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Blind to carbon risk? An analysis of stock market's reaction to the Paris Agreement

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Abstract

It is increasingly recognized that a transition to sustainable finance is crucial to scale up the low-carbon investments needed to achieve the global climate targets. A main barrier to portfolios' decarbonization is the lack of conclusive evidence on whether low-carbon investments add value to a portfolio, and on whether markets react to climate announcements by rewarding (penalizing) low-carbon (carbon-intensive) assets. To fill this gap, we develop an empirical analysis of the low-carbon and carbon-intensive indices for the EU, US and global stock markets. We test if financial markets are pricing the Paris Agreement (PA) by decreasing (increasing) the systematic risk and increasing (decreasing) the portfolio weights of low-carbon (carbon-intensive) indices afterwards. We find that after the PA the correlation among low-carbon and carbon-intensive indices drops. The overall systematic risk for the low-carbon indices decreases consistently, while stock markets' reaction is mild for most of carbon-intensive indices. Moreover, the weight of the low-carbon indices within an optimal portfolio tends to increase after the PA. This evidence suggests that stock market investors have started to consider low-carbon assets as an appealing investment opportunity after the PA but have not penalized yet carbon-intensive assets.

Keywords: asset pricing, Paris Agreement announcement, low-carbon indices, carbon-intensive indices, systematic risk, Markowitz's portfolio optimization, market model, Fama-French five-factor model, risk-adjusted return, stranded assets.

JEL: C22, C58, Q54

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1. Introduction

On December 12, 2015 the Paris Agreement (PA hereafter) was announced at the UNFCCC COP21 conference in Paris. The PA is broadly considered as a landmark step for global climate mitigation and adaptation action, and as such, it came at surprise for the most. Indeed, for the first time, most UN countries agreed on the need to limit global temperature increase “well below 2°C” above pre-industrial levels (Art 2.1(a)); to strengthen the ability of countries to deal with the impacts of climate change (Art 2.1(b)), and to commit to "making finance flows consistent with a pathway towards low Greenhouse Gas emissions and climate-resilient development" (Art 2.1(c)).

The PA was followed by an unprecedented consensus among scholars, policy makers and financial institutions on the importance of aligning finance to sustainability to achieve the global climate and sustainability targets (UNEP-FI, 2018; HLEG, 2018). This requires both the scaling up of investments in low-carbon production and consumption activities, and the divestment from fossil fuels production and carbon-intensive activities (NCE, 2018).

Nevertheless, financial capital is still largely allocated into economic activities whose profits rely directly or indirectly on fossil fuels’ extraction, combustion and use, and that thus do not align to the PA targets. The Climate Stress-test by Battiston et al. (2017) showed that financial actors in the EU and US are largely exposed to contracts issued by economic activities that could lose value in a disorderly transition to a low-carbon economy and become “carbon stranded assets” (Leaton et al., 2012; Caldecott, 2018; Mercure et al., 2018). In particular, Battiston et al. (2017) found that insurance and pension funds are exposed for 45% circa of their equity portfolio, making climate financial risk material. The financial losses associated to stranded assets could be amplified by financial interconnectedness, thus introducing a new potential risk for countries’ economic competitiveness and financial stability (Gros et al., 2016; Battiston et al., 2017; Roncoroni et al., 2019). In 2015, the Governor of the Bank of England, Mark Carney, warned investors about the materiality of climate-related financial risks, identifying investors’ exposure to climate-related financial risks assets as a potential driver of asset prices volatility and financial instability (Carney 2015). Finally, several central banks and regulators that joined the Network for Greening the Financial System (NGSF) recommended investors to disclose their exposure to climate risks and to mainstream climate risk assessment in their portfolios’ management strategies, by running climate stress-test (NGFS, 2019).

The PA policy announcement, the research results on the materiality of climate-related financial risks, and the response from central banks and financial regulators, represent all strong market signals. But investors and financial market’s reactions to such signals are still unclear. Indeed, no conclusive evidence has been provided so far on whether (and if so, how) stock markets have started to react to the PA announcement.

In this paper, we contribute to fill this gap by developing a comprehensive empirical analysis of the financial performance of most popular low-carbon and carbon-intensive indices in the EU, US and global stock markets, before and after the PA, implementing the most used and robust financial methods. First, by extending the market model (Sharpe, 1964), we analyze the performance of both low-carbon and carbon-intensive stock markets' indices in terms of systematic risk (beta) before and after the PA. Second, we test for the presence of a structural break in the beta after the PA by extending the market model to the five-factor model specification proposed by Fama and French (2015). Third, by applying Markowitz (1952)'s portfolio optimization, we analyze whether the optimal weights of the low-carbon indices have increased after the PA relative to the optimal weights of the carbon-intensive indices.

We focus on equity holdings and indices traded on the EU, US and global stock markets for two reasons. First, despite representing a large share of the market, they have not been covered by the literature in a comprehensive way. Second, stock markets and equity contracts, given their financial characteristics, usually react faster to announcements and shocks than debt securities.

The results of our analysis are aimed to inform the portfolios' risk management strategies of investors in the transition to sustainable finance, and to support financial supervisors in the assessment of financial market's exposure to and (mis)pricing of climate transition risk that could give rise to financial instability.

A main disclaimer applies. In order to identify "low-carbon" and "carbon-intensive" indices and companies, we use the same information set available to investors, who do not dispose yet of a standardized and operational classification of green and brown economic activities and assets. We collect daily and monthly prices of EU, US and global stock markets indices composed of companies whose business is based on renewable energy production and commercialization, and of companies whose main business is related to the production and commercialization of fossil fuel and fossil fuel-based electricity².

The paper is organized as follows. Section 2 provides the economic motivation and review of the state of the art on stock markets' reaction to climate announcements, while Section 3 describes the methodology. Section 4 presents the data and discusses the results, while Section 5 concludes.

2. Motivation and state of the art

Since the announcement of the PA, the scientific evidence on the materiality of climate-related financial risks, and the number of international financial initiatives for disclosing and assessing climate

² Despite the European Commission has launched in July 2019 a "green taxonomy" that allows to identify economic activities contributing to climate mitigation and adaptation objectives, its market implementation has still to be enforced.

risks in investors' portfolios has increased. Recently, a group of central bankers in Europe signed an "Open letter on climate-related financial risks"³ talking about climate-driven "Minsky Moments", i.e. a sudden collapse of prices of fossil-based assets (Carney, Villeroy de Galhau and Elderson 2019).

