatte, Fay, Bangalore, Kane, & Bonzanigo, 2015), and financial values.

The second category of climate change risks has been labeled “low-carbon transition risk" or “carbon risk". Low-carbon transition risk refers to the cost of the adjustment towards a low-carbon economy. Hence, it includes all drivers of risk linked to the decarbonisation of the economy: a) market-based instruments like a carbon tax or an emission allowance price; b) command and control induced technological shifts, e.g. stranded assets or assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities (Caldecott et al., 2016); and c) market risk, i.e. market demands for low carbon products (Zhou et al., 2016).

This paper brings upon the impact of extreme climate events upon financial values. Specifically, we are interested in the way changes in extreme climate phenomena (temperatures extremes, high sea levels extremes, and precipitation extremes) are related to changes in the value of stocks. This research question has, to the best of our knowledge, scarcely being addressed.

Literature on the relation between extreme climate events and stock returns is scarce. Anttila-Hughes (2016) finds that new record temperature announcements are associated with negative excess returns for energy firms while ice shelf collapses are associated with positive returns. Balvers, Du & Zhao (2016) find that a significant risk premium exists on a temperature tracking portfolio and its impact on the cost of equity capital has been increasing over time; furthermore, loadings at industry level on the tracking portfolio are generally negative. Bourdeau-Brien and Kryzanowski (2016) find that major natural disasters induce abnormal stock returns and return volatilities and volatility more than doubles following large natural hazards. Hong, Li and Xu (2017) investigate whether the prices of food stocks efficiently discount drought risk finding that high drought exposure is related to poor profit growth and poor stock returns for food companies.

We answer the research question of the impact of extreme climate events upon stock returns by means of a climatic extension of the Fama and French (2015) five-factor model for stocks. This is the first time a factor model is employed for assessing the implications of climate changes upon stock returns. The reasoning proceeds as follows: augmenting the Fama and French (2015) five-factor model with a sixth factor amounts to asserting that a systematic risk is missing from the framework. There is, at least, another common factor that affects stock returns: global warming. The climatic factor we put forward, LME (light minus extreme), responds to the need of capturing the risk factor in stock returns related to global warming which is associated with extreme climate phenomena like temperature extremes, high sea levels extremes, and precipitation extremes (Intergovernmental Panel on Climate Change, 2014). The climatic factor is built by building two portfolios: the extreme climatic impact (ECI) portfolio and the light climatic impact (LCI) portfolio. The procedure to form the two portfolios leverages an analysis of global extreme climate events in the 2008-2017 timeframe. Weekly value-weighted returns of the ECI portfolio are then subtracted from the weekly value-weighted returns of the LCI portfolio. The returns to be explained in our setting are value-weighted excess returns for six portfolios sorted on climate exposure and size (market capitalisation) taken from a sample of 227 firms belonging to the STOXX 1800 index for which data on geographical fixed asset location was available.

In the end, we find that the slopes on the newly proposed risk factor in stock returns gradually increase from the extreme climate impact portfolio to the light climate impact portfolio. Furthermore, these results are statistically highly significant. Overall, we find that there is a climate effect in average excess stock returns, which confirms our hypothesis that a systematic risk factor, global warming in this case, was missing from the classical framework. However, results show that the climate factor (LME), just like the value factor (HML) are absorbed by the remaining four factors in stock returns: $RM - R_F$ (market's excess return), SMB (small minus big, the size factor), RMW (robust minus weak, the profitability factor) and CMA (conservative minus aggressive, the investment factor). This is also observed after computing the GRS statistics, which show that adding LME and HML to the other four factors never improves the effectiveness of the model. The observation that HML becomes redundant in a five-factor model has already been made by Fama and French, and we can confirm it. Coherently with their analysis, we ultimately propose a six-factor model which leverages two orthogonal factors: LMEO (orthogonal LME) and HMLO (orthogonal HML).

The rest of the paper proceeds as follows: section two presents the climatic factor, section three exposes the model, section four puts forward the data, section five introduces the results, section six presents the climate stress test and section seven concludes.

4.2 The climatic factor

The climatic factor we put forward is meant to mimic the risk factor in returns related to global warming. First of all, the sample shall be representative of global stocks, which is why we used as a starting base the STOXX 1800 index. In order to construct the climatic factor, we first need to develop a method to classify a firm according to