Hedging Climate Change News*

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PRELIMINARY DRAFT

Abstract

We propose and implement a procedure to dynamically hedge climate change risk. To create our hedge target, we extract innovations in climate news series that we construct through textual analysis of high-dimensional data on newspaper coverage of climate change. We then use a mimicking-portfolio approach to build climate change hedge portfolios using a large panel of equity returns. We discipline the exercise by using third-party ESG scores of firms to model their climate risk exposures. We show that this approach yields parsimonious and industry-balanced portfolios that perform well in hedging innovations in climate news both in sample and out of sample. The resulting hedge portfolios outperform alternative hedging strategies based primarily on industry tilts. We discuss multiple directions for future research on financial approaches to managing climate risk.

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1 Introduction

The climate is changing, but there is substantial uncertainty around the exact climate trajectory and as well as the economic consequences of climate change. As a result, investors around the world have a huge demand for hedging themselves against the realizations of climate risk. Due to the long-run and non-diversifiable nature of climate risk, standard futures or insurance contracts in which one party promises to pay the other in the event of a climate disaster are hard to implement. Indeed, no counterparty could credibly guarantee to pay claims during a climate disaster event that might materialize in many decades, partly because a bad outcome would mandate all contracts to be paid at the same time. Individual investors are therefore largely constrained to self-insure against climate risk.

In this paper, we propose an approach for constructing climate risk hedge portfolios using publicly traded assets. We follow a dynamic hedge approach similar to Black and Scholes (1973) and Merton (1973). In this approach, rather than buying a security that directly pays off in the event of a climate change disaster in the distant future, we construct portfolios whose short-term returns hedge *news* about future climate change over the holding period. By hedging, period by period, the innovations in expected long-run climate change, an investor can ultimately hedge her long-run exposure to climate risk. In the short run, such a portfolio differs from the Markowitz mean-variance efficient portfolio and will thus exhibit a lower Sharpe ratio; but in the long run, the dynamic hedging approach will compensate investors for losses that arise from the realization of climate risk. We show that our approach, which uses tools from standard asset pricing theory, allows us to construct portfolios that can successfully hedge climate news out of sample.

The first challenge to implementing such a dynamic hedging strategy is to construct a time-series that captures news about long-run climate risk, and which can therefore help us to construct an appropriate hedge target. We start from the observation that when there are events that plausibly contain such information about changes in climate risk, this will likely lead to newspaper coverage of these events; indeed, newspapers may even be the direct source that investors use to update their subjective probabilities of the risk of climate change. Our approach in this paper therefore is to extract a climate news series

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from textual analysis of news sources. A wide range of events covered in newspapers can potentially carry relevant information. The list of topics that are often covered by newspapers in relation to discussions about climate change includes extreme weather events (e.g., floods, hurricanes, droughts, wild fires, extreme temperatures), physical changes to the planet (e.g., sea level changes, glacial melting, ocean temperatures), regulatory discussions, technical progresses in alternative fuel delivery, and the price of fossil fuels.

We construct two complementary indices that measure the extent to which climate change is discussed in the news media. The first is calculated as the correlation between the text content of *The Wall Street Journal* (WSJ) each month and a fixed climate change vocabulary, which we construct from a list of authoritative texts published by various governmental and research organizations. The WSJ is among the most salient media outlets for market participants, and thus our index captures the intensity of climate change discourse that is accessible to the investment community at very low cost.

Our WSJ Climate Change News Index associates increased climate change reporting with news about elevated climate risk, based on the idea that climate change only rises to media attention when there is cause for concern. An alternative approach is to directly differentiate between positive and negative news in our index construction. To this end, we study a second news-based climate index that is designed to focus specifically on bad news about climate change. This index applies sentiment analysis to climate-related articles to measure the intensity of *negative* climate news in a given month.

The second step in implementing our dynamic hedging strategy is to construct portfolios that allow us to hedge innovations in these two news series. In particular, we seek to systematically explore which stocks rise in value and which stocks fall in value when (negative) news about climate change materializes. Then, by constructing portfolios that overweight stocks that perform well on the arrival of such negative news, an investor will have a portfolio that is well positioned to profit the next time when such news about climate change materializes. Continued updating of this portfolio based on new information about the relationship between climate news and stock returns will ultimately lead to a portfolio which is long the winners from climate change and short the losers.

Our econometric approach to forming such hedge portfolios follows standard meth-

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ods in the asset pricing literature. If climate risk represents a risk factor for asset markets (i.e, if it is a factor that drives the comovement of different assets), it is possible to construct a well-diversified portfolio whose return isolates the exposure to that risk factor. Investors can then hedge their climate risk exposure by trading this hedge portfolio, without changing their exposures to the other risk factors in their portfolios. Various approaches to construct such hedge portfolios have been proposed in the literature. The two main ones are cross-sectional regressions like Fama-MacBeth (in which the hedging portfolio is obtained through period-by-period cross-sectional regressions of asset returns onto exposures to the risk factors), and direct projections of the risk factor onto a set of asset returns (the so-called mimicking-portfolio approach).[1] Among the many prominent papers in this literature are Fama and MacBeth (1973), Chen et al. (1986), Huberman et al. (1987), Breeden et al. (1989), Lamont (2001), Balduzzi and Robotti (2008), Lönn and Schotman (2017), and Roll and Srivastava (2018). Giglio and Xiu (2018) study the asymptotic properties of the different estimators in large cross-sections, and investigate their robustness to model specification errors. In this paper, we will apply the mimicking-portfolio approach, as advocated by Lamont (2001).

The challenge with implementing these approaches is that we only observe a limited number of months of climate news realizations, but have a large set of assets that we could use to form hedge portfolios. This leads to concerns about data mining, where we construct hedge portfolios that perform very well in-sample but that are not stable going forward. To address this concern, we use characteristics that proxy for a firm's exposure to climate risk to parsimoniously parameterize the weights of the hedge portfolios. For example, one such characteristic might be the carbon footprint of each firm. In particular, it might be that when there is news about increasing climate risk, individuals will buy low carbon footprint stocks and sell high carbon footprint stocks. If this were the case, one could construct a portfolio that increases in value when there is (negative) news about climate risk using thousands of long and short positions based on just one parameter, the firms' carbon footprints.

[1] The literature on cross-sectional regressions like Fama-MacBeth typically focuses on estimating the risk premia of the factor, but these are simply the average excess returns of the corresponding hedge portfolios.

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We implement this characteristics-based approach by using firm-level environmental performance scores constructed by the ESG ("**E**nvironmental, **S**ocial, and **G**overnance") data providers MSCI and Sustainalytics to proxy for firms' climate risk exposure. In particular, we use these scores as characteristics on which to sort individual stocks to form portfolios. We then construct the final hedge portfolios by projecting our climate change indices onto these ESG-characteristic-sorted portfolios, together with standard Fama-French factor-sorted portfolios (market, size, and value). When we compare our hedge portfolios to alternative hedge portfolios that add simple industry bets (such as positions in the energy ETF XLE) to the standard Fama-French factors, we find that our ESG-characteristic-based mimicking portfolios procedure produces hedge portfolios that perform better than the alternatives in hedging innovations in climate risk. In particular, our portfolios deliver higher in-sample and out-of-sample correlation with those innovations. Our hedge portfolios also do not resemble industry bets; rather, they identify, both within and across industries, those firms with largest exposures to climate change risk, yielding a climate hedge portfolio that is relatively industry-balanced.

Our work contributes to a burgeoning literature that studies how climate change affects asset markets, and how asset markets in turn may affect the dynamics of climate change. Andersson et al. (2016) propose a passive investment strategy tilted to low-carbon stock as a climate risk hedging portfolio, while Choi et al. (2018) explore how investors update their information about climate risk. Hong and Li (2018) investigate whether international stock markets efficiently price drought risk, and Kumar et al. (2018) explore whether fund managers misestimate the risk of climate disasters. Giglio et al. (2018), Baldauf et al. (2018), Bernstein et al. (2018), and Murfin and Spiegel (2018) explore the pricing of climate risk in real estate markets, while Giglio et al. (2015, 2018) use real estate pricing data to back out very long-run discount rates that are appropriate for valuing projects aimed at mitigating climate change. In related work, Daniel et al. (2015) apply standard asset pricing theory to calibrate the social cost of carbon.

Section 2 outlines the statistical methodology underlying our climate hedge portfolios. Section 3 reports our empirical analysis. The final section concludes, and discusses a number of exciting directions for future research on how to construct hedge portfolios.

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2 Construction of the Hedge Portfolios: Theory

This section discusses our methodology to construct portfolios that hedge news about climate change. We denote by r_t an $n \times 1$ vector of excess returns over the risk-free rate of n assets at time t. We assume that these returns follow a linear factor model, in which asset returns are driven by innovations in climate news, which we denote by CC_t, as well as by p other (tradable or non-tradable) risk factors v_t:

$$\underbrace{r_t}_{n\times 1} = (\underbrace{\beta_{CC}}_{n\times 1}\underbrace{\gamma_{CC}}_{1\times 1} + \underbrace{\beta_{CC}}_{n\times 1}\underbrace{(CC_t - E[CC_t])}_{1\times 1}) + (\underbrace{\beta}_{n\times p}\underbrace{\gamma}_{p\times 1} + \underbrace{\beta}_{n\times p}\underbrace{v_t}_{p\times 1}) + \underbrace{u_t}_{n\times 1} \tag{1}$$

The vectors β_{CC} and β are risk exposures of the n assets to the climate news factor and the other p factors, respectively. Similarly, γ_{CC} and γ are the corresponding risk premia for the climate news factor and the other risk factors. Finally, u_t is an idiosyncratic error term. In this basic setup the risk exposures are constant; we relax this assumption below.

Our objective is to construct a hedge portfolio for CC_t. This is defined as a portfolio that has unit exposure (beta) to climate risk shocks CC_t, but no exposure to any of the other p factors v_t. This ensures that investors can change their exposure to climate risk by trading in this portfolio, without modifying their exposure to the other risk factors.

The asset pricing literature has followed two different approaches to construct hedge portfolios, which we briefly review below: the Fama-MacBeth cross-sectional regression approach and the mimicking-portfolio approach. Giglio and Xiu (2018) derive theoretical properties of the two estimators in large-dimensional settings. The review below is based on results in that paper and on the large existing literature on factor model estimation.

Fama-MacBeth Regressions. To apply the Fama-MacBeth procedure, the econometrician needs to take a stand on all the factors in the model: CC_t and v_t. Once the factors in the model are determined, the procedure follows two steps. In the first step, the risk exposures β_{CC} and β are estimated via time-series regressions of returns onto the factors, CC_t and v_t. In particular, for each asset i, $(\hat{\beta}^i_{CC}, \hat{\beta}^i)$ are estimated from the time-series regression:

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$$r_t^i = \alpha^i + \beta_{CC}^i CC_t + \beta^i v_t + u_t$$

In the second step, in each period t, hedge portfolios for all factors are obtained via cross-sectional regressions of returns r_t onto the estimated betas $(\hat{\beta}_{CC}, \hat{\beta})$:

$$r_t = h_t^{CC} \hat{\beta}_{CC} + h_t \hat{\beta} + e_t$$

where $\hat{\beta}_{CC}$ and $\hat{\beta}$ are the betas estimated in the first step. The slopes of this regression in each period t are precisely the returns of the hedge portfolio in period t: h_t^{CC} (that hedges CC_t) and h_t (that hedges the remaining factors v_t). The hedge portfolios h_t^{CC} and h_t have, by construction, a beta of one with respect to the corresponding factors and zero with respect to all other factors. Their time-series means (the expected excess returns of the hedge portfolios) recover the risk premia of the factors: $E[h_t^{CC}] = \gamma_{CC}$ and $E[h_t] = \gamma$.

The Fama-MacBeth procedure for constructing hedge portfolios has two potential drawbacks. First, it requires knowing all the factors in the model, CC_t and v_t. Second, the procedure is not robust to measurement error in the factor of interest, CC_t, which is a natural concern in many settings, including in ours.