This statement follows a series of climate financial-related announcements. In 2016, a group of 130 investors signed a letter calling on the G20 to take steps to meet the PA, and several investors announced divesting strategies from fossil fuels⁴ in response to potential losses driven by carbon stranded assets. In 2017, the G20's Financial Stability Board Task Force for Climate-Related Financial Disclosure issued its recommendations for climate-related financial risk disclosure in investors' portfolios (TCFD 2017). In 2019, thirty-four central banks and financial regulators of countries representing 50% of global emissions and two-thirds of systemically relevant financial institutions who are part of the NGSF recommended investors to introduce climate stress-testing to disclose their exposures to climate risks (NGFS 2019). In 2018, in its Financial Stability Report, the European Insurance and Occupational Pension Authority (EIOPA) assessed the climate-related assets exposure of the European insurance sector⁵, by building on the methodology developed in Battiston et al. (2017). The same methodology was followed by the European Central Bank (ECB) who assessed Euro-Area investors' exposure to economic activities that are considered as "climate policy relevant" in its 2019 Financial Stability Review⁶.

This represents an unprecedented and fast policy response that markets, if rational, should have reflected immediately by changes in asset prices and by pricing the "risk of stay brown" and the "opportunity to go green". Thus, we would expect a decrease (increase) in the systematic risk exposure (beta) for low-carbon (carbon-intensive) listed companies, meaning that low-carbon investments (carbon-intensive) have become more (less) appealing for investors.

A recent stream of literature has started to analyze market's pricing of low-carbon investment strategies and market's reaction to climate announcements. However, this literature is still limited and has mostly focused on debt contracts (in particular, corporate bonds). Moreover, the results published so far are not univocal (see e.g. the case of a green bonds' premium, Alessi et al., 2019; Zerbib 2019; Karpf and Mandel 2018).

With regard to the pricing of green investment performance in stock market indices, Singh & Shrimali (2018) find that the S&P Clean Energy index does not add value to portfolios in the sense that this index is not useful in diversifying the portfolio. However, the time window and the methodology

³ <https://www.bankofengland.co.uk/news/2019/april/open-letter-on-climate-related-financial-risks>

⁴ See e.g. Axa in 2017 <http://www.climateaction.org/news/axa-investment-managers-pledge-193-million-divestment>

⁵ <https://eiopa.europa.eu/Pages/EIOPA--Financial-Stability-Report---December-2018.aspx>

⁶ https://www.ecb.europa.eu/pub/financial-stability/fsr/special/html/ecb.fsrart201905_1~47cf778cc1.en.html

used, i.e. a static mean-variance optimization over 10 years returns, do not allow for short-term price volatility effects on the market and do not take into account the possible impact of the recent climate-related announcement as the PA. Lee et al. (2015) use a market model to assess whether firms engaging in voluntary carbon disclosure experience abnormal returns in asset prices. Using a sample of firms from the Climate Disclosure Project (CDP) Korea 2008 and 2009, they find that the market is likely to respond negatively to firms' voluntary carbon disclosure, implying that investors tend to perceive carbon disclosure as bad news.

When it comes to market's reaction to climate announcements, Ramelli et al. (2018) show that investors reacted to two main policy "shocks" in 2016, i.e. Trump's presidential election and the nomination of Scott Pruitt (a climate skeptic) to head the Environmental Protection Agency (EPA), by rewarding companies in high-emissions industries, at least in the short run. In contrast, for the same policy events, Wagner et al. (2018) find that investors rewarded companies demonstrating more responsible climate strategies. Sterner and Mukanjari (2018) studied the stock market's reaction to the announcement of the PA and the election of Donald Trump as a President of the USA, expecting to find a different effect on the financial performance of fossil energy firms. They did not find unique evidence of stock prices' response to the announcement of the PA or Trump election on fossil-based energy companies.

From an economic point of view, the possibility of mispricing weakens the assumption of complete markets on which traditional financial pricing models stand (e.g. Black and Scholes 1973, Merton 1974). In presence of asymmetric information (Greenwald and Stiglitz 1986) and incomplete markets, investors cannot compute their risk-adjusted returns under scenarios associated to certain probabilities of occurrence, and multiple equilibria become a possible outcome. In this case, investors cannot identify ex-ante a preferred investment strategy. Mispricing of climate-related financial risks can slow down the low-carbon transition by limiting firms' green financing opportunities on the credit and debt market. This, in turn, contributes to keep (or even increase) investors' exposure to and trading of carbon-intensive assets, and to dismiss potential opportunities for returns in low-carbon sectors. Mispricing of climate risks in the value of financial contracts and investors' portfolios can lead to price volatility if large asset classes are involved, with implications on financial stability (Monasterolo et al. 2017).

Since financial investors take decisions based on what they can measure, and their decisions do influence (and are influenced by) the benchmark in their respective markets, robust portfolio's analyses of the conditions under which low-carbon investments could provide systematically higher risk-adjusted returns than carbon-intensive investments are urgently needed.

3. Methodology

We analyze financial market's reaction to, and pricing of, the announcement of the PA by applying robust financial econometric models to a selection of low-carbon and high-carbon indices⁷.

We consider the null hypothesis (H_0) of no change in the value of beta before/after the PA, i.e. no impact of the announcement of the PA for both low-carbon and carbon-intensive indices (equity contracts), against two alternative hypotheses:

- H_{1A} : after the PA, low-carbon indices show lower systematic risk than before the PA;
- H_{1B} : after the PA, carbon-intensive indices show higher systematic risk than before the PA.

We test for the presence of significant differences in systematic risk (beta) across low-carbon and carbon-intensive indices to understand if the market is pricing them in a different (and statistically significant) way in terms of the systematic risk profile (beta) of the two classes of assets.

Then, to control for other possible determinants of stocks' returns in addition to the market factor, we test for the presence of a structural break in the index beta after the PA by extending the market model to the five-factor model specification proposed by Fama and French (2015). The multi-factor approach allows us to find other factors that might explain the risk-return profile of low-carbon and carbon-intensive indices, thus strengthening the economic meaning of our analysis.

Finally, we consider the well-established Markowitz (1952)'s portfolio optimization technique to analyze portfolio's performance before and after the PA, assessing whether the optimal weights in a portfolio composed by low-carbon ("green") and carbon-intensive ("brown") equity contracts and indices change before and after the PA. In particular, we assess whether the "green" component is more relevant after the PA than before, i.e., whether it adds value to a portfolio.

