i.e. the EU countries plus Iceland, Liechtenstein and Norway. We consider firms to be “green" if a) they belong to the sectors which do not take part to the EU-ETS since the beginning of phase II, b) no firm installations are inventoried on the EU-ETS transaction log, and c) the firm is listed on a European stock exchange of the countries participating to the EU-ETS . Participant sectors are the following: power stations and other combustion plants $> 20MW$, oil refineries, coke ovens, iron and steel plants, cement clinker, glass, lime, bricks, ceramics, pulp, paper and board (European Commission, 2015).

Table 1 displays the averages of monthly percent returns for the environmental factor, GMC, for each year from 2008 to 2018. We can see that at the very beginning of phase II of EU-ETS (2008), GMC is positive (+2.71%). It is slightly negative in 2009 and then picks up in 2010 (+1.66%), 2011 (+1.45%), 2012 (+0.69%), and 2013 (+0.86%, beginning of phase III), it lowers to almost zero in 2014 (+0.02%) and then picks up again in 2015 (+1.37%). It then drops in 2016 (-1.24%), which singularly is the year after the COP 21 meeting (which took place in Paris in December 2015) and starts to increase slowly from 2017 onwards. There is a clear path in the magnitude of GMC, starting from the beginning of phase II in 2008 and which is only stopped in 2016 by, we suppose, a market negatively perceived COP 21 outcome. Over the 11-year span the average monthly percent return for the GMC factor is 0.73%.

TABLE 2.1: Average monthly GMC percent return from 2008 to 2018

Years	**returns**
2008	2.71
2009	-0.17
2010	1.66
2011	1.45
2012	0.69
2013	0.86
2014	0.02
2015	1.37
2016	-1.24
2017	0.52
2018	0.24
Average	**0.73**

Table 1 provides an argument to test a 5+1 version of Fama and French’s (2015) five factor model and see if the augmented model outperforms — in Europe in the 2008-2018 time span — the classical one. The 5+1 model specification, which we call

EE-FF (environmentally-extended Fama and French) model is the following:

$$\begin{aligned} R_{i,t} - R_{F,t} =& \alpha_i + \beta_i(R_{M,t} - R_{F,t}) + s_i SMB_t + h_i HML_t \\ & + r_i RMW_t + c_i CMA_t + g_i GMC_t + e_{i,t} \end{aligned} \tag{2.2}$$

2.3 The data

The EE-FF model (2) aims at capturing patterns in average returns related to size, value, profitability, investment and EU-ETS compliance. The explanatory variables include the returns on a market portfolio of European stocks, R_M, and mimicking portfolios for the size, SMB, value, HML, profitability, RMW, investment, CMA, and EU-ETS compliance, GMC, factors in returns. The returns to be explained are the value weight returns for subsets of the portfolio of 182 European stocks upon which the GMC factor is based. Such subsets are formed by breaking up the 182 firms into 8 portfolios based on market capitalization and EU-ETS compliance: the 8 stock portfolios are formed from annual (2008-2018) sorts of stocks into 4 size groups (4 quartiles) and two EU-ETS groups — liable firms, which we call carbon, and exempt firms, which we call green —. Liable firms participate to the EU-ETS in the 2008-2018 time frame while exempt firms do not participate. The risk free rate, R_F, is the 1-month Euribor rate.

2.3.1 Explanatory returns

The 5 classical factors —R_M, SMB, HML, RMW, CMA— are taken directly from Fama and French's database of factors for the European market. For a complete description of the construction of the factors we refer the reader to Fama and French (2015): here it suffices to mention that the 5 classical factors (2x3) are constructed using 6 value-weight portfolios formed on size and book-to-market, 6 value-weight portfolios formed on size and operating profitability, and 6 value-weight portfolios formed on size and investment. All the portfolios are shuffled on a yearly basis. SMB (small minus big) is the average return on the nine small stock portfolios minus the average return on the nine big stock portfolios, HML (high minus low) is the average return on the two value portfolios minus the average return on the two growth portfolios, RMW (robust minus weak) is the average return on the two robust operating profitability portfolios minus the average return on the two weak operating profitability portfolios, CMA (conservative minus aggressive) is the average return on the two conservative investment portfolios minus the average return on the two aggressive investment portfolios, while R_M is the return on Europe's value-weight market portfolio.