Mimicking-portfolio Projections. In the mimicking-portfolio approach, the climate risk factor CC_t is directly projected onto a set of excess returns of a set of portfolios, $\tilde{r}_t$:

$$CC_t = \xi + w' \tilde{r}_t + e_t. \tag{2}$$

The hedge portfolio for CC_t is constructed using the weights $\hat{w}$ estimated from this regression; its excess return is $h_t^{CC} = \hat{w}' \tilde{r}_t$. The vector e_t captures the measurement error in CC_t, so that this approach explicitly accounts for potential measurement error in the climate risk factor CC_t. A sufficient condition for this procedure to recover the desired hedge portfolio for climate news is that the returns of the portfolios used in the projection, $\tilde{r}$, span the same space as the true factors, (CC_t, v_t).[2]

[2]Formally, write the model in compact form by calling f the vector of all factors: $f_t \equiv (CC_t, v_t)$ with covariance matrix Σ_f, and β_f the matrix of betas: $\beta_f = (\hat{\beta}_{CC}, \hat{\beta})$. Call η the $(p+1) \times 1$ vector with 1

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2.1 Implementation and construction of the hedge portfolios

Given its robustness to measurement error, which is likely to affect the construction of our climate risk measure, we proceed by build hedge portfolios using the mimicking-portfolio approach. We choose a set of projection portfolios which are well diversified, so that idiosyncratic error is approximately eliminated, and which at the same time capture different dimensions of risk, so that their returns $\tilde{r}_t$ span the factor space.

The portfolios used in the projection need to satisfy one further requirement. In particular, the setup described in equation 1 includes the assumption that the risk exposures of the assets used in the estimation are constant over time. We therefore need to construct the portfolios $\tilde{r}$ in such a way that their exposures to the underlying risk factors are constant. A standard approach to achieve this is to form portfolios by sorting assets on characteristics. Indeed, to the extent that risk exposures of individual assets depend directly on these characteristics, sorting the assets by characteristics will ensure that the resulting portfolios have constant risk exposures. We follow this approach and choose a matrix of firm-level characteristics Z_t, appropriately cross-sectionally normalized, to construct the portfolio returns as:

$$\tilde{r}_t = Z'_{t-1} r_t$$

where r_t are excess returns of individual stocks, and portfolio weights are equal to the normalized characteristics.[3] Substituting this expression into equation 2, we write:

$$CC_t = \xi + w' Z'_{t-1} r_t + e_t \tag{3}$$

Equation 3 can be interpreted in two ways. It can either be thought of as a projection of the hedge target CC_t onto characteristic-sorted portfolios $Z'_{t-1} r_t$ that are assumed to have constant risk exposure and to span the entire factor space. Alternatively, it can be thought of as a constrained projection of CC_t on *all* individual asset returns r_t, but with time-

as the first element and 0 everywhere else, so that $CC_t = \eta' f_t$. The population vector of weights w is $Var(\tilde{r}_t)^{-1} Cov(\tilde{r}_t, CC_t)$. If returns $\tilde{r}_t$ span the same space as the true factors, it means there exists an invertible matrix H such that $\tilde{r}_t = H f_t$. We can then write: $w = (H \Sigma_f H')^{-1} H \Sigma_f \eta = H'^{-1} \eta$. The return of this portfolio is: $h_t^{CC} = w' \tilde{r}_t = w' H f_t = \eta' H^{-1} H f_t = \eta' f_t = CC_t$.

[3] Note that we are working exclusively with excess returns, so there are no theoretical constraints on portfolio weights.

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varying weights $w'Z'_{t-1}$; the weights are modeled as a linear function of characteristics, so that any individual firm's weight depends on its risk exposure to the different factors. The equation therefore performs a one-step dimension reduction that estimates the hedge portfolio while modeling the time variation in risk exposures (see Kelly et al., 2018).

3 Hedging Climate Change News

In this section we implement the mimicking portfolio approach to hedging climate risk. As we have highlighted in the introduction, the relevant performance measure for the resulting hedge portfolios is how well they hedge innovations to climate news out-of-sample. However, given the relatively short time period for which we observe measures of both climate news and firm-level climate risk exposures, there are a limited number of out-of-sample test periods on which to evaluate the climate hedge portfolios.[4] As will become apparent below, there are many degrees of freedom in how to construct these hedge portfolios, including decisions on how to construct measures of firm-level climate risk exposures, and what other portfolios to include in regression 2. As a result, there is the danger of optimizing over these degrees of freedom to construct portfolios that provide optimal out-of-sample hedges to climate news over the short period we observe, but that may not be effective at hedging this news going forward.

To avoid such data mining concerns, we will clearly describe the various choices we encountered in the construction of the climate hedge portfolios. However, instead of optimizing over these degrees of freedom to find a portfolio that optimally hedges climate news over our short test sample, we make choices that appear reasonable to us, and that will hopefully lead to more stable approaches to hedging climate news that is yet to occur. This means that the hedge portfolios we construct are not designed to provide optimal out-of-sample hedges for the period we observe. Indeed, much exciting work on opti-

[4] In addition, even if we could easily extend our time series further into the past, it is unclear whether the additional sample periods would help us with constructing climate hedge portfolios today. In particular, it is plausible that climate risk has only started to be priced in stocks in recent years as investors' attention to this risk has increased. Indeed, some indirect evidence for such a suggestion comes from the fact that demand for ESG measures has increased substantially over the past few years. As a result, it is unclear whether firms with different climate risk exposures have had different excess returns in response to climate news that materialized in, say, the 1990s.

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mizing climate hedge portfolios along many dimensions remains, and longer time series of measures of climate news and climate risk exposures will allow for more systematic ways of testing the true out-of-sample performance of climate hedge portfolios.

3.1 Measuring Climate Change News

The first step in our analysis is to construct an index that measures innovations in news about climate risk. There are a variety of choices to be made in constructing this hedge target. How should we identify the news sources that reflect the information investors use in their climate risk-based investment decisions? Once we identify the appropriate news, how do we measure its relative intensity over time? How do we quantify the extent of good news versus bad news? Should one differentiate among sub-types of climate news (such as news about physical climate risks versus news about regulatory risks)?

Below, we follow two different approaches to building a climate news index. We believe they have the virtues of breadth and simplicity, and offer some scope for comparing tradeoffs in some of our construction choices. At the same time, our indices have obvious imperfections and leave much room for other researchers to propose improvements. Indeed, different investors might want to make different choices to ours in order to optimally align their hedge targets with the overall climate exposure of the rest of their portfolio. For example, investors with a strong coastal real estate portfolio might want to focus more on news about physical climate risk (since such real estate is strongly exposed to rising sea levels), while investors with a strong exposure to the coal industry might want to focus more on news about regulatory interventions in response to climate risk.[5]

3.1.1 Wall Street Journal Climate Change News Index

The first index that we construct is based on climate news coverage in *The Wall Street Journal* (WSJ). Two considerations favor our use of the WSJ. One is a desire to measure news that is relevant to and salient for investors concerned about climate risks, and the WSJ

[5] In addition, some researchers and investors may want to expand the list of publications they consider beyond our newspaper-based approach. Additional publications of interest could include coverage in scientific journals or social media posts.

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is among the most important media sources consumed by financial market participants. The second advantage is that we have access to the full text of WSJ articles since the early 1980s, which offers complete flexibility in choosing how to build a climate news index from raw news content.

To quantify the intensity of climate news coverage in the WSJ, we compare the news content to a corpus of authoritative texts on the subject of climate change. In particular, we collect 19 climate change white papers from sources such as the Intergovernmental Panel on Climate Change (IPCC), the Environmental Protection Agency (EPA), and the U.S. Global Change Research Program. We complement these white papers with 55 climate change glossaries from sources such as the United Nations, NASA, the IPCC, the EPA, and others. The full list of authoritative texts is presented in Appendix A.1. We aggregate the 74 text documents into a "Climate Change Vocabulary (CCV)," which amounts to the list of unique terms (stemmed unigrams and bigrams) and the associated frequency with which each term appears in the aggregated corpus. Figure 1 provides an illustration of the CCV in the form of a word cloud, with term sizes proportional to their frequency.

We form an analogous list of term counts for the WSJ. Each (daily) edition of WSJ is treated as a "document," and term counts are tallied separately for each document. Next, we convert WSJ term counts into "term frequency–inverse document frequency," or *tf-idf*, scores. Common terms that appear in most documents earn low scores because they are less informative about any individual document's content (they have low *idf*), as do terms that are rare in a given article (they have low *tf*). The *tf-idf* transformation defines the most representative terms in a given document to be those that appear infrequently overall, but frequently in that specific document (see Gentzkow et al., 2018).

The main choice going into our index construction is to treat the CCV as our definition of phraseology associated with climate change discourse. That is, our CCV takes a stand on the specific terms, and their relative usage intensity, to identify the topic of climate change. Like with the WSJ, we convert Climate Change Vocabulary term counts into *tf-idf*. We treat the aggregated CCV as a single document when calculating term frequencies, and apply the inverse document frequency calculation from the WSJ corpus.[6]

[6]The choice to use the same *idf* for WSJ and CCV counts ensures that the document-frequency weights

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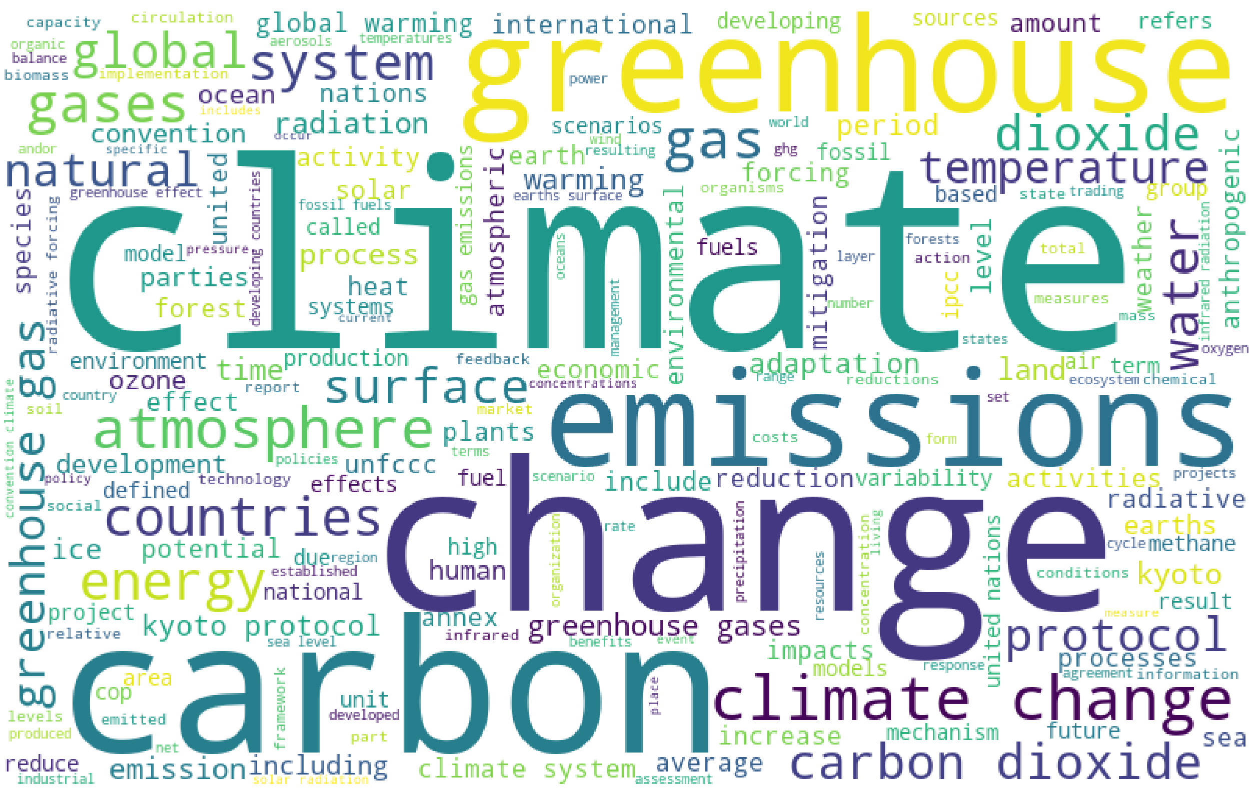
Figure 1: Climate Change Vocabulary



Note: Word cloud summary of climate change vocabulary from a corpus of 74 authoritative climate change texts. Term sizes are proportional to their frequency in the corpus.