3.1 Market model: stock market indices performance and sensitivity to the Paris Agreement

We consider the following linear model:

$$r_{i,t} = \alpha_i + \beta_i r_{m,t} + \gamma_i r_{m,t} d_t + \varepsilon_{i,t} \quad (1)$$

where $r_{i,t}$ and $r_{m,t}$ are the (log-)return at time t of an equity index i and the market index m , respectively, d_t is a dummy variable which takes value 1 after the PA and 0 otherwise, and $\varepsilon_{i,t}$ is an i.i.d. error term with $E(\varepsilon_{i,t}) = 0$ and $E(\varepsilon_{i,t} r_{m,t}) = 0$.⁸

⁷ See Section 4 for the description of the financial data used.

⁸ In our preliminary analyses, we have also allowed for a break in the intercept, i.e. including $\delta_i d_t$ in the specification of model (1) (and model (2) below). However, for all of the estimated models, we found $\hat{\delta}_i$ being non-significant. Therefore, we have preferred to exclude it from the specification of models (1) and (2) in order to reduce the number of parameters to be estimated.

The model allows to estimate the impact of climate announcements, and specifically considering the announcement of the PA at the UN COP21 conference in Paris (2015/12/12) on indices' performance in the EU, US and global stock markets.

The model that we propose is akin to the market model within the CAPM framework (Sharpe, 1964) as it derives the linear relationship between the asset's expected return and its beta, which is a standard measure of the asset's systematic risk. This means that, similarly to the market model, our model identifies the risk-return profile of asset i in a simple and straightforward way. There are several well-known statistical limitations of the market model and of the CAPM framework, including the assumptions of absence of autocorrelation, of homoskedasticity and Gaussianity, and of independence between the market index used as regressor and the stochastic component. Nevertheless, despite these limitations, the market model is still considered as one of the main benchmarks in financial studies for its simplicity and interpretability⁹.

In our analysis, we address these potential limitations by:

- Using Heteroskedasticity and Autocorrelation Consistent (HAC) standard errors to account for possible autocorrelation, heteroskedasticity and, to some extent, the deviation from the normal distribution;
- Considering highly diversified market indices, i.e. indices composed of numerous stocks, in order to weaken the possible correlation between the regressor and the model's stochastic component.

Further, we extend the standard market model specification by including the interaction variable $r_{m,t}d_t$, which allows to capture the impact of the PA on the level of systematic risk and the risk-return profile of the asset. In this regard, a rejection of the null hypothesis $H_0: \gamma_i = 0$ implies that the systematic risk of the asset has significantly changed after the PA. More precisely, rejecting the null hypothesis in favor of the alternative $H_{1A}: \gamma_i < 0$, implies that the asset has reduced its level of systematic risk. In contrast, rejecting the null hypothesis in favor of the alternative $H_{1B}: \gamma_i > 0$ implies an increase in the asset's systematic risk.

Our approach is in the spirit of the Chow test to assess the presence of a structural break at a given date in time (Chow, 1960). In particular, here we focus on the break of the slope parameter, i.e. an abrupt change in the level of systematic risk related to the PA announcement.

⁹ In addition, we are well aware of the fact that future climate impacts are characterized by large uncertainty and non-linearity, thus implying the need to consider stochasticity. For a discussion of the challenges for pricing climate policy risks in financial contracts see Battiston and Monasterolo (2019).

3.2 Beyond the market factor: determinants of indices performance and sensitivity to the Paris Agreement in a Fama-French five-factor model

In this section we extend the market model in (1) to the multi-factor approach developed by Fama and French (2015). In particular, we consider the following model specification

$$r_{i,t} - r_{f,t} = \alpha_i + \beta_i(r_{m,t} - r_{f,t}) + \gamma_i(r_{m,t} - r_{f,t})d_t + \zeta_i SMB_t + \xi_i HML_t + \rho_i RMW_t + \zeta_i CMA_t + \varepsilon_{i,t} \quad (2)$$

where $r_{f,t}$ is (the proxy of) the risk-free rate, *SMB* (Small Minus Big) denotes the size factor, i.e., the mean return on the small company stock portfolio minus the mean return on the big company stock portfolio, *HML* (High Minus Low) is the value factor computed as the difference between the mean returns on the “value” portfolio and the “growth” portfolio in terms of company’s book-to-market value, *RMW* (Robust Minus Weak) is the profitability factor, that is the mean return on the robust operating profitability portfolios minus the mean return on the weak operating profitability portfolios, and *CMA* (Conservative Minus Aggressive) denotes the investment factor, i.e., the difference between the mean returns on the conservative and aggressive investment portfolios. More details on these factors can be found in the online Kenneth R. French’s data library. As for model (1), $\varepsilon_{i,t}$ is assumed to be an i.i.d. error term uncorrelated with the regressors and with $E(\varepsilon_{i,t}) = 0$ and we test the null hypothesis $H_0: \gamma_i = 0$ against the alternatives $H_{1A}: \gamma_i < 0$ and $H_{1B}: \gamma_i > 0$ to evaluate the abrupt change in the asset’s systematic risk after the PA.

3.3 Portfolio optimization: reweighting optimal portfolio in response to the Paris Agreement

We assess the impact of the PA announcement on the financial performance of low-carbon and carbon-intensive investments. We consider the standard Markowitz (1952)’s optimization technique based on Lagrange multipliers to construct optimal portfolios that include both low-carbon and carbon-intensive indices, recording their value both before and after the PA in order to compare the weights for the low-carbon and carbon-intensive components of the portfolios.

Markowitz’s portfolio optimization is chosen because it is a standard methodology adopted by academics and practitioners. It consists in minimizing the weighted variance of the portfolio of n assets (in our analysis, the stock market’s indices) for a given level of expected return. More formally, we define the optimal weights as the vector \hat{w} such that

$$\operatorname{argmin}_w w' \Sigma w$$

subject to the following restrictions

$$\begin{aligned} R'w &= \mu \\ \sum_{i=1}^n w_i &= 1 \end{aligned} \quad (2)$$

using Lagrange multipliers, where w is a n -dimensional vector of portfolio weights, Σ is the covariance matrix for the returns on the n indices in the portfolio, R is the vector of indices' returns, and μ is the expected return objective of the portfolio. The restriction in (2) excludes the possibility of investors' short positions on the portfolio.

4. Results

4.1 Data and preliminary analysis

We select and analyze a sample of the most popular and capitalized equity holding indices from the US, EU and global financial markets, including S&P, Stoxx, FTSE and Nasdaq (see Table 1), collected at daily and monthly frequencies. This selection allows us to provide a comprehensive overview of the financial performance of low-carbon and carbon-intensive equity holdings on EU, US and global markets, evaluating and comparing their risk-return profiles.