The environmental factor, GMC (green minus carbon), is constructed using a portfolio of 182 European stocks, out of which 91 participate to the EU-ETS since the beginning of phase II (2008) and 91 do not participate to the EU-ETS since the beginning of phase II. A firm participates to the EU-ETS since the beginning of phase II if it belongs to one of the following sectors: power stations and other combustion plants $> 20MW$, oil refineries, coke ovens, iron and steel plants, cement clinker, glass, lime, bricks, ceramics, pulp, paper and board (European Commission, 2015). The EU-ETS liable group of firms (“carbon" firms) is formed on the following three criteria: a) belonging to the sectors that take part to the EU-ETS since the beginning of phase II (2008), b) having at least one installation listed in the EU-ETS transaction log, and c) listing on a European stock exchange of the countries participating to the EU-ETS, i.e. the EU countries plus Iceland, Liechtenstein and Norway. We consider firms to be “green", i.e. EU-ETS exempt, if the following three criteria are met: a) belonging to the sectors which do not take part to the EU-ETS since the beginning of phase II, b) no firm installations are inventoried on the EU-ETS transaction log, and c) the firm is listed on a European stock exchange of the countries participating to the EU-ETS.

Two portfolios, comprising in one case stocks of carbon firms and, in the other, stocks of green firms, have been formed from January 2008 to December 2018. The portfolios do not need to be shuffled on a yearly basis since the 182 European firms that are under examination constantly participate (or not) to the EU-ETS in the 2008-2018 time frame. Monthly value-weight stock returns have been calculated for the two portfolios for the 11-year time frame for a total of 24,024 observations. Lastly, GMC is obtained by subtracting the monthly value-weight carbon portfolio return from the monthly value-weight green portfolio return.

2.3.2 Explained returns

In the EE-FF model (2), the returns to be explained, R_i, are the value weight returns for subsets of the portfolio of 182 European stocks upon which the GMC factor is based. Descriptive statistics for the 182 European stock portfolio are provided in Table 2.

TABLE 2.2: Descriptive statistics for the 182 European stocks: country and sector (ICB) breakdown for Carbon and Green firms

Panel A: Country breakdown			
Green firms		**Carbon firms**	
EU country	**Firms**	**EU country**	**Firms**
Austria	4	Austria	6
Belgium	4	Belgium	3
Czech Republic	2	Czech Republic	2
Denmark	1	Denmark	2
Finland	6	Finland	6
France	11	France	7
Germany	9	Germany	7
Hungary	1	Hungary	1
Ireland	1	Ireland	1
Italy	6	Italy	13
Lithuania	3	Lithuania	2
Netherlands	3	Netherlands	1
Poland	8	Poland	10
Portugal	1	Portugal	3
Romania	2	Romania	2
Slovenia	1	Slovenia	1
Spain	7	Spain	10
Sweden	6	Sweden	5
UK	15	UK	9
Total	91	**Total**	91

Panel B: ICB Sector breakdown			
Green firms		**Carbon firms**	
Sector	**Firms**	**Sector**	**Firms**
Asset managers	2	Alternative Electricity	4
Banks	10	Alternative fuels	2
Broadcasting & Entertainment	4	Building materials and fixtures	13
Broadline retailers	4	Containers and packaging	4
Business support services	9	Conventional electricity	18
Computer hardware	2	Exploration and production	3
Computer services	3	Forestry	1
Distillers & Vintners	1	Gas distribution	3
Durable Household products	1	Integrated Oil & Gas	14
Electronic equipment	3	Iron & Steel	9
Fixed-line telecommunications	4	Multiutilities	7
Full-line insurance	7	Paper	11
Gambling	3	Pipelines	2
Industrial machinery	2		
Media agencies	7		
Publishing	2		
Real-estate holding & development	6		
Recreational services	5		
Software	8		
Specialty finance	3		
Telecommunications equipment	4		
Toys	1		
Total	91	**Total**	91