Finally, we construct our daily climate change index as the "cosine similarity" between the *tf-idf* scores for the CCV and each daily WSJ edition. Days in which the WSJ uses the same terms in the same proportion as the CCV earn an index value of one, while days in which WSJ use no words from the CCV earn an index value of zero. In other words, our raw *WSJ Climate Change News Index* describes the fraction of the WSJ dedicated to the topic of climate change each day, as defined by the texts that underlie the CCV. We scale this index by a factor of 10,000 to allow interpretation of the magnitudes of innovations in the index, which will represent our eventual hedge targets.

Figure 2 shows a time series of the *WSJ Climate Change News Index* since 1984. It shows that the intensity of climate news coverage has steadily increased since about the year 2000. In addition, the climate risk index spikes during salient climate events such as the

of CCV terms match the weights of WSJ terms. If we were to instead calculate *idf* based on the corpus of authoritative climate texts, we would end up down-weighting the most informative climate change terms and unduly distort the measurement of climate change discourse in the WSJ.

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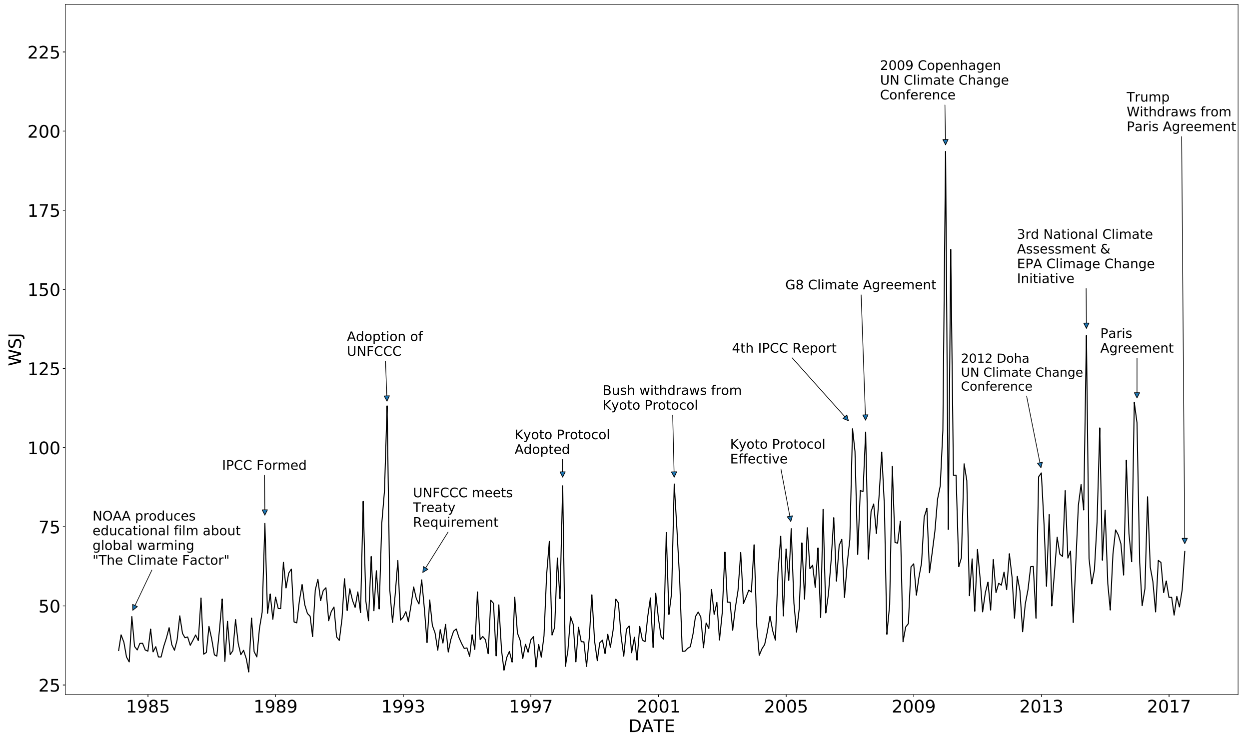
Figure 2: WSJ Climate Change News Index



Note: Figure shows the *WSJ Climate Change News Index* climate change news index from 1984–2017, annotated with climate-relevant news announcements.

adoption of global climate treaties (e.g., the UNFCCC or the Kyoto protocol), or important global conferences to battle climate change (e.g., the 2009 UN Climate Change Conference in Copenhagen).

3.1.2 Crimson Hexagon's Negative Sentiment Climate Change News Index

Implicit in our construction of the *WSJ Climate Change News Index* is the assumption that there is more climate change discussion when climate risk is elevated. In other words, the WSJ index embeds the view that, when it comes to climate change, no news is good news, and that climate change only rises to media attention when there is cause for concern. While we view this as a plausible assumption, there is a risk of inaccurately capturing discussions of positive climate news (e.g., news about new mitigation technologies) as increases in climate risk. A separate potential shortcoming of the WSJ index is that, being based on a single source, it may be too narrow in its quantification of climate discourse.

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To address these possible concerns, we study a second news-based climate risk index that is designed to focus specifically on negative climate news, and that is drawn from a much more expansive collection of news articles. For this purpose, we use the services of the data analytics vendor Crimson Hexagon (CH). Starting in May 2008, Crimson Hexagon has collected a massive corpus of over one trillion news articles and social media posts. The underlying news sources cover over 1,000 outlets, including the WSJ, *The New York Times*, *The Washington Post*, Reuters, BBC, CNN, and Yahoo News. Coverage in terms of total articles available expands over time. Cross-sectionally, the distribution of article counts is fairly evenly distributed across news outlets, with the top 100 outlets accounting for approximately 14% of the total article count. For a given user-provided search term, CH applies a variety of proprietary natural language processing analytics, such as sentiment analysis and topic modeling, to construct time series of the sentiment of coverage of that term across the sources it collects.

We provide CH with the search phrase "climate change," and restrict our analysis to discussions in the news media (excluding social media). Based on these choices for terms and content sources, CH provided us with an array of indices that summarize the total number of articles that include climate change news, as well as the fraction of those summarized to contain positive and negative climate change news. It also provided indices for further sentiment sub-categories (e.g., fear, joy, anger, etc.), as well as a topic decomposition of climate-related articles. Thus, there are many potential degrees of freedom in using Crimson Hexagon data to construct a climate news series. For example, we could tune our choice of search terms, or optimize across each of the finer indices that CH supplies for any given set of search terms. As described above, given the brevity of our data sample, we need to guard against data mining, and we do so in this case by restricting ourselves to the most obvious search term ("climate change") and focusing on the most obvious category that resolves our desire for "signed" news, namely those that CH categorizes as basic "negative sentiment." We calculate our *CH Negative Climate Change News Index* as the share of all news articles that are both about "climate change" and that have been assigned to the "negative sentiment" category; we multiply this measure by 10,000 in order to interpret the magnitudes of innovations in the index.

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Figure 3 plots the time series of the *CH Negative Climate Change News Index*, in addition to that of the *WSJ Climate Change News Index* for comparison. Both indices regularly spike around salient climate events, such as climate conferences. The initial level of the CH index is somewhat higher than that of the WSJ index, though this is during a period for which Crimson Hexagon has relatively little data; this is also a period that will not be included in our final analysis (as we discuss below, our empirical analysis starts in September 2009, the first month for which we observe complete coverage of firm-level climate risk exposures). Interestingly, there are a number of instances when the WSJ index spikes, but the CH index does not. One of these was in early 2010, a period during which the WSJ reported extensively on the "Climategate" controversy.[7]

3.1.3 Constructing Hedge Targets

To measure innovations in climate news, we average the daily values for the *WSJ Climate Change News Index* and *CH Negative Climate Change News Index* to the monthly level, and then construct values of CC_t as residuals from an AR(1) model. This gives us our two monthly hedge targets: CC_t^{WSJ}, which captures innovations in the *WSJ Climate Change News Index*, and $CC_t^{NegNews}$, which captures innovations in the *CH Negative Climate Change News Index*. Figure 4 shows the correlation across these measures across the 88 months that will be included in our final analysis (September 2009 to December 2016, see below). The correlation coefficient is 0.3, which suggests that, while both measures capture common elements of climate risk, they are by no means identical. As we have discussed above, which of the two series (or any one of the potential alternative series that we could have constructed) represents the ideal hedge target depends on the precise application; as a result, we view the construction of alternative hedge targets as an exciting area for further research.

[7]The Climategate controversy started with the publication of emails obtained through a November 2009 hacking of a server at the Climatic Research Unit at the University of East Anglia. Several climate-change "skeptics" alleged that these emails documented global warming to be a scientific conspiracy, with scientists manipulating climate data.

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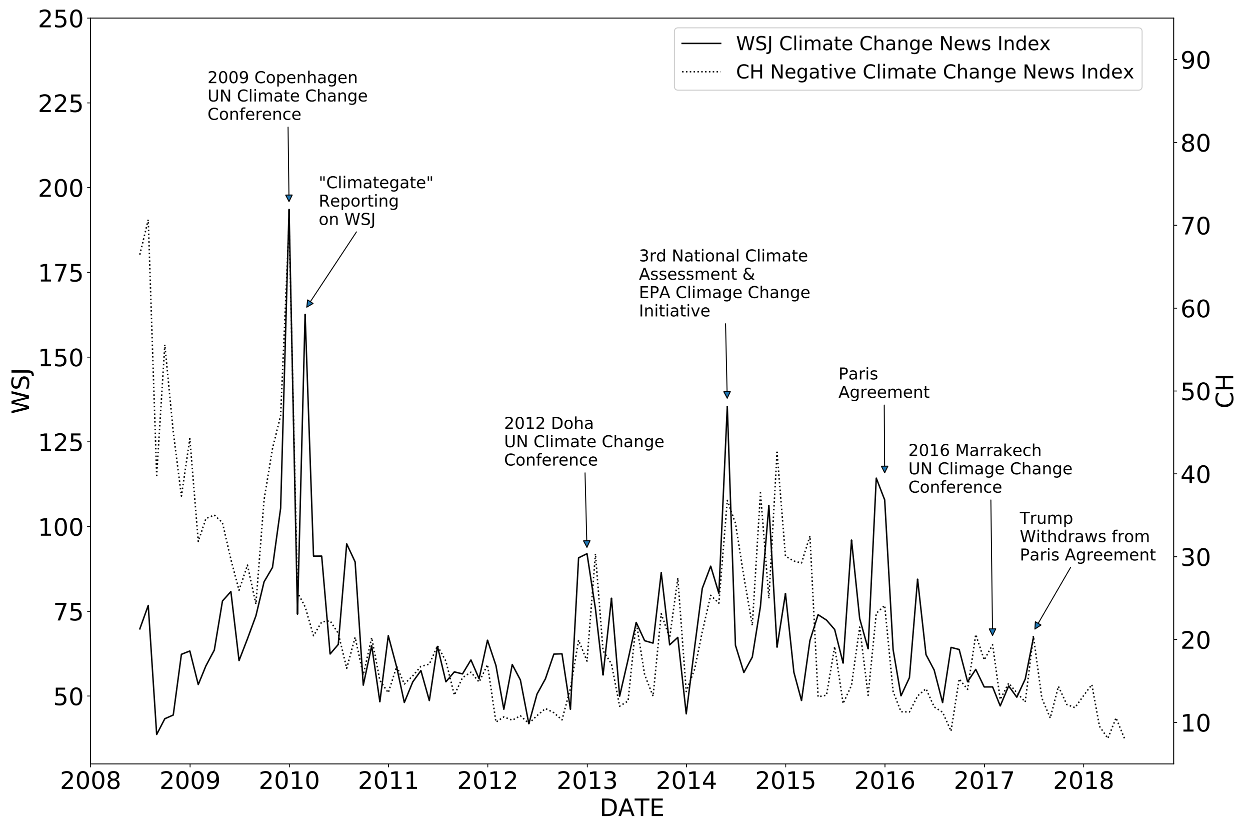
Figure 3: CH Negative Climate Change News Index



Note: Figures shows the *CH Negative Climate Change News Index* from 2008–2017, overlaid against the *WSJ Climate Change News Index*, and annotated with climate-relevant news announcements.