Since a standardized classification of "green" or "brown" sectors and firms is not available yet, we use the best and same information available to investors. We collect daily and monthly data on indices' prices from Thomson Reuters Datastream and Bloomberg¹⁰. With the aim to increase the robustness of our results, we consider a set of global, EU and US stock market's indices as proxies of market return, i.e. the regressor $r_{m,t}$ in model (1). The empirical analysis is developed using the indices that are listed in Table 1. Table 1 also shows the results for two well-known and commonly adopted reward-to-risk performance indicators, namely the Sharpe ratio (Sharpe, 1966), defined as the ratio between the mean return of the index in excess with respect to (the proxy of) the risk-free rate and the index's standard deviation, and the Sortino ratio (Sortino and Van der Meer, 1991), where the mean return of the index in excess with respect to (the proxy of) the risk-free rate is divided by the downside risk, defined as $DSR = \sqrt{\frac{1}{T} \sum_{t=1}^T (\text{Min}(0, r_{i,t} - r_{f,t}))^2}$. The significance of the difference between the mean returns and the standard deviations before/after the PA, i.e. the outcome of the tests for the null hypotheses of equal means and equal variances respectively, are displayed using asterisks (see the 'After PA' panel of Table 1, columns 'Mean' and 'Std Dev').

We start our analysis from the low-carbon asset class. From the standard deviations reported in Table 1, we note that the volatility of all the low-carbon indices has sensibly decreased after the PA announcement. For instance, the standard deviation of Renixx has more than halved after the date of the PA announcement both at daily and monthly frequencies. On the other hand, we observe that the

¹⁰ The selection of these indices was carried out by searching for keywords such as "clean energy", "renewable", "green energy", and "ESG environment" to identify low-carbon indices while the carbon-intensive indices were selected using the conventional "oil and gas" definition.

majority of the low-carbon indices shows an overall increase in the mean returns in the period after the PA, in particular in relation to the Nasdaq Clean Edge Green Energy, Wilderhill Clean Energy and Renixx indices. However, it is also interesting to note that some low-carbon indices show negative daily mean returns both in the whole sample and after the PA (S&P Global Clean Energy and Renixx indices) or before PA (Wilderhill Clean Energy index). The overall performance of the low-carbon indices has increased after the PA, in particular thanks to a reduction in the risk level of their assets.

Now we consider the carbon-intensive assets class. From Table 1, we notice a strong reduction in the standard deviation for carbon-intensive indices as well, when comparing the whole sample period and the period after the PA. Also, the carbon-intensive class shows similar mean returns, thus suggesting an improvement in their overall financial performance after the end of 2015 (i.e. the time of the PA announcement). Finally, the market indices considered in our analysis show performances in line with those observed for the low-carbon and carbon-intensive asset classes, i.e. a reduction in volatility after the PA and similar mean returns. Thus, Table 1 does not allow to infer univocal conclusions on an impact of the PA announcement on the risk-return profiles of these indices.

INSERT TABLE 1 HERE

Figure 1 depicts the sample correlations between the monthly returns of the indices listed in Table 1 for the entire sample (left panel) and for the period after the PA (right panel of Figure 1). If we consider the whole sample (left panel of Figure 1), the correlations between indices are quite large, in particular among indices that belong to the same class. However, focusing on the relationship between low-carbon and carbon-intensive indices, we observe that the correlations are smaller and range between 0.3 and 0.6. After the PA announcement (right panel of Figure 1), the correlations have in general decreased, except for those between the carbon-intensive indices class, which shows a similar correlation structure than before the PA. Conversely, the correlations between the low-carbon and carbon-intensive indices are close to zero, thus suggesting that there is no linear relationship between the returns of these two classes of assets after the PA. This result is interesting also from an investor's viewpoint, in so far, uncorrelated asset classes might be particularly useful for portfolio's optimization (as shown in Section 4.3).

INSERT FIGURE 1 HERE

To improve our understanding of the impact (if any) of the PA on the financial performance of the low-carbon and carbon-intensive indices considered, we estimate the extended market model (1) and the extended Fama-French five-factor model in (2). Within the risk-adjusted framework provided by models (1) and (2), we investigate whether the improvement in the risk-return profile after the PA obtained for several indices is market-driven or statistically significant, once we have controlled for market risk (model (1)) as well as other factors (model (2)), i.e. after comparing and testing the betas of the indices before and after PA.

4.2 Market model's results: stock market's indices performance and sensitivity to the Paris Agreement

The results for the estimation of model (1) are reported in Table 2 for daily and monthly data frequencies. All regressions are estimated using the MSCI World index as regressor $r_{m,t}$. Moreover, when a regional (i.e., either US or EU) index is analyzed, we also estimate model (1) with S&P500 ES Energy index and Stoxx Europe 600 index as regressor for US and EU, respectively. This allows us to control for possible regional effects.

Table 2 results show that estimated intercepts are not significant for any index. In a CAPM/market model framework, this result allows us to avoid considering other factors to explain the linear relationship between an asset's expected return and the return of the market index (or market portfolio).

Let's now consider the estimated betas. The results in Table 2 show that the level of systematic risk ($\hat{\beta}_i$) associated to the low-carbon equity indices are, as expected, all significantly different from zero and larger than one, except for the Nasdaq Clean Edge Green Energy index (against S&P500 ES Energy index as regressor at daily frequency) and the STOXX Global ESG ENV Leaders index at both frequencies¹¹. Moreover, according to the robust HAC standard errors, we do not reject the null hypothesis that beta is equal to one for Renixx (at daily frequency) and Nasdaq Clean Edge Green Energy index (against S&P500 ES Energy index as regressor at monthly frequency), thus suggesting that the level of systematic risk for these indices is in line with the one of the market itself, i.e. they co-move as the benchmark market index.

Therefore, except for the cases discussed above, the results in Table 2 show that the low-carbon asset class is characterized by a risk-return profile larger than the market in the whole sample. However, focusing on the estimates for the dummy interaction variable that measures the impact of the PA announcement, we find that the level of systematic risk associated to the low-carbon equity indices has significantly decreased after the PA in the US, EU, and globally. In particular, we find a

¹¹ It must be noted that the different behaviour of the Stoxx Global ESG Env Leaders index with respect to the other low-carbon indices might be due to its short time series as it exists only from mid 2011 (see Table 1).

significant reduction of the systematic risk after the PA for monthly data. The estimates of γ_i in model (1) are significantly smaller than zero, and we reject the null hypothesis $H_0: \gamma_i = 0$ in favour of the alternative hypothesis $H_{1A}: \gamma_i < 0$ for all the low-carbon equity indices analyzed. After the PA, we observe that the level of systematic risk, measured as $\hat{\beta}_i + \hat{\gamma}_i$, is now strictly less than 1 for S&P Global Clean Energy and Renixx indices at daily frequency. This means that overall the low-carbon class has sensibly reduced the level of systematic risk, thus representing an appealing investment opportunity.