Such subsets are formed from annual (2008-2018) sorts of stocks into 4 size groups (4 quartiles) and 2 EU-ETS compliance groups: EU-ETS liability and EU-ETS exemption. Table 3 shows the average monthly value-weight excess returns for the 8 portfolios obtained from annual sorts of the 182 European stocks into 4 size groups (4 quartiles) and two EU-ETS compliance groups. Once again, we call the portfolio "carbon" if it includes firms that do participate to the EU-ETS, and we call the portfolio "green" if it includes firms which do not take part to the EU-ETS. Here, average return typically falls from small stocks to big stocks, i.e. there is a clear size effect pattern. Even though the size effect isn't evident from the second to the third quartile, it clearly shows from the first to the fourth quartile. This holds both in the case of carbon stocks and in the case of green stocks. What matters to us, rather that the size effect, which has been proven elsewhere, is the EU-ETS effect. The latter shows up even more clearly than the size effect: the green portfolio systematically outperforms its carbon counterpart at each size level.

TABLE 2.3: Averages of monthly percent excess returns for 8 value-weight portfolios formed from sorts on size and EU-ETS compliance. January 2008-December 2018.

Size	**Green**	**Carbon**
Small	0.03	-0.14
Medium/low	0.46	-0.73
Medium/high	0.20	-0.54
Big	-0.18	-0.55

2.4 Results

The classical Fama and French's (1) five factor model and the EE-FF model (2) have been run for each dependent variable for a total of 16 time-series regressions. There is direct evidence that the addition of a sixth factor improves the effectiveness of the classical five factor model, at least in Europe in the 2008-2018 time span. Overall, the slopes and the R^2 values obtained with the EE-FF model are direct evidence of the impact of the EU-ETS (low-carbon policy) upon European stock returns.

Table 4 displays the results of the 8 regressions, one for each response variable, that have been run with five explicatory variables — R_M, SMB, HML, RMW, CMA — and of the 8 regressions which have been run with six explicatory variables —

$R_M, SMB, HML, RMW, CMA, GMC$— . The response variables are the monthly value weight excess returns of the eight portfolios formed from annual sorts of the 182 European stocks into 4 size groups (4 quartiles) and two EU-ETS groups (liable and exempt).

TABLE 2.4: Results of the regressions carried out with the five factor model (FF) and the EE-FF for 8 value-weight portfolios formed on size and EU-ETS participation. January 2008-December 2018.