3.2 Potential Assets in Hedge Portfolio

After defining the hedge targets, the second step in implementing the mimicking portfolio hedge approach described in Section 2 is to determine the universe of assets used to build the hedge portfolio. In this project, we focus on constructing hedge portfolios using U.S. equities as the underlying assets. We obtain monthly individual U.S. stock return data from CRSP. We include only common equity securities (share codes 10 and 11) for firms traded in the NYSE, AMEX and NASDAQ. Following Amihud (2002) and many others, we exclude penny stocks, defined as stocks with a price below $5 at the time of portfolio formation. This is to avoid returns whose behavior is dominated by market microstructure issues. We also drop microcap stocks, defined as stocks with market capitalization in the bottom 20% of the sample traded in NYSE, following the observation in Fama and

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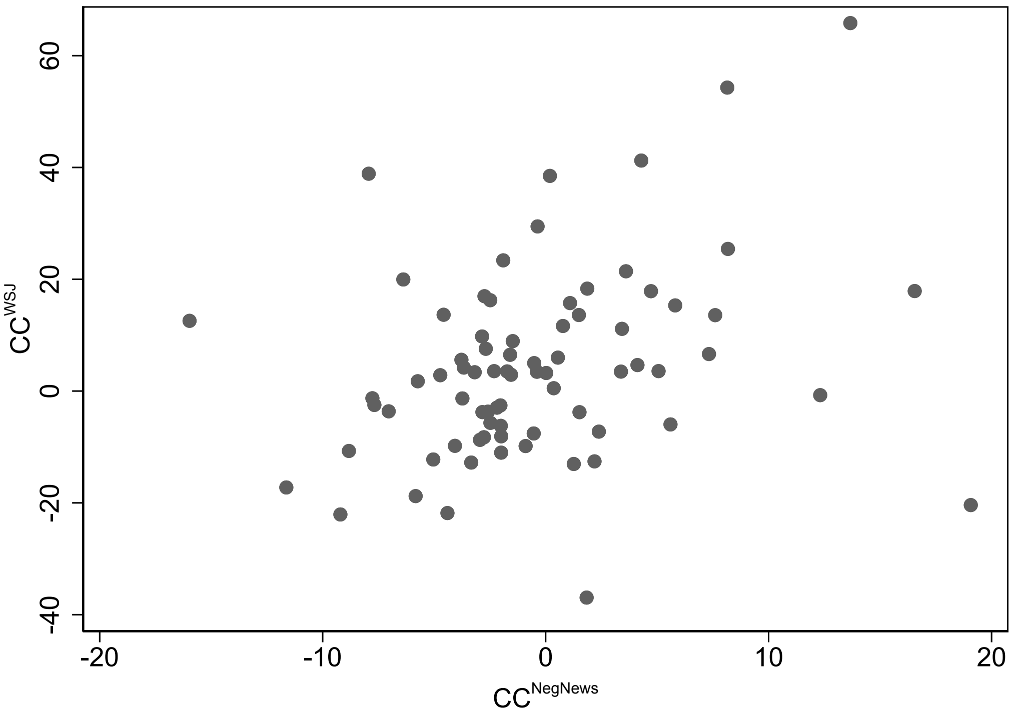
Figure 4: Correlation Across CC_t Measures



Note: Figure shows a scatter plot that highlights the correlation across our two climate hedge targets, CC^{WSJ} and CC^{NegNes}. Each observation corresponds to one month between September 2009 to December 2016. The correlation coefficient is 0.30.

French (2008) that the returns of hedge portfolios obtained from long-short positions can be distorted by the inclusion of microcaps (see also the discussion in Hou et al., 2015).

3.3 Measuring Climate Risk Exposures

Having identified the set of possible assets to include in the hedge portfolio, the next empirical challenge is to systematically measure different firms' exposures to climate risk, i.e., to identify the characteristics in Z_t that drive such exposures. Our approach in this paper is to build on measures of firms' environmental exposures produced by third-party ESG data providers. Indeed, there has been a growing interest in ESG investing among investors who are increasingly demanding assets that fulfill certain environmental ("E"),

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social ("S"), and governance ("G") criteria.[8] Given this trend, measuring the ESG characteristics of firms has become an important task for investors, and firm-level ESG scores are available from numerous providers that collect raw data gathered from sources such as firms' disclosures, SEC filings, and reports by governments or NGOs. These raw data are then translated into numerical ESG scores using proprietary algorithms.

Our study uses information on firm-level ESG scores from two leading data providers, MSCI and Sustainalytics.[9] Both data providers construct various sub-scores that evaluate firms on different aspects of their ESG performance. From these sub-scores, we choose the broadest scores that plausibly proxy for firms' exposure to climate risk.

MSCI. We obtained from MSCI a data set of annual firm-level ESG scores between 1995 and 2016.[10] MSCI evaluates firms along several sub-categories that capture either positive or negative environmental performance; the full list of sub-categories is presented in Appendix A.2. Each sub-category is either scored as a "1" when the firm satisfies a certain condition, or a "0" if the firm does not satisfy the condition. For instance, a "1" in the positive *"Climate Change - Energy Efficiency"* sub-category means that the company operates in a relatively energy-efficient way. The thresholds for satisfying each condition are determined by MSCI, and are not disclosed with the data. Following Hong and Kostovetsky (2012), we calculate an overall environmental score for each firm by subtracting the total scores in the negative environmental sub-categories from the total scores in positive environmental sub-categories. We call the resulting variable the "MSCI E-Score," where a higher score suggests a firm is more environmentally friendly. In principle, it would be possible to also construct E-Scores from only a selection of all "E" sub-categories, perhaps by focusing on those sub-categories that are labeled as being particularly climate-change relevant. The out-of-sample performance of hedge portfolios constructed by using different combinations of "E" sub-categories could then be compared to select the one with

[8]According to The U.S. SIF Foundation, the dollar value of ESG assets owned by institutional investors grew to $4.73 trillion in 2016, an increase of 11% a year since 2005.

[9]There is a growing number of providers of ESG data, including firms such as Arabesque and TruValue Labs. An analysis of which of these E-Scores results in the optimal hedge portfolio is an interesting avenue for further research, but in the absence of longer time-series is likely subject to concerns of data mining.

[10]These scores were formerly known as KLD scores. In 2010, following MSCI's acquisition of RiskMetrics, KLD scores were re-tooled into what are now known as MSCI KLD scores.

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the best performance. However, given the relatively short time series to evaluate the performance of the resulting hedge portfolios, even such an "out-of-sample" approach of finding the "best" E-Scores is naturally subject to data mining concerns. We hence decided to restrict ourselves to only analyzing the relatively broad overall E-Score, following prior approaches in the literature; we leave a more detailed exploration of the various sub-categories to future research.

Sustainalytics. Sustainalytics provided us with monthly firm-level ESG scores beginning in September 2009. The broadest score in the data is the "Total ESG Score," which is the average of the "Total Environment Score," the "Total Social Score," and the "Total Governance Score." To determine each of the "E," "S," and "G" scores, Sustainalytics uses a number of sub-categories and evaluates each firm's score by comparing it to peers in the same industry (Sustainalytics uses a non-standard industry classification). For instance, the 57 sub-categories for the "Total Environment Score" include evaluations of a firm's efforts to reduce greenhouse gas emissions, increase renewable energy use, and reduce water use; the full list of sub-categories is presented in Appendix A.2. The scores in the sub-categories are then aggregated by weighting them according to how exposed each industry is to each ESG risk, though this aggregation procedure is not well documented. Final scores are between 0 and 100. As before, a higher score suggests a firm is more environmentally friendly. We use the "Total Environment Score" in our empirical analysis.

Summary Statistics. Our analysis of climate hedge portfolios focuses on the period between September 2009 and December 2016. This is a period for which we observe both measures of innovations of climate news, CC_t^{WSJ} and $CC_t^{NegNews}$, and both the Sustainalytics and MSCI E-Scores. We can therefore conduct a direct comparison of the performance of the various hedge portfolios for the two climate news series over this time horizon. For the MSCI E-Score, which is only reported annually, we assign the same score to all the months in the relevant year. Panels (a) and (b) of Figure 5 plot the number of firms in our pool of potential hedge assets for which we observe each E-Score over time. For Sustainalytics, we usually observe E-Scores for between 700 and 800 firms. MSCI

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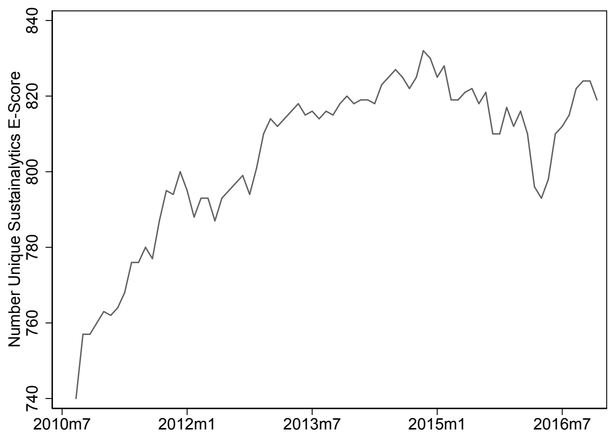
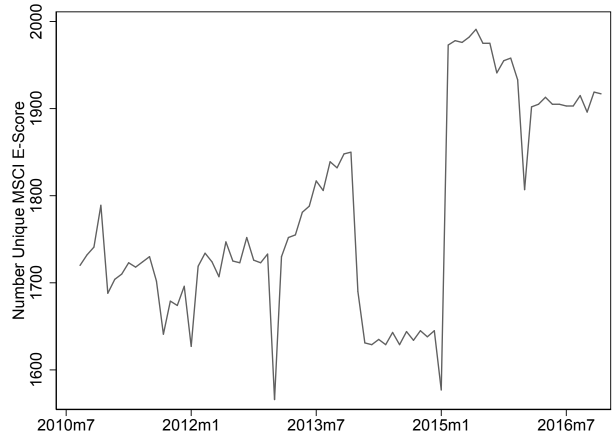
E-Scores have broader coverage, and are provided for between 1,700 and 1,900 firms.

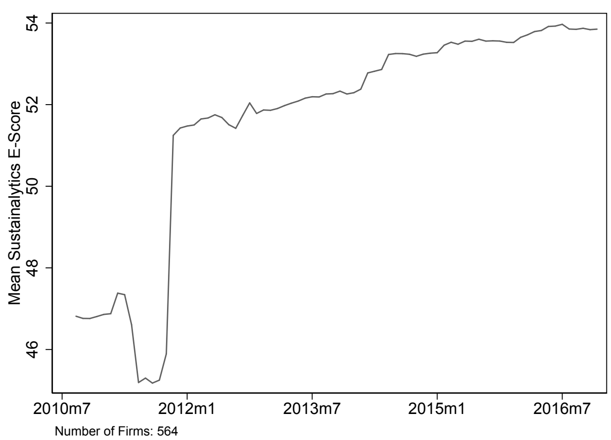
Figure 5: E-Scores – Summary Statistics Over Time



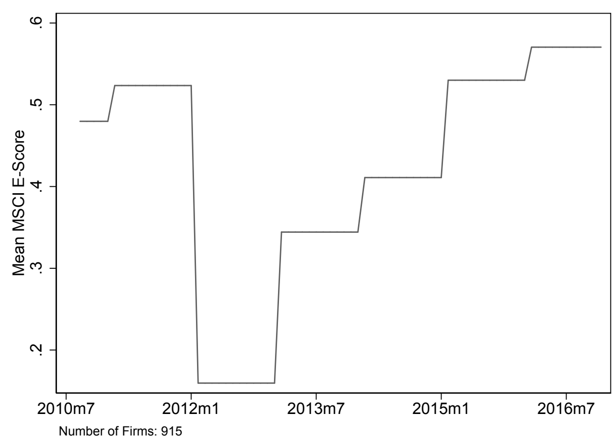
(a) Sustainalytics – Number of Firms Over Time



(b) MSCI – Number of Firms Over Time



(c) Sustainalytics – Mean Over Time



(d) MSCI – Mean Over Time

Note: Figure provides summary statistics for our two E-Scores. The top row shows the number of firms in our sample for which we observe E-Scores. The bottom row shows the average E-Score over time across those firms that we observe in every period in our sample. The left column shows these statistics for the Sustainalytics E-Score, the right panel shows the statistics for the MSCI E-Score.