Moreover, in the last column of Table 2, we report the results for the HAC robust F statistics to test for the null hypothesis $H_0: \beta_i + \gamma_i = 1$, i.e., we test whether the risk-return profile of the indices non-significantly different from the risk-return profile of the market portfolio (or benchmark). The results show that we do not reject the null hypothesis for all the low-carbon indices considered, except for the STOXX Global ESG ENV Leaders index and Nasdaq Clean Edge Green Energy index (against S&P500 ES Energy index as regressor). Interestingly, for the latter we find evidence of non-rejection of the null hypothesis $H_0: \beta_i + \gamma_i = 0$, i.e., the return of the Nasdaq Clean Edge Green Energy index is uncorrelated with the return on the S&P500 ES Energy index after the PA (see also Figure 1).

When considering the carbon-intensive equity indices, the results in Table 2 show that the level of systematic risk ($\hat{\beta}_i$) is close to and in general not significantly different from one at daily frequency, and in general slightly smaller than one at monthly frequency. Conversely to the low-carbon asset class, the impact of the PA announcement leads to an increase of the overall systematic risk (rejection of H_0 in favour of $H_{1B}: \gamma_i > 0$) for all the carbon-intensive indices considered. Exceptions are represented by the S&P 500 Integrated Oil & Gas and the Stoxx Europe 600 Oil & Gas (against the Stoxx Europe 600 index as regressor – but not against the MSCI World) indices, where either we do not reject the null $H_0: \gamma_i = 0$ or we even find that the level of systematic risk has declined ($\hat{\gamma}_i < 0$) for S&P 500 Integrated Oil & Gas index vs S&P500 ES Energy index used as a regressor.

INSERT TABLE 2 HERE

4.3 Results for the Fama-French five-factor model

The results for the estimation of model (2) are reported in Table 3. All the data for the factors, as well as the proxy for the risk-free rate, are taken from Kenneth French's data library¹² at monthly frequency. In line with the results for the market model, the results in Table 3 show that estimated intercepts are not significant for any index, at least at 5% significance level, thus suggesting that no other factor than the five included in the model specification is required.

¹² https://mba.tuck.dartmouth.edu/pages/faculty/ken.french/data_library.html

The results for the estimated beta coefficients are similar to those obtained in Table 2 for all the indices at monthly frequency. Then, the estimates for the dummy interaction variable that measures the impact of the PA announcement show that the level of systematic risk associated to the low-carbon equity indices has significantly decreased after the PA in all the stock markets considered, again in line with the results for the market model reported in Table 2 and with the only exception of the Stoxx Global ESG Env Leaders index (see footnote 11 for a possible explanation). In particular, the estimates of γ_i in model (2) are significantly smaller than zero, thus rejecting the null hypothesis $H_0: \gamma_i = 0$ in favour of the alternative hypothesis $H_{1A}: \gamma_i < 0$ for all the low-carbon equity indices analyzed. After the PA, we observe that the level of systematic risk for monthly data, given by $\hat{\beta}_i + \hat{\gamma}_i$, is not only strictly less than 1 but also close to zero for all the low-carbon indices. Therefore, overall the low-carbon indices have sensibly reduced their level of systematic risk and, interestingly, their dynamic behavior is basically uncorrelated with the dynamics of the market after the PA. Indeed, the correlations between the returns on the indices and the returns on the market portfolio after the PA are small as reported in Figure 1.

The results in Table 3 also shows the presence of other significant factors, in addition to the market factor, that explain the (excess) return dynamics of the indices. In particular, for the Nasdaq Clean Edge and Wilderhill indices we find evidence of three additional factors, namely size (SMB), profitability (RMW) and investment (CMA) factors. The latter is also found significant for the other three low-carbon indices considered, even though only at 10% significance level for Stoxx Global ESG ENV Leaders index. Moreover, the size factor is also significant for Renixx as well as the profitability factor for S&P Global Clean Energy index (at 10% level). All the coefficients for these factors have concordant sign. The estimated coefficients for the size factor are positive while those for the profitability and investment factors are negative.

Despite it is difficult to provide an economic interpretation of the results from a factor model (Table 3), our results are consistent with the characteristics of the renewable energy companies that mostly compose the low-carbon indices and their business models. These companies are usually small and with low access to capital markets (and thus small-capitalized). They have higher initial fixed capital costs of investments despite then running on a quasi-zero marginal costs, and they face higher costs of borrowing from banks in comparison to traditional energy companies. They have overall a weak initial operating profitability but when they go on capital markets, they usually have an aggressive investment attitude. For a discussion of investment decisions of renewable energy firms, including the role of capital costs, immobilized costs, project finance and other non-financial factors affecting investments (e.g. policy, governance), see respectively Hall et al. (2017), Hirth and Steckel (2016), Steffen (2018), Masini and Menichetti (2013).

Conversely, the results in Table 3 show that the profitability factor (RMW) is the only significant factor for all the carbon-intensive indices. As opposed to low-carbon indices, the estimated coefficients for the RMW factor are positive, thus suggesting that the constituents of carbon-intensive indices are positively correlated with firms characterized by robust operating profitability.

INSERT TABLE 3 HERE

4.4 Results for portfolio optimization: reweighting optimal portfolio in response to the Paris Agreement

Figure 2 shows the optimal weights in percentage for the low-carbon (in shades of green) and carbon-intensive (in yellow and brown) indices resulting from the Markowitz's portfolio optimization technique.

In particular, Figure 2 shows the optimal weights of the portfolio composed by the low-carbon and carbon-intensive indices listed in Table 1 before and after the PA for two (monthly) expected return objectives, namely $\mu = 0.35\%$ (i.e. 4.2% on annual basis) and $\mu = 0.5\%$ (i.e. 6% annually). The results show that the aggregated weight of the low-carbon component tends to increase after the PA announcement relative to the carbon-intensive component that is underweighted within the optimal portfolio after the PA. In particular, the cumulated weight for the low-carbon component increases from 53.97% (69.04%) before the PA to 87.62% (77.96%) after the PA for $\mu = 0.35\%$ ($\mu = 0.5\%$). Moreover, the resulting portfolio's (monthly) standard deviations are smaller after the PA than before as $\hat{\sigma} = \sqrt{\hat{w}'\Sigma\hat{w}} = 3.60\%$ (3.48%) before the PA vs. $\hat{\sigma} = 3.01\%$ (3.04%) after the PA for $\mu = 0.35\%$ ($\mu = 0.5\%$). From Figure 2 it also is interesting to observe that the green component in the optimal portfolio, at individual level, is constituted only by the Stoxx Global ESG Env Leaders index before the PA, while two other indices (Nasdaq Clean Edge Energy and S&P Global Clean Energy¹³) contribute to the low-carbon component in the optimal portfolio after the PA. On the other hand, the carbon-intensive component is constituted only by the S&P-500 Integrated Oil & Gas index before the PA, in addition to the Stoxx Europe 600 Oil & Gas index after the PA.