Portfolio	*FF*		*EE-FF*		**Portfolio**	*FF*		*EE-FF*	
	α	$t(\alpha)$	α	$t(\alpha)$		α	$t(\alpha)$	α	$t(\alpha)$
Green/Small	0.01	0.1	-0.01	-0.17	Carbon/Small	0.01	0.40	0.01	1.22
Green/M-l	0.01	2.12	0.01	1.21	Carbon/M-l	-0.01	-1.12	0.01	0.57
Green/M-h	0.01	2.15	0.01	1.41	Carbon/M-h	-0.01	-1.02	0.01	1.02
Green/Big	0.01	0.15	-0.01	-0.41	Carbon/Big	-0.01	-1.51	0.01	0.06
	β	$t(\beta)$	β	$t(\beta)$		β	$t(\beta)$	β	$t(\beta)$
Green/Small	0.49	8.90	0.50	8.93	Carbon/Small	0.42	5.29	0.40	5.12
Green/M-l	0.66	11.28	0.68	11.73	Carbon/M-l	0.51	5.80	0.46	5.87
Green/M-h	0.69	13.06	0.70	13.34	Carbon/M-h	0.79	11.47	0.74	12.57
Green/Big	0.64	10.64	0.65	10.84	Carbon/Big	0.65	11.98	0.62	12.53
	s	$t(s)$	s	$t(s)$		s	$t(s)$	s	$t(s)$
Green/Small	0.58	3.90	0.59	3.95	Carbon/Small	0.16	0.75	0.11	0.53
Green/M-l	0.38	2.39	0.42	2.67	Carbon/M-l	0.84	3.55	0.73	3.41
Green/M-h	0.13	0.91	0.15	1.10	Carbon/M-h	0.45	2.43	0.35	2.20
Green/Big	-0.10	-0.62	-0.07	-0.46	Carbon/Big	-0.22	-1.47	-0.28	-2.05
	h	$t(h)$	h	$t(h)$		h	$t(h)$	h	$t(h)$
Green/Small	0.03	0.16	0.08	0.37	Carbon/Small	-0.20	-0.68	-0.42	-1.37
Green/M-l	-0.38	-1.72	-0.22	-0.99	Carbon/M-l	0.58	1.77	0.12	0.41
Green/M-h	-0.31	-1.56	-0.20	-0.98	Carbon/M-h	0.09	0.36	-0.32	-1.40
Green/Big	0.08	0.34	0.19	0.80	Carbon/Big	0.51	2.49	0.24	1.25
	r	$t(r)$	r	$t(r)$		r	$t(r)$	r	$t(r)$
Green/Small	0.20	0.70	0.23	0.79	Carbon/Small	-0.45	-1.09	-0.58	-1.42
Green/M-l	-0.05	-0.17	0.04	0.14	Carbon/M-l	-0.15	-0.33	-0.42	-1.02
Green/M-h	-0.36	-1.32	-0.30	-1.08	Carbon/M-h	0.18	0.52	-0.06	-0.19
Green/Big	0.15	0.47	0.21	0.68	Carbon/Big	0.55	1.96	0.39	1.52
	c	$t(c)$	c	$t(c)$		c	$t(c)$	c	$t(c)$
Green/Small	-0.08	-0.35	-0.10	-0.42	Carbon/Small	-0.30	-0.90	-0.22	-0.66
Green/M-l	-0.30	-1.20	-0.36	-1.48	Carbon/M-l	-0.73	-2.00	-0.55	-1.67
Green/M-h	-0.49	-2.19	-0.53	-2.40	Carbon/M-h	-0.67	-2.35	-0.51	-2.05
Green/Big	-0.42	-1.68	-0.47	-1.86	Carbon/Big	-0.42	-1.85	-0.32	-1.51
	g	$t(g)$	g	$t(g)$		g	$t(g)$	g	$t(g)$
Green/Small			0.09	0.79	Carbon/Small			-0.44	-2.60
Green/M-l			0.33	2.61	Carbon/M-l			-0.93	-5.44
Green/M-h			0.22	2.00	Carbon/M-h			-0.85	-6.61
Green/Big			0.23	1.73	Carbon/Big			-0.54	-5.02

The adjusted R^2 values for the original Fama and French (FF) model fall in between the 0.31-0.72 range, meaning that the FF model fares quite well in the representation of the variance of the outcome variables, at least in Europe in the 2008-2018 time frame. The 0.31 R^2 value comes from the small cap/carbon portfolio regression, while the second lowest R^2 value is 0.51 (medium-low cap/carbon), which is followed by an R^2 value of 0.54 (small cap/green). All other R^2 values are above 0.64.

We can report that all intercepts of the 8 time-series regressions carried out with the FF model are almost indistinguishable from zero — the lowest being -0.01 and the highest being 0.01 — and 2 intercepts out of 8 are statistically significant at the 0.05 level. Fama and French (2015) suggest two interpretations of the zero-intercept hypothesis: the mean-variance-efficient tangency portfolio combining the explanatory returns and interpreting the factor model as the regression equation of Merton's (1973) model in which unspecified state variables lead to risk premiums that are not captured by the market factor. If the coefficients of the time-series regression —$\beta_i, s_i, h_i, r_i, c_i$ — completely capture variation in expected returns, then the intercept, α_i, is indistinguishable from zero. Under the assumption of the zero-intercept hypothesis, the range of values obtained for the intercepts provide evidence of the accuracy of the FF model to represent the financial reality under analysis.