Panels (c) and (d) of Figure 5 show average values for each of the two E-Scores for a constant set of firms that we observe throughout the sample. There are a number of discontinuous breaks in the averages of each score. For the MSCI E-Score, which is determined annually, these breaks could either be due to changes in firms' true ESG performance between years, or due to changes in the modeling procedure. For Sustainalytics, which computes monthly scores, the discontinuous breaks are more likely due to changes in the

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modeling methodology over time, though we have been unable to obtain documentation on such changes that would allow us to verify this conjecture.[11] Such modeling changes would be problematic for building time-series models that perform well out-of-sample.

To minimize the complications from any modeling changes, we construct Z_t by cross-sectionally demeaning each E-Score in each month. However, this approach might still be problematic if changes to the model do not just shift the mean of the E-Scores over time, but also the cross-sectional dispersion. In that case, the meaning of absolute differences in the demeaned E-Score would change over time. As a second way to construct measures of Z_t, we therefore rank the E-Scores of all firms at each point in time, and then demean and re-scale the ranked measure such that it ranges from -0.5 to +0.5. This approach preserves the ordinal content of the E-Scores but discards any information contained by the absolute differences between scores. There are a number of issues with such a ranking-based approaches as well. In particular, as highlighted by Panels (a) and (b) of Figure 5, the number of firms for which E-Scores are available changes throughout the sample period. It is plausible that the firms that are added later in the sample are systematically different from those that are added earlier; for example, they might be less exposed to climate risk. The cross-sectional ranking of the same firm might therefore change over time without the true climate exposure of that firm changing. Since neither the demeaned absolute value nor the demeaned and re-scaled ranked value of E-Scores are ex-ante superior methods to construct climate exposures in Z_t, we will present hedge portfolios using both approaches to constructing exposure measures, and compare their relative performance.[12]

An interesting question is what firm characteristics are captured by the two E-Scores. A first hypothesis is that they primarily pick up industry-membership, whereby firms in "clean" industries such as wind and solar energy are assigned high E-Scores, and firms

[11] Most uses of ESG scores by the financial services sector build on the cross-section of ESG scores at a given point in time, for example by forming portfolios that have a relatively higher performance on these measures. Such use cases often do not require a stable meaning of the same numerical score over time.

[12] There are other potential ways to construct climate exposure measures in Z_t from the various raw E-Scores. For example, one could cross-sectionally standardize each absolute measure to have a constant standard deviation over time. Alternatively, one could rank firms' E-Scores within industry rather than across all firms. However, in the absence of longer time series, a systematic analysis of which of these approaches obtains the best out-of-sample fit during our sample period is subject to the data mining concerns described earlier. As a result, we did not pursue these alternative approaches in this project.

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in "dirty" industries such as coal mining are assigned low E-Scores. To explore the extent to which the scores are primarily capturing a firm's industry, we begin by taking the firm-level E-scores in December 2016 (the last period in our data) and regressing them onto industry fixed effects. When regressing the absolute value of the Sustainalytics E-Score on 2-digit SIC code fixed effects, the adjusted R-Squared of the regression is 0.103; it is 0.184 when regressing on fixed effects for 4-digit SIC codes. The measures of R-Squared were similar when using the ranked measure of the Sustainalytics E-Score. When regressing the absolute value of the MSCI E-Score on 2-digit SIC codes (4-digit SIC codes), the adjusted R-Squared of the regression is 0.099 (0.203). These numbers show that, while there is some industry effect in determining E-Scores, most of the variation occurs within relatively narrow industries rather than across these industries.

Indeed, the three 2-digit SIC industries with the lowest Sustainalytics E-Scores are Personal Services (SIC code 72), Water Transportation (SIC code 44), and Motion Pictures (SIC code 78), probably not the first industries that come to mind when thinking of "dirty" industries. Similarly, the 2-digit SIC industries with the highest Sustainalytics E-Scores are Building Materials & Gardening Supplies (SIC code 52), Textile Mill Products (SIC code 22), and Furniture & Homefurnishings Stores (SIC code 57). When ranking by MSCI E-Scores, we similarly find that low-scoring firms are not necessarily those one would expect ex ante, such as those operating in the Oil and Gas sector.

A second question is the extent to which the MSCI and Sustainalytics E-Scores capture the same object. Figure 6 shows the correlation across the raw Sustainalytics and MSCI E-Scores in December 2016. They have a positive correlation of about 0.65, suggesting that they are both measuring aspects of the same object. However, there is enough independent variation across the two measures to suggest that their usefulness in constructing climate hedge portfolios might vary. Indeed, we show below that the performance of the hedge portfolios varies noticeably when these hedge portfolios are constructed using the different E-Scores.

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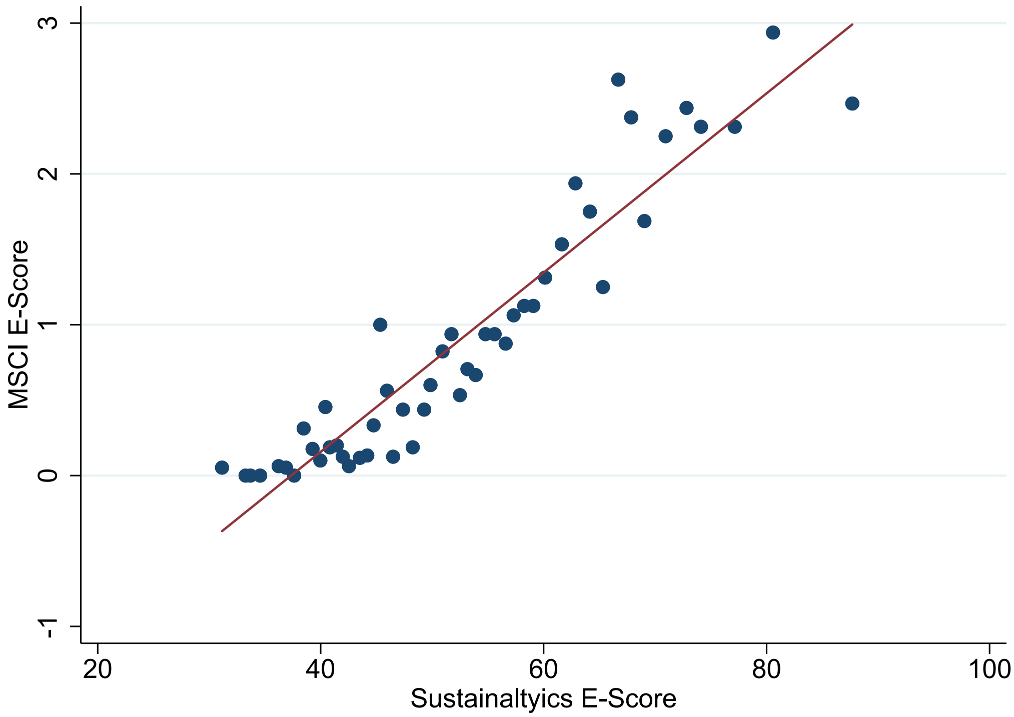
Figure 6: Correlation Across E-Scores – December 2016



Note: Figure shows a binned scatter plot that highlights the correlation across the Sustainalytics and MSCI E-Scores for all 796 firms in our sample that have both scores in December 2016. The correlation coefficient is 0.65.

3.4 Forming Hedge Portfolios

In this section, we construct hedge portfolios for innovations in climate news, CC_t, using the mimicking-portfolio approach described in Section 2.1. As discussed above, we use two different approaches to transform the raw E-Scores into the characteristic vector Z_t:

(i) Using firms' cross-sectionally demeaned absolute value of the E-Score ("absolute scores", e.g., $Z_t^{SUS\_A}$)

(ii) Ranking the firms cross-sectionally by their E-Score, and then standardizing these rankings to range between -0.5 and +0.5 ("ranked scores", e.g., $Z_t^{SUS\_R}$).

Recall that one of the conditions for the mimicking-portfolio approach to isolate climate change risk (and to avoid picking up other potentially correlated risks in the economy)

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is that the projection portfolios span all the risk factors driving returns. In addition to portfolios sorted on the climate characteristics, we therefore also include in regression 2 three additional factors that might be correlated with climate risk and that are known to be important in explaining the cross-section of returns: size (using cross-sectionally standardized market value to create Z_t, so that half the firms, sorted by market value, have positive weight, and half have negative weight), value (using cross-sectional standardized values of book-to-market to create Z_t), and the market (setting Z_t to equal the share of total market value).[13]

For example, when we use the absolute Sustainalytics E-Score to measure firms' climate risk exposures, regression 3 becomes:

$$CC_t = \xi + w_{SUS} Z_{t-1}^{SUS\_A'} r_t + w_{SIZE} Z_{t-1}^{SIZE'} r_t + w_{HML} Z_{t-1}^{HML'} r_t + w_{MKT} Z_{t-1}^{MKT'} r_t + e_t, \quad (4)$$

where $w_{SUS}, w_{SIZE}, w_{HML}$ and w_{MKT} are scalars that capture the weight of the corresponding portfolios in the mimicking (hedge) portfolio for CC_t.

For comparability, we also analyze the performance of hedge portfolios constructed using returns of the ETFs XLE and PBD instead of the returns of portfolios of stocks sorted by their E-Scores. XLE is the ticker of the Energy Select Sector SPDR ETF, which represents the energy sector of the S&P 500. PBD is the ticker of the Invesco Global Clean Energy ETF, which is based on the WilderHill New Energy Global Innovation Index, and is composed of companies that focus on greener and renewable sources of energy and technologies facilitating cleaner energy. Constructing hedge portfolios based on those ETFs allows us to (i) analyze the extent to which our E-Score-based hedge portfolios simply represent a market tilt away from "brown energy" and towards "green energy," and (ii) explore whether hedge portfolios based on XLE and PBD would have performed better than our E-Score-based hedge portfolios.[14]

[13] In order to maximize the number of stocks used to construct the hedge portfolios, we include stocks even if some of the characteristics Z_t are missing for that stock. To do so, we set all missing characteristics equal to zero.

[14] As before, there are many degrees of freedom for how to compute hedge portfolios based on ETFs, and we do not want to suggest that portfolios constructed using XLE and PBD constitute the "best" ETF-based portfolios for hedging climate risk. Indeed, we view the analysis of which ETFs and other funds are most helpful in hedging climate risk to be an exciting area for future research.

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3.5 Results - In-Sample Fit

We begin by exploring the in-sample fit of various versions of regression 4 over the full sample period. Table I shows regressions when hedging innovations to the *CH Negative Climate Change News Index* described in Section 3.1. Columns 1 and 2 show that portfolios based on Sustainalytics E-Scores have a positive and significant relationship with $CC_t^{NegNews}$; in periods with more innovations in negative climate news, a portfolio that goes long firms with higher (more "green") E-Scores has relatively larger excess returns. The R-Squared measures of these regressions show that the portfolios based on the Sustainaltyics E-Scores can hedge around 13% of the in-sample variation in CC_t. Columns 3 and 4 show that portfolios based on the MSCI E-Scores also have higher excess returns during periods with innovations in negative climate news, though the coefficients are no longer statistically significant and the R-Squared of the regressions are slightly lower than those in columns 1 and 2. Portfolios based on ranked versions of both E-Scores have a slightly higher in-sample fit than portfolios based on absolute demeaned values. In column 5, we include the returns of XLE and PBD instead of the return of a characteristic-sorted portfolio. The in-sample fit of this regression is lower than that of any of the regressions in columns 1 - 4, even though we have fewer explanatory variables in those regressions. This suggests that the characteristic-weighted portfolios might have some advantages over a hedge approach that creates industry tilts using energy-related ETFs.[15]

Table II presents the same set of regressions as Table I, this time hedging innovations in the *WSJ Climate Change News Index.*, CC_t^{WSJ}. As before, the in-sample fits of the hedge portfolios based on Sustainalytics E-Scores are higher than the fits of the hedge portfolios based on MSCI E-Scores; similarly, the in-sample fits of the portfolios constructed using ranked E-Scores are marginally higher than those of the portfolios constructed using the absolute (demeaned) E-Score. Finally, the in-sample fits of all four portfolios based on E-Scores are somewhat higher than that of the portfolio based on XLE and PBD.