The evidence of an increase in the portfolio weights for the low-carbon indices can be partially explained by the fact that, after the PA, the correlations among carbon-intensive indices remain high. In contrast, the correlations among low-carbon indices, as well as the cross-correlations decrease (see Figure 1).

INSERT FIGURE 2 HERE

¹³ Therefore, unlike the findings in Singh & Shrimali (2018), we find evidence that S&P Global Clean Energy does add value to a portfolio (but only after the PA announcement).

5. Conclusions

In this paper, we have developed a first comprehensive analysis of the financial performance of most used and capitalized low-carbon and carbon-intensive equity indices in the EU, US and global stock markets, before and after the PA. With our analysis, we want to assess if and to what extent stock markets have priced the PA announcement by rewarding (penalizing) low-carbon (carbon-intensive) indices. We have also analyzed whether the announcement of the PA has influenced investors' behavior towards low-carbon and carbon-intensive assets in their portfolio composition. On the one hand, this information is crucial to timely inform investors' portfolio risk management strategies, thus creating the conditions for a smooth low-carbon transition. On the other hand, this information can support financial supervisors in the identification of the market drivers of assets prices volatility related to climate policy shocks and of effective measures to mitigate such risk, thus delivering on their mandate of preserving financial stability.

A remark applies. It is well known that a main barrier to assess the performance of "low-carbon" vs "carbon-intensive" investments is represented by the lack of a standardized "green" and "brown" taxonomy. Being a classification of assets according to their "shade of green" beyond the scope of our analysis, and yet being aware of this limitation, we classify stock markets' indices into low-carbon and carbon-intensive using the most relevant information set available to investors.

Our results show that before the PA announcement, the low-carbon (carbon-intensive) asset class was generally perceived as riskier than (as risky as) the market. In contrast, after the PA announcement, in general the risk-return profile of the low-carbon (carbon-intensive) asset class has significantly reduced (increased at daily frequency – but less evidence is found for monthly data). In particular, we find that:

- The overall performance of the low-carbon indices has increased after the PA due to a significant reduction in the index's risk level. Moreover, most low-carbon indices considered show an overall increase in the mean returns after the PA, albeit non-significantly;
- The correlations among low-carbon indices decrease after the PA while the correlations between carbon-intensive indices remain high. Moreover, the cross-correlations between low and carbon-intensive indices decrease almost to zero after the PA;
- The level of systematic risk (beta) associated to the low-carbon equity indices has significantly decreased after the PA both in the US and EU, as well as globally;
- The optimal weights of the low-carbon indices tend to increase after the PA relative to the optimal weights of the carbon-intensive indices.

Therefore, our results suggest that after the PA announcement the market has considered most low-carbon indices as less risky and hence more appealing for investment opportunities, but its

reaction on the carbon-intensive indices was milder and appreciable only considering daily returns. The drivers of this behavior deserve to be properly understood and will be object of future analysis.

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Index	Class	Mkt	Sample length		Whole sample				After PA			
			From	To	Mean	Std Dev	Sharpe	Sortino	Mean	Std Dev	Sharpe	Sortino
NASDAQ CLEAN EDGE GREEN ENERGY	Green	US	2006-11-20	2018-11-26	0.0004	2.010	0.0355	0.0472	0.0317	1.207***	0.1931	0.3031
					0.3500	8.046			0.8179	3.909***		
WILDERHILL CLEAN ENERGY	Green	World	2000-12-29	2018-11-26	-0.0296	1.965	-0.0342	-0.0459	0.0100	1.270***	0.0852	0.1173
					-0.1968	9.083			0.4644	4.665***		
S&P GLOBAL CLEAN ENERGY	Green	World	2003-11-24	2018-11-26	-0.0137	1.683	-0.0063	-0.0080	-0.0117	1.012***	-0.0140	-0.0190
					0.0477	8.304			0.0041	4.949***		
WORLD RENEWABLE ENERGY (RENIXX)	Green	World	2002-01-03	2018-11-26	-0.0212	2.365	-0.0003	-0.0004	-0.0006	1.087***	-0.0065	-0.0088
					0.0980	10.04			0.0465	4.051***		
STOXX GLOBAL ESG ENV LEADERS	Green	World	2011-04-05	2018-11-26	0.0226	0.860	0.1574	0.2318	0.0175	0.767*	0.0356	0.0477
					0.5487	3.310			0.1700	2.769*		
STOXX EUROPE 600 OIL & GAS	Brown	EU	1999-12-30	2018-11-26	0.0012	1.611	0.0124	0.0177	0.0029	0.893***	0.1035	0.1612
					0.2073	6.071			0.5348	4.524***		
S&P 500 INTEGRATED OIL & GAS	Brown	US	1999-12-30	2018-11-26	0.0167	1.491	0.0739	0.1102	0.0127	1.084***	0.0475	0.0657
					0.5065	5.085			0.2760	4.340*		
FTSE USA OIL & GAS	Brown	US	1999-12-30	2018-11-26	0.0197	1.577	0.0842	0.1256	0.0137	1.230***	0.0296	0.0423
					0.5890	5.445			0.2263	5.265		
FTSE WORLD OIL & GAS	Brown	World	1999-12-30	2018-11-26	0.0126	1.387	0.0546	0.0789	0.0196	1.120***	0.0401	0.0586
					0.4429	5.710			0.2579	4.680**		
MSCI WORLD	Market	World	1999-12-30	2018-11-26	0.0070	0.990			0.0264	0.662***		
					0.2538	4.301			0.5553	2.725***		
STOXX EUROPE 600	Market	EU	1999-12-30	2018-11-26	0.0014	1.337			0.0059	0.955***		
					0.1679	5.260			0.0443	3.501***		
S&P500 ES ENERGY	Market	US	1999-12-30	2018-11-26	0.0163	1.613			0.0084	1.237***		
					0.5266	5.683			0.0692	5.270		

Table 1: The indices considered in the analysis. ‘Class’ denotes the asset class (‘Green’ is low-carbon, ‘Brown’ is carbon-intensive, ‘Market’ is market index or benchmark). ‘Mkt’ denotes the market. ‘Mean’ and ‘Std Dev’ denote the daily (first rows) and monthly (second rows) mean return in percentage and the standard deviation for the index in the entire sample and in the period after the PA (2015/12/15). ‘Sharpe’ and ‘Sortino’ denote the Sharpe ratio and the Sortino ratio, respectively. *** denotes significance at 1% level; ** denotes significance at 5% level; * denotes significance at 10% level for the mean and standard deviation tests before/after the PA. All prices are expressed in USD.