Table 4 also shows coefficients and t-statistics for the five factors. While the market factor is always highly statistically significant, the size factor is significant at the 0.05 level in 4 out of 8 cases (small cap/green, medium-low cap/green, medium-low cap/carbon, medium-high cap/carbon). The value factor is statistically significant at the 0.05 level in one case out of eight (big cap/carbon) and the investment factor —CMA— in three out of eight cases (medium-high cap/green, medium-low cap/carbon, medium-high cap/carbon).

The EE-FF model finds adjusted R^2 values in the 0.34-0.76 range. The regressions carried out with the EE-FF model find adjusted R^2 values which are larger is 6 cases out of 8 than the regressions carried out with the classical FF model. The only R^2 values which do not improve in the *passage* from a five factor model to a six factor model come from the small cap/green regression and the big cap/green regression. In these two cases the adjusted R^2 values are exactly the same for the FF model and the EE-FF model.

We find highly statistically significant coefficients for the GMC factor in 6 regressions out of 8, the only exception being the small cap/green portfolio (t-statistic=0.79) and the big cap/green portfolio (t-statistic= 1.73). As expected, coefficients are positive when the dependent variable is a green (i.e. does not participate to the EU-ETS) portfolio and negative when the dependent variable is a carbon (i.e. does participate to the EU-ETS) portfolio. GMC's positive coefficients range from 0.09 (small cap/green) to 0.33 (medium-low cap/green), whereas GMC's negative coefficients range from -0.44 (small cap/carbon) to -0.93 (medium-low cap/carbon).

Again, the GMC coefficient for the small cap/green portfolio (0.79) and the big cap/green portfolio (t-statistic= 1.73) are the only two coefficients which are not statistically significant at the 0.05 level. Additionally, the magnitude of the coefficients of the green portfolios are evidently lower than their carbon counterparts, i.e. firms are more penalized for their participation to the EU-ETS rather than rewarded for their exemption from the EU-ETS. We suspect this is due to the fact that there are some sectors which are considered as carbon-intensive by the market but which are not yet included in the EU-ETS participant list. Armed with statistical evidence, we conclude it is legitimate to consider the addition of the GMC factor to the classical Fama and French's five factors in Europe, at least from 2008.

2.5 Redundant factors

The previous section has shown that the inclusion of a sixth factor —GMC— improves the effectiveness of Fama and French's five factor model in Europe from 2008 onwards. Nevertheless, such addition may hinder the explication power of the classical five factors, i.e. the portion of variance in returns explained by a "classical" factor may be partially absorbed by the GMC factor we are putting forward. As such addition may lead to a factor redundancy, we perform a principal component analysis (PCA) on the 5+1 factors in order to figure out how many factors to include in the regression of the returns to be explained, $R_i - R_F$.

Table 5 shows the correlations matrix between the 6 factors. Noticeable correlations are shown between R_M, or MkT, and HML (0.49), between RMW and HML

(-0.83) and between RMW and R_M (-0.41).

TABLE 2.5: Correlation Matrix for the market, size, value, profitability, investment and EU-ETS factor

	MkT	**SMB**	**HML**	**RMW**	**CMA**	**GMC**
MkT	1.00	-0.02	0.49	-0.41	-0.27	-0.31
SMB	-0.02	1.00	-0.05	-0.08	-0.21	-0.06
HML	0.49	-0.05	1.00	-0.83	0.33	-0.35
RMW	-0.41	-0.08	-0.83	1.00	-0.31	0.24
CMA	-0.27	-0.21	0.33	-0.31	1.00	0.06
GMC	-0.31	-0.06	-0.35	0.24	0.06	1.00

Table 6 displays the eigenvalues and the proportion of variances retained by the principal components. If we were to follow Kaiser's rule we would have to retain only two components and thus discard 4 factors out of 6. Given the high correlation between RMW and HML and the relative low contribution of SMB to the two main principal components (figure 1), these would be natural candidates to the discarded. Unfortunately, figure 1 shows that the contribution of CMA is superior to that of GMC. Ultimately, if we were to follow Kaiser's rule we would just settle for the market factor, R_M (MkT), and the investment factor, CMA. As this choice is not coherent with our research objective, we decide not to follow Kaiser's rule and settle for three components which account for 80% of the total variance: R_M (MkT), CMA and GMC. The reduced version of the EE-FF model, then, becomes:

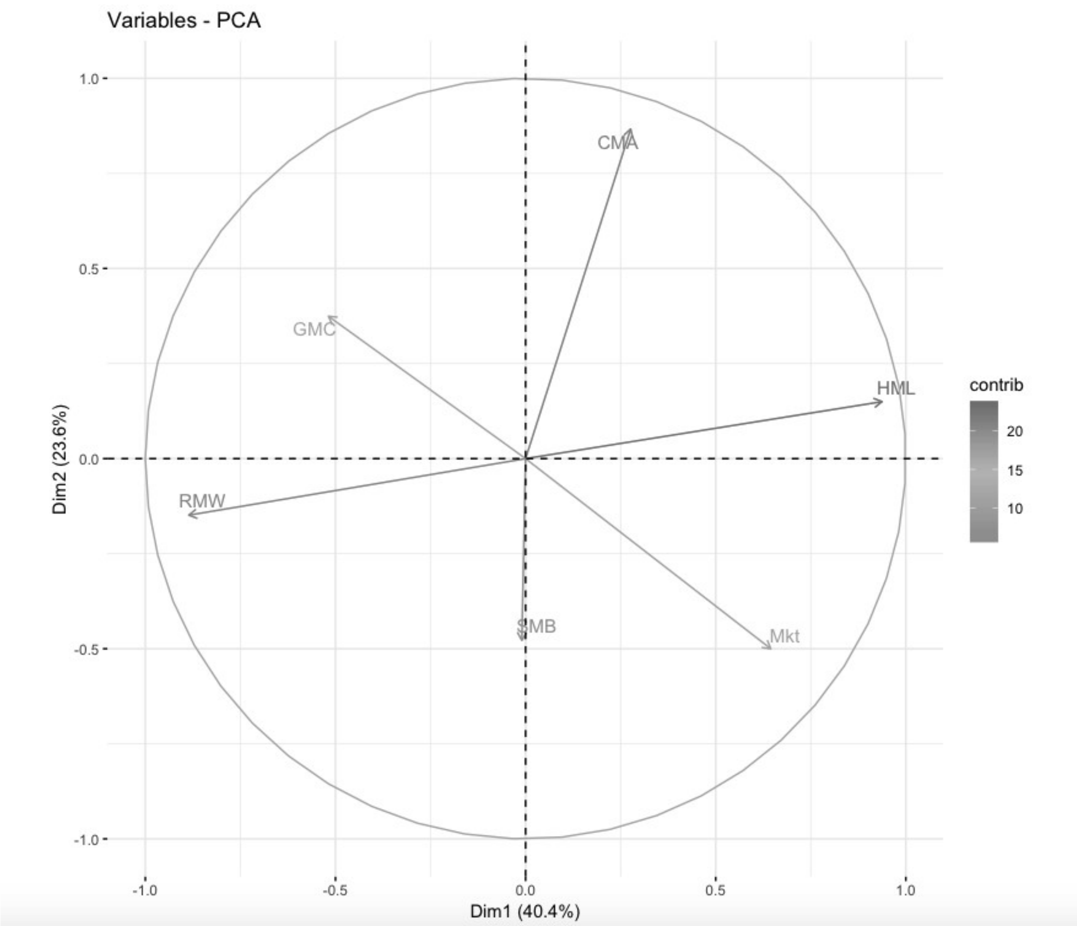
$$R_{i,t} - R_{F,t} = \alpha_i + \beta_i(R_{M,t} - R_{F,t}) + c_i CMA_t + g_i GMC_t + e_{i,t} \tag{2.3}$$

TABLE 2.6: Eigenvalues, variance and cumulative variance for the 6 components

	Eigenvalues	**Percent variance**	**Cum. percent variance**
Dimension 1	2.42	40.41	40.41
Dimension 2	1.41	23.57	63.98
Dimension 3	0.97	16.20	80.19
Dimension 4	0.75	12.58	92.77
Dimension 5	0.29	4.88	97.66
Dimension 6	0.14	2.23	100.00

Table 7 displays the results of the 8 regressions, one for each response variable, that have been run with three explicatory variables — R_M, CMA, GMC —. The response variables are the monthly value weight excess returns of the eight portfolios

FIGURE 2.1: Contributions of MkT, SMB, HML, RMW, CMA and GMC variables to the two first dimensions



formed from annual sorts of the 182 European stocks into 4 size groups (4 quartiles) and two EU-ETS groups (liable and exempt).