How would the hedge portfolios implied by these regressions look? To determine

[15]The inclusion of the other factors in regression 4 make the resulting hedge portfolios in column 5 of Table I different from a simple industry-tilt away from the market. Indeed, the resulting hedge portfolio will have a beta of 1 with CC_t, and a beta of zero with the other factors. It is this factor neutrality that is a desirable property of hedge portfolios, not industry neutrality.

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Table I: Full-Sample Regression: CH Negative Climate Change News Index

	(1)	(2)	(3)	(4)	(5)
$Z^{SUS\_A'}_{t-1} r_t$	0.266*				
	(0.141)				
$Z^{SUS\_R'}_{t-1} r_t$		12.286**			
		(5.864)			
$Z^{MSCI\_A'}_{t-1} r_t$			1.089		
			(2.173)		
$Z^{MSCI\_R'}_{t-1} r_t$				6.641	
				(8.696)	
r^{XLE}_t					-0.092
					(0.252)
r^{PBD}_t					0.036
					(0.196)
$Z^{HML'}_{t-1} r_t$	-4.536**	-4.390*	-5.934***	-5.919***	-5.520**
	(2.272)	(2.260)	(2.182)	(2.177)	(2.519)
$Z^{SIZE'}_{t-1} r_t$	-0.137	-0.179	0.210	0.100	0.501
	(0.761)	(0.753)	(0.880)	(0.856)	(0.770)
$Z^{MKT'}_{t-1} r_t$	0.315	0.314	0.287	0.295	0.297
	(0.208)	(0.206)	(0.219)	(0.216)	(0.400)
Constant	-0.115	-0.137	0.313	0.306	0.376
	(0.868)	(0.859)	(0.857)	(0.847)	(0.902)
R-Squared	0.125	0.133	0.090	0.094	0.089
N	88	88	88	88	88

Note: Table shows results from regression 4. The dependent variable captures innovations in the *Newspaper-Based Negative Climate News Measure*. The unit of observation is a month, and the sample runs between September 2009 and December 2016. Standard errors are presented in parentheses. Significance levels: * (p<0.10), ** (p<0.05), *** (p<0.01).

each firm i's weight in the hedge portfolio, we construct the following sum, where $Z_{i,t}$ values are taken as of December 2016: $\hat{w}_{SUS\_A} Z^{SUS\_A'}_{i,Dec16} + \hat{w}_{SIZE} Z^{SIZE'}_{i,Dec16} + \hat{w}_{HML} Z^{HML'}_{i,Dec16} + \hat{w}_{MKT} Z^{MKT'}_{i,Dec16}$, and where the various $\hat{w}$-terms represent the estimated coefficients from regression 4. This means that a firm's weight in the hedge portfolio is determined by its E-Score as well as its book-to-market ratio and its size. The resulting portfolio is the portfolio that an investor would form in December 2016 to hedge climate news in January 2017. Table III presents the average portfolio positions by 2-digit SIC code classification for the industries with the six largest negative average portfolio weights and the industries with the six largest positive average portfolio weights. We only present the portfolio positions based on the absolute E-Scores, since they look very similar to the positions in the hedge

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Table II: Full-Sample Regression: WSJ Climate Change News Index

	(1)	(2)	(3)	(4)	(5)
$Z_{t-1}^{SUS\_A'} r_t$	1.416***				
	(0.436)				
$Z_{t-1}^{SUS\_R'} r_t$		67.789***			
		(17.834)			
$Z_{t-1}^{MSCI\_A'} r_t$			12.658*		
			(6.849)		
$Z_{t-1}^{MSCI\_R'} r_t$				53.743*	
				(27.401)	
r_t^{XLE}					0.085
					(0.810)
r_t^{PBD}					0.208
					(0.630)
$Z_{t-1}^{HML'} r_t$	1.221	2.309	-5.862	-5.941	-6.772
	(7.019)	(6.873)	(6.878)	(6.858)	(8.093)
$Z_{t-1}^{SIZE'} r_t$	-5.680**	-6.034**	-5.511*	-5.459**	-2.765
	(2.350)	(2.289)	(2.773)	(2.696)	(2.474)
$Z_{t-1}^{MKT'} r_t$	0.783	0.789	0.841	0.789	0.091
	(0.642)	(0.628)	(0.692)	(0.680)	(1.285)
Constant	2.894	2.673	4.659*	4.891*	5.959**
	(2.681)	(2.613)	(2.700)	(2.669)	(2.897)
R-Squared	0.153	0.187	0.083	0.088	0.047
N	88	88	88	88	88

Note: Table shows results from regression 4. The dependent variable captures innovations in the WSJ-Based Climate News Measure. The unit of observation is a month, and the sample runs between September 2009 and December 2016. Standard errors are presented in parentheses. Significance levels: * ($p<0.10$), ** ($p<0.05$), *** ($p<0.01$).

portfolio constructed using the ranked E-Scores. For the portfolio constructed using Sustainlytics E-Scores to hedge innovations in the *CH Negative Climate Change News Index*, the largest short position is “General Building Contractors,” followed by “Water Transportation." The largest long positions are “Building Materials & Gardening Supplies“ and “Tobacco Products.” This analysis highlights that the resulting hedge portfolios will not necessarily conform with common priors that the optimal way to hedge climate change news involves primarily going long green energy stocks and short oil companies; this is consistent with our observation that industry membership can only explain a small amount of the cross-sectional variation in firm-level E-Scores.

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Table III: Largest Average Short and Long Positions (By 2-digit SIC Code).

(a) CH Negative Climate Change News Index

Sustainalytics E-Score (absolute)		**MSCI E-Score (absolute)**	
Top Negative Portfolio Weights	***SIC2***	***Top Negative Portfolio Weights***	***SIC2***
General Building Contractors	15	General Building Contractors	15
Water Transportation	44	Nondepository Institutions	61
Coal Mining	12	Auto Repair, Services, & Parking	75
Insurance Agents, Brokers, & Service	64	Communications	48
Holding and Other Investment Offices	67	Water Transportation	44
Insurance Carriers	63	Insurance Carriers	63
Top Positive Portfolio Weights	***SIC2***	***Top Positive Portfolio Weights***	***SIC2***
Railroad Transportation	40	Chemical & Allied Products	28
Transportation by Air	45	Textile Mill Products	22
Furniture & Homefurnishings Stores	57	General Merchandise Stores	53
Textile Mill Products	22	Lumber & Wood Products	24
Building Materials & Gardening Supplies	52	Building Materials & Gardening Supplies	52
Tobacco Products	21	Tobacco Products	21

(b) WSJ Climate Change News Index

Sustainalytics E-Score (absolute)		**MSCI E-Score (absolute)**	
Top Negative Portfolio Weights	***SIC2***	***Top Negative Portfolio Weights***	***SIC2***
Coal Mining	12	Water Transportation	44
Water Transportation	44	Petroleum & Coal Products	29
Insurance Agents, Brokers, & Service	64	Motion Pictures	78
Mining Non-Metallic Minerals, Except Fuels	14	Communications	48
Transportation Services	47	Security & Commodity Brokers	62
Security & Commodity Brokers	62	Oil & Gas Extraction	13
Top Positive Portfolio Weights	***SIC2***	***Top Positive Portfolio Weights***	***SIC2***
Building Materials & Gardening Supplies	52	Pipelines, Except Natural Gas	46
Tobacco Products	21	Tobacco Products	21
Food & Kindred Products	20	Miscellaneous Manufacturing Industries	39
Paper & Allied Products	26	Lumber & Wood Products	24
Textile Mill Products	22	Paper & Allied Products	26
Furniture & Homefurnishings Stores	57	Textile Mill Products	22

Note: Table shows the industries (2-digit SIC code) with the largest average short and long positions in the estimated hedge portfolios resulting from regressions presented in Tables I and II. Panel (a) explores hedge portfolios based on regression 4 using innovations in the *CH Negative Climate Change News Index* as CC_t, while Panel (b) explores hedge portfolios based using innovations in the *WSJ Climate Change News Index* as CC_t. All portfolios are constructed using the absolute demeaned value of the E-Scores. Within each portfolio, industries are arranged in ascending order of portfolio weights.

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3.6 Results - Out-Of-Sample Fit

The most important test of the hedge portfolios is their ability to hedge out-of-sample innovations to climate news, i.e., to hedge innovations in months that were not included in the estimation of the portfolio weights. To construct a first measure of the out-of-sample performance of the hedge portfolios, for every period t we run regression 4 using data between periods t_{min} and $t-1$, where t_{min} corresponds to the first month for which we observe all climate exposures and CC_t series (September 2009). We then form the hedge portfolio based on these estimates, and explore the correlation of the returns of that hedge portfolio in period t with CC_t. This corresponds to the approach one would have taken to hedge climate news in real time. Since we require a certain amount of data to estimate regression 4, we only compare the out-of-sample performance of the hedge portfolios starting in period $t_{min}+30$ (March 2012).

Figure 7 presents the out-of-sample performance of portfolios constructed to hedge innovations in the *CH Negative Climate Change News Index*. The top panels show portfolios constructed using absolute values of the Sustainalytics E-Score, the bottom panels show portfolios that build on the absolute values of the MSCI E-Score. The left columns present scatter plots of the out-of-sample returns of the hedge portfolios together with the realizations of the innovation of climate news. The right panels plot the time-series of the climate news series and the return series of the hedge portfolios. Overall, there is a positive out-of-sample correlation with CC_t of 0.22 for the Sustainalyatics hedge portfolio and 0.18 for the MSCI hedge portfolio. In other words, the hedge portfolios indeed have higher returns during periods with positive innovations to climate news.

Panel A of Table IV provides additional information about the out-of-sample performance of the various portfolios designed to hedge innovations in the *CH Negative Climate Change News Index*. The first column is the most important one, showing the correlation between the realizations of $CC_t^{NegNews}$ and the returns of the various hedge portfolios (e.g., $R_{OOS}^{SUS\_A}$ corresponds to the out-of-sample returns of a hedge portfolio constructed using absolute values of the Sustainalytics E-Score). Overall, the hedge portfolios based on Sustainalytics E-Scores somewhat outperform the hedge portfolios based on the MSCI

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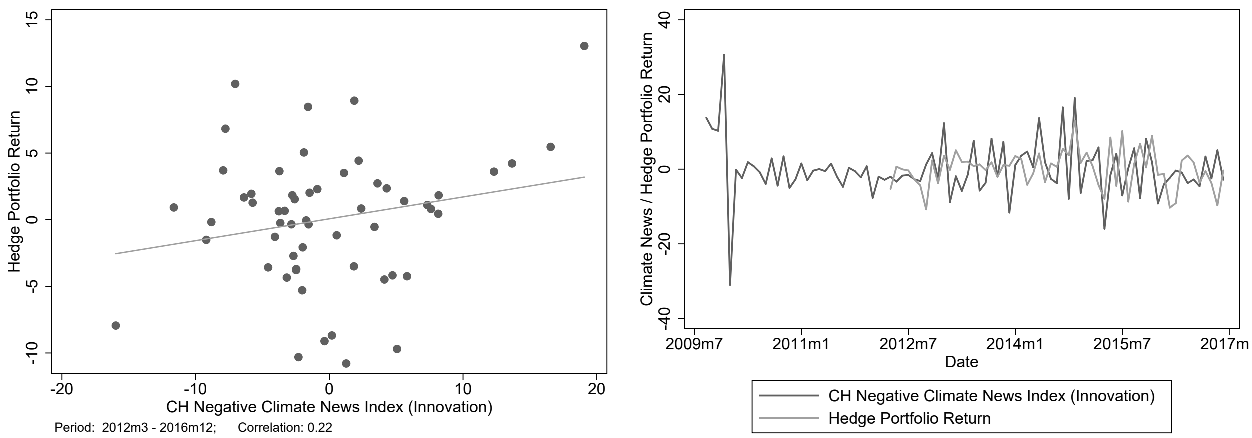
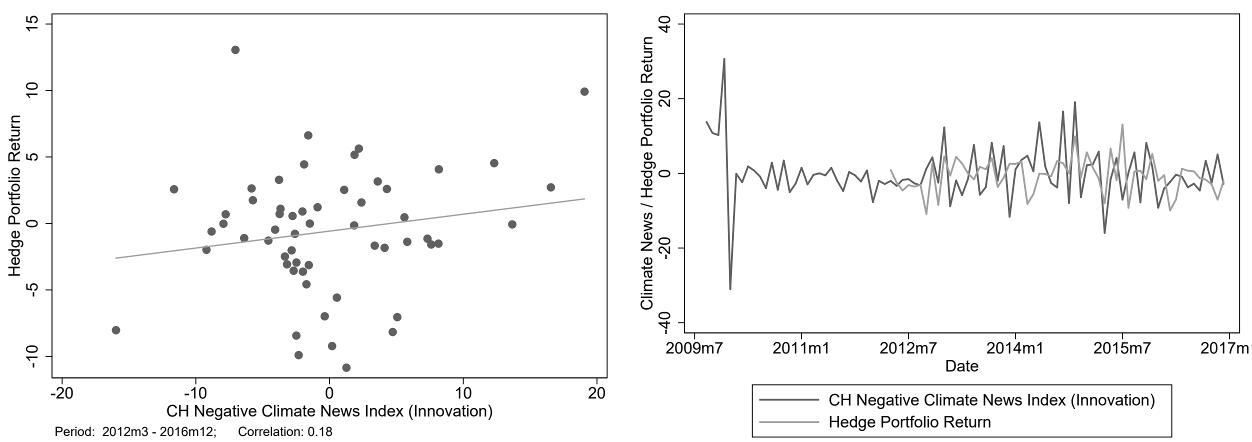
Figure 7: Out-of-Sample Fit: *CH Negative Climate Change News Index*