Index	Class	Mkt	Regressor $r_{m,t}$	Daily data				Monthly data				F-test for $H_0: \beta_i + \gamma_i = 1$	Adj. R ²
				$\hat{\alpha}_i$	$\hat{\beta}_i$	$\hat{\gamma}_i$	Adj. R ²	$\hat{\alpha}_i$	$\hat{\beta}_i$	$\hat{\gamma}_i$			
NASDAQ CLEAN EDGE GREEN ENERGY	Green	US	MSCI WORLD	-0.00014 (0.00019)	1.50272*** (0.04227)	-0.16497** (0.07056)	0.5977	-0.08293 (0.41744)	1.50804*** (0.08759)	-0.53893*** (0.16911)	0.0441	0.6563	
NASDAQ CLEAN EDGE GREEN ENERGY	Green	US	S&P500 ES ENERGY	-0.00001 (0.00025)	0.90159*** (0.03738)	-0.37355*** (0.05690)	0.5307	0.156551 (0.51503)	1.03433*** (0.11156)	-0.93221*** (0.14574)	80.397***	0.4384	
WILDERHILL CLEAN ENERGY	Green	World	MSCI WORLD	-0.00045 (0.00018)	1.50708*** (0.04007)	-0.17566*** (0.07181)	0.2689	-0.68554 (0.38729)	1.70411*** (0.07024)	-0.85500*** (0.23372)	0.46699	0.6160	
S&P GLOBAL CLEAN ENERGY	Green	World	MSCI WORLD	-0.00036 (0.00019)	1.27425*** (0.06079)	-0.37299*** (0.10234)	0.5149	-0.69734 (0.43231)	1.64230*** (0.10567)	-0.65734*** (0.21878)	0.0062	0.6299	
WORLD RENEWABLE ENERGY (RENIXX)	Green	World	MSCI WORLD	-0.00037 (0.00025)	1.10732*** (0.06138)	-0.33447*** (0.10969)	0.2050	-0.54495 (0.63143)	1.58121*** (0.16074)	-0.83803*** (0.23464)	2.3746	0.4138	
STOXX GLOBAL ENV LEADERS	Green	World	MSCI WORLD	0.00005 (0.00010)	0.87111*** (0.02147)	0.030759 (0.06376)	0.6689	0.17809 (0.22174)	0.78916*** (0.07549)	-0.04374 (0.12354)	5.7914**	0.6308	
STOXX EUROPE 600 OIL & GAS	Brown	EU	MSCI WORLD	-0.00007 (0.00014)	1.08149*** (0.03409)	0.239199*** (0.11525)	0.4574	-0.03815 (0.25733)	1.04575*** (0.08634)	-0.22631 (0.17733)	1.32775	0.5312	
STOXX EUROPE 600 OIL & GAS	Brown	EU	STOXX EUROPE 600	0.000020 (0.00015)	0.95388*** (0.04342)	0.054496 (0.06559)	0.5106	0.058997 (0.23909)	0.88828*** (0.06012)	-0.11720 (0.18322)	1.74559	0.5785	
S&P 500 INTEGRATED OIL & GAS	Brown	US	MSCI WORLD	0.000969 (0.00013)	0.99744*** (0.04881)	-0.017514 (0.09269)	0.4375	0.324271 (0.23347)	0.71789*** (0.06601)	0.00091 (0.23667)	1.54717	0.3631	
S&P 500 INTEGRATED OIL & GAS	Brown	US	S&P500 ES ENERGY	0.000020 (0.00005)	0.90486*** (0.00879)	-0.09604*** (0.02269)	0.9399	0.056414 (0.12003)	0.85695*** (0.03485)	-0.10658 (0.07182)	15.968***	0.8875	
FTSE USA OIL & GAS	Brown	US	MSCI WORLD	0.000116 (0.00014)	1.05431*** (0.05034)	0.139723* (0.08631)	0.4470	0.363869 (0.24354)	0.80494*** (0.06144)	0.23711 (0.23056)	0.0357	0.4166	
FTSE USA OIL & GAS	Brown	US	S&P500 ES ENERGY	0.000039 (0.00002)	0.96920*** (0.00467)	0.018756*** (0.00655)	0.9862	0.093069 (0.06307)	0.94070*** (0.01802)	0.05101** (0.02206)	0.45626	0.9781	
FTSE WORLD OIL & GAS	Brown	World	MSCI WORLD	0.000044 (0.00012)	1.08634*** (0.04210)	0.129252** (0.06961)	0.6123	0.196855 (0.24586)	0.97756*** (0.06746)	-0.02350 (0.186296)	0.06921	0.5364	

Table 2: Results for the market model estimations considering different green and brown indices for daily and monthly frequencies. HAC robust standard errors in parenthesis. *** denotes significance at 1% level; ** denotes significance at 5% level; * denotes significance at 10% level.