A comparison of table 4 — the EE-FF with 6 factors— and table 7 — EE-FF with 3 factors — shows that reducing the number of factors improves t-values for the intercepts in five cases out of eight. On the other hand reducing the number of factors increases the statistical significance of the market coefficient for eight portfolios out of eight and of the investment coefficient for six portfolios out of eight. With regard to the GMC coefficient, moving on from 6 to 3 factors only improves the statistical significance of the coefficient in 4 cases out of 8. The adjusted R^2 values of the EE-FF with 3 factors (table 7) only improve over the adjusted R^2 values of the EE-FF with 6 factors (table 4) in one case out of eight: the big cap/green portfolio. The adjusted R^2 values for the other portfolios are exactly identical or slightly inferior.

TABLE 2.7: Results of the regressions for 8 value-weight portfolios formed on size and EU-ETS participation carried out with the 3 factor EE-FF model. January 2008-December 2018.

Size	**Green**	**Carbon**	**Green**	**Carbon**
	α		$t(\alpha)$	
Small	0.01	0.01	0.64	0.85
Medium/low	0.01	0.01	1.70	0.67
Medium/high	0.01	0.01	1.28	1.31
Big	-0.01	0.01	-0.24	0.37
	β		$t(\beta)$	
Small	0.46	0.38	10.04	6.17
Medium/low	0.61	0.52	13.01	7.85
Medium/high	0.69	0.67	16.59	14.01
Big	0.67	0.63	14.12	15.73
	c		$t(c)$	
Small	-0.33	-0.30	-1.73	-1.18
Medium/low	-0.70	-0.44	-3.58	-1.61
Medium/high	-0.59	-0.86	-3.41	-4.31
Big	-0.39	-0.23	-2.01	-1.37
	g		$t(g)$	
Small	0.05	-0.40	0.44	-2.49
Medium/low	0.35	-1.05	2.86	-6.02
Medium/high	0.23	-0.81	2.17	-6.48
Big	0.21	-0.55	1.68	-5.18

Overall, we find that the reduced version of the EE-FF model (3 factors), while leading to some moderate statistical improvements over the EE-FF model with 6 factors, partially loses economic and financial significance by dropping the size, value and profit factor.

2.6 The carbon stress test

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 realized 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,

TABLE 2.8: 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.

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 low granularity, while in the bottom-up approach the empirical relationship is estimated at the highest possible level of granularity of a banking variable.The division refers to the US definitions whereas in Europe top-down refers to stress tests carried out by regulators and bottom-up by banks 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 subjects 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 carbon stress test we put forward is based on the GMC factor obtained with the EE-FF model (6 factors). The GMC is a proxy that mimics the risk factor in returns related to the payment of a carbon price and its coefficient —in the EE-FF model — is interpreted as the average effect on stock returns of a one unit increase in GMC holding all other predictors fixed. It follows that, if GMC increases, the risk factor related to participating to the EU-ETS raises accordingly. Conversely, if GMC decreases, the risk factor related to participating to the EU-ETS diminishes. It is evident that a carbon risk factor increase goes with a higher EU-ETS price, whereas a carbon risk factor decrease goes with a lower EU-ETS price. In order to understand the impact of a hypothetical, but plausible and severe, EU-ETS price upon the stock returns under examination, we stress the average GMC portfolio value by 20% (low shock), 50% (medium shock), and 100% (high shock) and we look at the effect on each of the 8 value-weight portfolios formed from annual sorts of the 182 European stocks into 4 size groups (4 quartiles) and two EU-ETS compliance groups (liable, or carbon, and exempt, or green).