(a) Sustainalytics Hedge Portfolio



(b) MSCI Hedge Portfolio

Note: Figures explore the out-of-sample performance of hedge portfolios constructed to hedge the *Newspaper-Based Negative Climate News Measure*. The top panel presents hedge portfolios built on the absolute values of the Sustainalytics E-Score, the bottom panel presents portfolios built on the absolute values of the MSCI E-Score.

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Table IV: Cross-correlations: CH Negative Climate Change News Index

PANEL A: Out-of-Sample Fit

	$CC^{NegNews}$	$H_{OOS}^{SUS\_A}$	$H_{OOS}^{SUS\_R}$	$H_{OOS}^{MSCI\_A}$	$H_{OOS}^{MSCI\_R}$	H_{OOS}^{ETF}	r_t^{XLE}	r_t^{PBD}
$CC^{NegNews}$	1.000							
$H_{OOS}^{SUS\_A}$	0.217	1.000						
$H_{OOS}^{SUS\_R}$	0.183	0.992	1.000					
$H_{OOS}^{MSCI\_A}$	0.179	0.869	0.852	1.000				
$H_{OOS}^{MSCI\_R}$	0.175	0.865	0.850	0.998	1.000			
H_{OOS}^{ETF}	0.157	0.780	0.767	0.961	0.960	1.000		
r_t^{XLE}	-0.066	-0.412	-0.353	-0.387	-0.367	-0.410	1.000	
r_t^{PBD}	0.063	0.061	0.112	0.096	0.127	0.119	0.656	1.000

PANEL B: Cross-Validation Fit

	$CC^{NegNews}$	$H_{Cross}^{SUS\_A}$	$H_{Cross}^{SUS\_R}$	$H_{Cross}^{MSCI\_A}$	$H_{Cross}^{MSCI\_R}$	H_{Cross}^{ETF}	r_t^{XLE}	r_t^{PBD}
$CC^{NegNews}$	1.000							
$H_{Cross}^{SUS\_A}$	0.148	1.000						
$H_{Cross}^{SUS\_R}$	0.154	0.991	1.000					
$H_{Cross}^{MSCI\_A}$	0.024	0.864	0.836	1.000				
$H_{Cross}^{MSCI\_R}$	0.048	0.885	0.861	0.993	1.000			
H_{Cross}^{ETF}	0.053	0.829	0.799	0.973	0.968	1.000		
r_t^{XLE}	-0.066	-0.208	-0.183	-0.205	-0.237	-0.223	1.000	
r_t^{PBD}	0.063	0.169	0.171	0.158	0.157	0.185	0.656	1.000

Note: Table shows cross-correlations of different portfolios and innovations in the *CH Negative Climate Change News Index*. Panel A focuses on the performance of hedge portfolios from our out-of-sample approach, Panel B on the performance of hedge portfolios from our cross-validation approach.

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E-Scores. In addition, hedge portfolios based on absolute E-Scores marginally outperform those based on ranked E-Scores, though the returns of portfolios based on absolute and ranked E-Scores from the same data provider are highly correlated. Finally, the out-of-sample performance of all E-Score-based hedge portfolios is somewhat better than that of portfolios based on ETFs.[16] The returns of all hedge portfolios are negatively correlated with the returns to XLE, suggesting that these hedge portfolios are likely to hold short positions in the energy firms that constitute XLE. Similarly, we observe a positive correlation between the returns of all climate hedge portfolios and the returns of PBD, suggesting that the hedge portfolios likely hold long positions in many of the green energy firms that constitute PBD.

We also conduct a second test for the performance of the hedge portfolios based on a cross-validation approach. In particular, for every period t' we run regression 4 for all periods $t \neq t'$, and then use the resulting estimates to construct a hedge portfolio in a similar way as described above. The return of that hedge portfolio in period t' is then compared to $CC_{t'}$. Panel B of Table IV explores the cross-validation performance of the various hedge portfolios. The hedge portfolios based on Sustainalytics E-Scores continue to outperform those based on MSCI E-Scores or ETFs substantially; indeed, the cross-validation correlation between climate news and hedge portfolios based on MSCI E-Scores or ETFs is relatively close to zero.

Figure 8 and Table V present similar results as Figure 7 and Table IV, this time analyzing the performance of portfolios designed to hedge innovations in the *WSJ Climate Change News Index*, given by CC^{WSJ}. Portfolios based on Sustainalytics E-Scores have similar ability to hedge this second climate news series as they had in hedging the *CH Negative Climate Change News Index*, both in the out-of-sample evaluation as well as in the cross-validation evaluation. Portfolios based on MSCI E-Scores or ETFs, on the other hand, have very little ability to hedge innovations in the *WSJ Climate Change News Index*.

[16]Interestingly, in unreported results we find that the out-of-sample performance of hedge portfolios constructed based on *both* E-Scores and ETFs is lower than that just based on E-Scores, consistent with a problem of over-fitting the data in our relatively short training periods.

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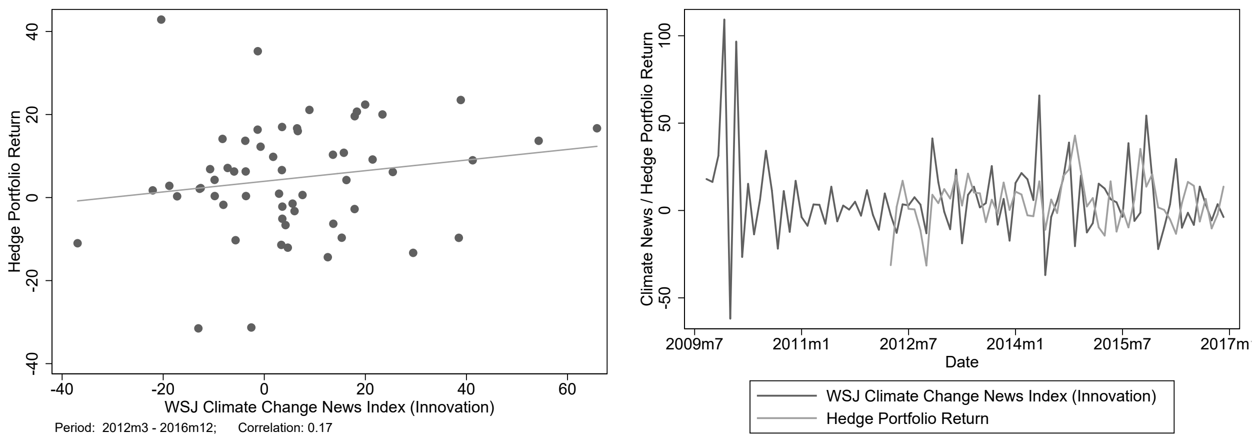
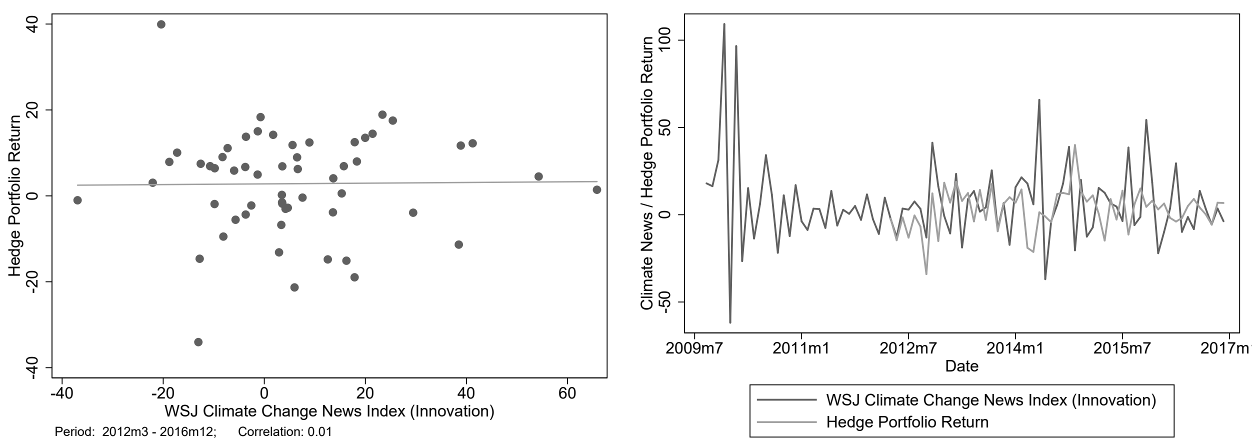
Figure 8: Out-of-Sample Fit: *WSJ Climate Change News Index*



(a) Sustainalytics Hedge Portfolio



(b) MSCI Hedge Portfolio

Note: Figures explore the out-of-sample performance of hedge portfolios constructed to hedge the *WSJ-Based Climate News Measure*. The top panel presents hedge portfolios built on the absolute values of the Sustainalytics E-Score, the bottom panel presents portfolios built on the absolute values of the MSCI E-Score.

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Table V: Cross-correlations: WSJ Climate Change News Index

PANEL A: Out-of-Sample Fit

	CC^{WSJ}	$H_{OOS}^{SUS\_A}$	$H_{OOS}^{SUS\_R}$	$H_{OOS}^{MSCI\_A}$	$H_{OOS}^{MSCI\_R}$	H_{OOS}^{ETF}	r_t^{XLE}	r_t^{PBD}
CC^{WSJ}	1.000							
$H_{OOS}^{SUS\_A}$	0.174	1.000						
$H_{OOS}^{SUS\_R}$	0.206	0.973	1.000					
$H_{OOS}^{MSCI\_A}$	0.013	0.688	0.621	1.000				
$H_{OOS}^{MSCI\_R}$	0.019	0.677	0.624	0.988	1.000			
H_{OOS}^{ETF}	-0.005	0.427	0.349	0.861	0.852	1.000		
r_t^{XLE}	0.068	-0.138	0.004	-0.097	-0.039	-0.141	1.000	
r_t^{PBD}	0.111	0.185	0.272	0.294	0.350	0.190	0.656	1.000

PANEL B: Cross-Validation Fit

	CC^{WSJ}	$H_{Cross}^{SUS\_A}$	$H_{Cross}^{SUS\_R}$	$H_{Cross}^{MSCI\_A}$	$H_{Cross}^{MSCI\_R}$	H_{Cross}^{ETF}	r_t^{XLE}	r_t^{PBD}
CC^{WSJ}	1.000							
$H_{Cross}^{SUS\_A}$	0.244	1.000						
$H_{Cross}^{SUS\_R}$	0.300	0.976	1.000					
$H_{Cross}^{MSCI\_A}$	0.039	0.742	0.671	1.000				
$H_{Cross}^{MSCI\_R}$	0.067	0.733	0.676	0.982	1.000			
H_{Cross}^{ETF}	-0.069	0.454	0.390	0.678	0.651	1.000		
r_t^{XLE}	0.068	0.041	0.072	-0.009	-0.034	0.297	1.000	
r_t^{PBD}	0.111	0.272	0.266	0.310	0.298	0.469	0.656	1.000

Note: Table shows cross-correlations of different portfolios and innovations in the *WSJ Climate Change News Index*. Panel A focuses on the performance of hedge portfolios from our out-of-sample approach, Panel on the performance of hedge portfolios from our cross-validation approach.