Index	Class	Mkt	$\hat{\alpha}_i$	$\hat{\beta}_i$	$\hat{\gamma}_i$	SMB	HML	RMW	CMA	Adj. R ²
NASDAQ CLEAN EDGE GREEN ENERGY	Green	US	-0.4597 (0.4370)	1.4588*** (0.0953)	-0.8584*** (0.2280)	0.5110*** (0.1514)	-0.2490 (0.1798)	-0.4978** (0.2373)	-0.8182*** (0.2653)	0.7217
WILDERHILL CLEAN ENERGY	Green	World	-0.7697* (0.3993)	1.3463*** (0.1018)	-0.9114*** (0.1984)	0.7814*** (0.1608)	-0.1923 (0.1772)	-0.7493*** (0.1786)	-0.4516** (0.2194)	0.7077
S&P GLOBAL CLEAN ENERGY	Green	World	-0.8396* (0.4760)	1.5086*** (0.1337)	-1.0828*** (0.2565)	0.0777 (0.2037)	0.0222 (0.2007)	-0.3676* (0.2217)	-1.2003*** (0.2876)	0.5584
WORLD RENEWABLE ENERGY (RENIXX)	Green	World	-0.5156 (0.6420)	1.3891*** (0.1702)	-1.2944*** (0.2517)	0.6263*** (0.2371)	-0.2177 (0.2918)	-0.4793 (0.3500)	-1.3047*** (0.3849)	0.4411
STOXX GLOBAL ESG ENV LEADERS	Green	World	-0.1698 (0.2477)	0.7782*** (0.0974)	-0.1570 (0.1140)	-0.1033 (0.1102)	0.1641 (0.1409)	-0.1374 (0.1641)	-0.3437* (0.1742)	0.5680
STOXX EUROPE 600 OIL & GAS	Brown	EU	-0.5648* (0.3073)	1.0993*** (0.0896)	-0.4586*** (0.1756)	-0.0285 (0.1243)	0.0631 (0.1884)	0.5802*** (0.1570)	-0.0600 (0.2143)	0.4347
S&P 500 INTEGRATED OIL & GAS	Brown	US	-0.2239 (0.2447)	0.8364*** (0.0643)	-0.0590 (0.1848)	-0.0700 (0.1100)	0.0870 (0.1549)	0.4056*** (0.1296)	0.2337 (0.1841)	0.3707
FTSE USA OIL & GAS	Brown	US	-0.1717 (0.2697)	0.8734*** (0.0673)	0.1542 (0.1937)	-0.0038 (0.1215)	0.1842 (0.1895)	0.3193** (0.1511)	0.1413 (0.2040)	0.3985
FTSE WORLD OIL & GAS	Brown	World	-0.3553 (0.2923)	1.0304*** (0.0793)	-0.1891 (0.1855)	0.0900 (0.1083)	0.1506 (0.1918)	0.4975*** (0.1461)	-0.0069 (0.2046)	0.4673

Table 3: Results for the 5-factor Fama and French model estimations considering different green and brown indices for monthly data. HAC robust standard errors in parenthesis. *** denotes significance at 1% level; ** denotes significance at 5% level; * denotes significance at 10% level.

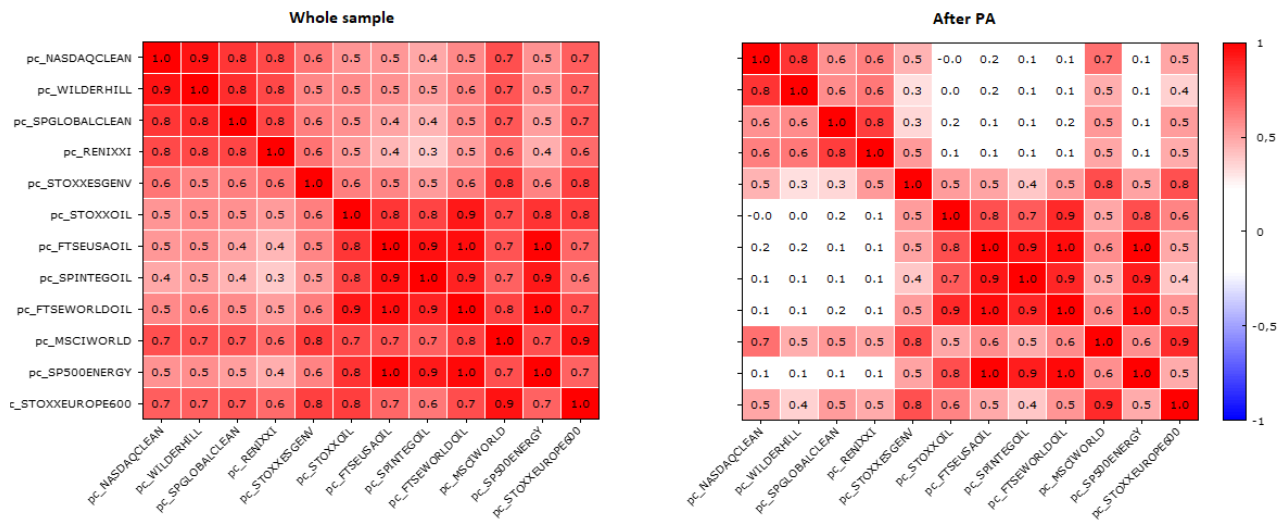


Figure 1: Correlations between the indices considered in the analysis for the entire sample (left panel) and in the period after the PA (right panel).

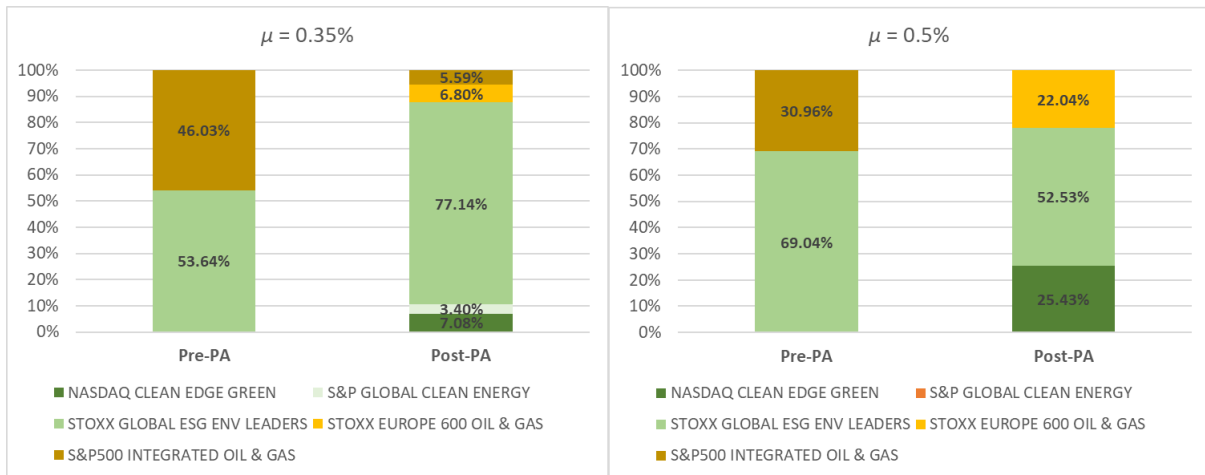


Figure 2: Optimal portfolio weights for low-carbon (in green) and carbon-intensive (in brown) indices resulting from the Markowitz's portfolio optimization for expected return objectives of 0.35% per month (4.2% annually) and 0.5% per month (6% annually).