TABLE 2.9: 11-year (2008-2018) average monthly percent excess returns explained by the GMC factor for stressed values of GMC.

Portfolio	**Average excess returns**		
	Low shock	Medium shock	High shock
Green/Small	0.08	0.10	0.13
Green/M-l	0.29	0.37	0.49
Green/M-h	0.19	0.24	0.32
Green/Big	0.20	0.25	0.34
Carbon/Small	−0.39	−0.49	−0.65
Carbon/M-l	−0.82	−1.03	−1.37
Carbon/M-h	−0.75	−0.94	−1.25
Carbon/Big	−0.48	−0.60	−0.80

Table 9 shows the results of the carbon stress test for each of the 8 value-weight portfolios for the three shock scenarios: the second, third and fourth column provide the averages of monthly percent excess returns explained by the GMC factor for stressed values of GMC. Results of the carbon stress test show the magnitude of the increase (decrease) of average excess stock returns for green firms (carbon firms) in case of an average ETS price appreciation of 20% (low shock), 50% (medium shock), and 100% (high shock) for each market cap tranche.

2.7 Conclusions

Changes in extreme climate phenomena such as temperature extremes, high sea levels extremes or precipitation extremes are likely to seriously affect several facets of natural and human systems. There is scientific evidence that human activity, by altering the composition of the atmosphere, contributes to global warming. Addressing climate change implies greenhouse gases (GHG) mitigation, and, while this can be sometimes autonomous, it is mostly carried out with policy, i.e. low-carbon policy. This leads to the research question of the effect of low-carbon policy upon financial values. In the context of EU-ETS, this question has found contradictory results: some studies find the impact of this low-carbon policy on financial values beneficial, some others find it detrimental.

The objective of this paper is to study the impact of low-carbon policy upon the value of financial assets, particularly stock returns. Specifically, we seek to understand and explain the impact of one particular European policy, the 2003/87/CE directive upon which the EU-ETS is based, upon European stock returns. To answer this question, we selected 182 European firms that fall in two categories: firms that do participate to the EU-ETS (carbon firms) and firms that do not participate to the EU-ETS (green firms) since the beginning of phase II (2008). With 11 years of data (2008-2018) we use a multi-factor model inspired by Fama and French (2015) whose key new component is an EU-ETS compliance factor, GMC (green minus carbon). The GMC portfolio is obtained by subtracting the monthly value-weight carbon portfolio returns from the monthly value-weight green portfolio returns.

Following our analysis, results show that, just as there are patterns in average returns related to size, profitability and investment, which have been proven elsewhere, there is also a pattern related to EU-ETS compliance. Such pattern exists, in Europe, since the implementation of EU-ETS: there is a high green premium, rather than a carbon premium like parts of the literature asserted previously, and this green premium is highly statistically significant, i.e. green stocks outperform on average carbon stocks over the 11-year span. Furthermore, we follow the recent carbon stress test trend by putting forward a stress test able to indicate what is the impact of a hypothetical EU-ETS price upon stock returns: our results show the effects of a plausible but more severe average EU-ETS price on both carbon firms and green firms for each market cap tranche.

These results are also the basis for the policy implications for legislators and financial practitioners. Our findings show that the 2003/87/CE directive has a positive effect in the financing of the low-carbon transition: the beginning of phase II of EU-ETS — the start date of our study — coincides with both capital outflows from high-carbon firms and capital inflows to low-carbon firms. The carbon stress test we put forward shows by how much an increase of the EU-ETS price would accelerate such process. The low-shock scenario, for example, would provide an additional boost to the low-carbon transition without harming excessively high-carbon firms. From a financial practitioner perspective, our findings show that, in Europe, in the 2008-2018 time span, low-carbon firms have outperformed high-carbon firms and that this outperformance is statistically significant. In other words, low-carbon investments cannot be considered anymore just an ethical stand: nowadays, as the green premium shows, investing in low-carbon firms is a profitable exercise.

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