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4 Conclusion and Directions for Future Research

We demonstrate how a mimicking portfolio approach can be successful in hedging innovations in climate change news across a number of out-of-sample performance tests. Across our two indices for climate news, the hedge portfolios based on Sustainalytics E-Scores have the best in-sample fit as well as the best out-of-sample and cross-validation performance. Portfolios based on MSCI E-Scores and ETFs (XLE and PBD) have a lower (but still positive) ability to hedge innovations in climate news. There are no systematic differences in the relative performance of hedge portfolios based on absolute or ranked versions of the raw E-Scores. In general, however, the differences between the out-of-sample and cross-validation performance of some of the portfolios highlight that the portfolios we construct are somewhat sensitive to the exact time series on which our models are trained. This is likely the result of only having a relatively few data points in each of our estimations. As we observe longer time series of E-Scores and climate news measures, our proposed method should deliver ever-better portfolios to hedge climate change news. Similarly, moving from hedging climate news that materializes over a monthly level to hedging on a daily level should allow researchers to substantially expand their training data, and thereby increase the out-of-sample performance of the hedge portfolios.

More generally, we view this article as providing a rigorous methodology for constructing portfolios that hedge against risks that are otherwise difficult to insure. We do not view our resulting hedge portfolios as the definitive best hedges against climate change risk, but instead as a starting point for further exploration. Indeed, there are many valuable directions for future research on climate finance, and we discussed many of the dimensions that should be explored further, including the addition of more assets to the hedge portfolios (such as international stocks) and the formation of hedge portfolios based both characteristic-sorted portfolios and ETFs.

One important direction for future work is to integrate more and better data for measuring firm-level climate risk exposures. These could come from commercial data providers or could be constructed by researchers themselves, for example by including information such as geographical proximity to potential climate disasters (e.g., rising sea-levels or

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hurricane-prone regions). Indeed, articles in this volume, such as Choi et al. (2018) and Kumar et al. (2018) make valuable progress towards developing new ways to quantify climate risk exposures.

Another direction for follow-on work is to develop alternative definitions of the climate change risks. One interesting question is whether it is important to differentiate between physical and policy-oriented climate risks. For example, a tax on greenhouse gas emissions, if comprehensively applied at an appropriate level, would reduce the demand for climate hedge portfolios and consequently the cost of insuring against climate change. Thus good regulation will mean less need for climate hedges. But regulation itself creates winners and losers from regulatory risk, and one might therefore want to construct regulatory hedge portfolios. The stability of such regulatory hedge portfolios may well be sensitive to the prevailing political environment.

A related question pertains to the expected returns of the various hedge portfolios. Indeed, an increasing use of climate hedge portfolios by investors will increase the price (and thus reduce the expected returns) of those firms whose stock provides the most effective hedge against innovations in climate change news. This lower expected return corresponds to the insurance premium paid for the climate hedge portfolio. An interesting avenue for future work will be to quantify the cost of the climate hedge portfolios by looking at the associated risk premia.[17] It is also interesting to study the general equilibrium effects resulting from the fact that a lower cost of capital for firms with high E-Scores might actually have a direct effect on the climate trajectory. For example, to the extent that green energy firms see a reduction in their cost of capital, this might allow them to achieve efficient scale faster, and thereby affect the path of greenhouse gas emissions. The design of structural asset pricing models that feature such general equilibrium feedback loops seems a promising direction for research.

[17]Note that this requires a substantial time-series data, since realizations of negative climate news in-sample might actually lead the hedge portfolios to outperform over any given period.

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A Appendix

A.1 Source of Climate Change Vocabulary (CCV)

To create the Climate Change Vocabulary, we collect 12 climate change white papers from various sources including the Intergovernmental Panel on Climate Change (IPCC), Environmental Protection Agency (EPA), and the U.S. Global Change Research Program. We complement this with 59 climate change glossaries from sources such as United Nations, NASA, IPCC, and EPA.

12 Climate change white papers : Table VI reports the institution, title and published year of climate change white papers that we use to construct the CCV.

59 climate change glossaries : We collect climate change glossaries–both words and their definition–from U.S. Environmental Protection Agency (EPA), BBC, United Nations(UN), Center for Climate and Energy Solutions Glossary of Key Terms, Intergovernmental Panel on Climate Change (IPCC), World Health Organization(WHO), European Climate Adaptation Platform, International Petroleum Industry Environmental Conservation Association(IPIECA), Lenntech, Wikipedia, Met Office, Integrated Regional Information Networks(IRIN), Climate Change in Australia, Guardian, International Rivers, Mekong River Commission, Exploratorium, New York Times, US Forest Service, US Department of Transportation, Durham Region, Classroom of the Future, Government of Canada, International Food Policy Research Institute (IFPRI), New Zealand Government, University of Miami , German Climate Finance, California Government, South West Climate Change Impacts Partnership (SWCCIP), Scent of Pine, Natural Climate Change, UN Climate Change Conference, Center for Strategic and International Studies(CSIS), Watts Up With That?, UK Climate Impacts Programme (UKCIP), Climate Change Zambia, Canadian Broadcasting Corporation(CBC), Auburn University, Global Warming Solved, REDD+, Climate Resilience Toolkit(CRT), What's your impact, The Nitric Acid Climate Action Group (NACAG), Garnaut Climate Change Review, Climate Policy Information Hub, Explaining Climate Change, Four Degrees Preparation, The European Initiative for Up-

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scaling Energy Efficiency in the Music Event Industry (EE MUSIC), Regional Education and Information Centre (REIC), Ecology, Climate Reality Project, National Geographic, Agricultural Marketing Resource Center (AgMRC), Global Greenhouse Warming, Conservation in a Changing Climate.

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Table VI: The list of climate change white papers

Source	Title	Year
Intergovernmental Panel on Climate Change (IPCC)	IPCC Systhesis Report	1990, 1995, 2001, 2007, 2014
IPCC	IPCC Special Report : The regional impacts of climate change : an assessment of vulnerability	1997
IPCC	IPCC Special Report : Aviation and the Global Atmosphere	1999
IPCC	IPCC Special Report : Methodological and Technological Issues in Technology Transfer	2000
IPCC	IPCC Special Report : Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons	2005
IPCC	IPCC Special Report : Carbon Dioxide Capture and Storage	2005
IPCC	IPCC Special Report : Renewable Energy Sources and Climate Change Mitigationn	2011
IPCC	IPCC Special Report : Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptationn	2012
American Association for the Advancement of Science	What We Know : The reality, risks, and response to climate change	2014
U.C. Berkley	American Climate Prospectus	2015
U.S. Environmental Protection Agency (EPA)	Climate Change Indicators in the United States (4th Edition)	2016
Science	Social and economic impacts of climate	2016
International Monetary Fund (IMF)	The Effects of Weather Shocks on Economic Activity	2017
U.S. Global change Research Program	Our change planet : The U.S. Global Change Research Program for Fiscal Year 2017	2017
U.S. Global change Research Program	Climate Science Special Repor (4th National Climate Assessment, Volume I)	2017

Note: IPCC reports provide scientific and technical assessments of the current state of climate change. Generally, these reports comprise of three volumes, one for each of the Working Groups of the IPCC. In addition to the main reports, Summaries for Policymakers and Synthesis Reports are provided. A Synthesis Report integrates materials covered by Assessment Reports and Special Reports. It is a non-technical report whose target audience is policymakers, and addresses a broad-range of policy-relevant but policy-neutral questions. Summary for Policymakers is an abridged version of the full Synthesis Report. In addition, IPCC Special Reports provide an assessment of a specific issue relating to climate change. They are generally structured similar to a volume of an Assessment Report.

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A.2 Sub-categories for "E" scores

MSCI. Positive indicators are: Environmental Opportunities - Clean Tech, Waste Management - Toxic Emissions and Waste, Waste Management - Packaging Materials & Waste, Climate Change - Carbon Emissions, Property/Plant/Equipment, Environmental Management Systems, Natural Resource Use - Water Stress, Natural Resource Use - Biodiversity & Land Use, Natural Resource Use - Raw Material Sourcing, Natural Resource Use - Financing Environmental, Environmental Opportunities - Green Buildings, Environmental Opportunities in Renewable Energy, Waste Management - Electronic Waste, Climate Change - Energy Efficiency, Climate Change - Product Carbon Footprint, Climate Change - Insuring Climate Change Risk, Environment - Other Strengths.
Negative indicators are: Regulatory Compliance, Toxic Emissions and Waste, Energy & Climate Change, Impact of Products and Services, Biodiversity & Land Use, Operational Waste, Water Stress, Environment - Other Concerns.

Sustainalytics. Sub-categories are Formal Environmental Policy, Environmental Management System, External Certification of Environmental Management Systems (EMS), Environmental Fines and Non-monetary Sanctions, Participation in Carbon Disclosure Project, Scope of Corporate Reporting on GHG emissions, Programmes and Targets to Reduce GHG Emissions from Own Operations, Programmes and Targets to Increase Renewable Energy Use, Carbon Intensity, Carbon Intensity Trend, % of Primary Energy Use from Renewables, Operations Related Controversies or Incidents, Reporting Quality Non-Carbon Environmental Data, Programmes and Targets to Protect Biodiversity, Guidelines and Reporting on Closure and Rehabilitation of Sites, Environmental and Social Impact Assessments, Oil Spill Reporting and Performance, Waste Intensity, Water Intensity, Percentage of Certified Forests Under Own Management, Programmes & Targets to Reduce Air Emissions, Programmes & Targets to Reduce Air Emissions, Programmes & Targets to Reduce Water Use, Other Programmes to Reduce Key Environmental Impacts, GHG Reduction Programme, Programmes and Targets to Improve the Environmental Performance of Own Logistics and Vehicle Fleets, Programmes and Targets to Phase out

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CFCs and HCFCs[18] in Refrigeration Equipment, Formal Policy or Programme on Green Procurement, Environmental Supply Chain Incidents, Programmes to Improve the Environmental Performance of Suppliers, External Environmental Certification Suppliers, Programmes and Targets to Stimulate Sustainable Agreculture, Programmes and Targets to Stimulate Sustainable Aquaculture/Fisheries, Food Beverage & Tabacco Industry Initiatives, Programmes and Targets to Reduce GHG Emissions from Outsourced Logistics Services, Data on Percentage of Recycled/Reused Raw Material Used, Data on Percentage of Forest Stewardship Council (FSC) Certified Wood/Pulp as Raw Material, Programmes and Targets to Promote Sustainable Food Products, Food Retail Initiatives, Products & Services Related to Controversies or Incidents, Sustainability Related Products & Services, Revenue from Clean Technology or Climate Friendly Products, Automobile Fleet Average CO2 Emissions, Trend Automobile Fleet Average Fleet Efficiency, Products to Improve Sustainability of Transport Vehicles, Systematic Integration of Environmental Considerations at R&D Stage, Programmes and Targets for End-of-Life Product Management, Organic Products, Policy on Use of Genetically Modified Organisms (GMO) in Products, Environmental & Social Standards in Credit and Loan Business, Responsible Asset Management, Use of Life-Cycle Analysis(LCA) for New Real Estate Projects, Programms and Targets to Increase Investment in Sustainable Buildings, Share of Property Portfolio Invested in Sustainable Buildings, Sustainability Related Financial Services, Products with Important Environmental/Human Health Concerns, Carbon Intensity of Energy Mix, Mineral Waste Management, Emergency Response Programme.

[18] Chlorofluorocarbons and Hydrochloroflourocarbons

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