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Executive summary

This report explores optimal combinations of financial and hedging instruments to support sustainable investments in the medium and long term. Through six interrelated analyses, it examines how climate risk can be priced and mitigated. Each study offers insight into how financial markets can evolve to more effectively support the transition to a sustainable economy.

We begin by examining green bonds as an emerging strategic asset class. An analysis of their dynamic dependencies, allocation potential, and diversification properties—both before and during the COVID-19 pandemic—reveals that green bonds offer meaningful diversification benefits and resilience during periods of market stress. These characteristics position them as valuable components of medium- and long-term sustainable investment strategies. A critical component of sustainable finance is the interpretation of ESG ratings, which are often used to guide investment decisions. The report investigates the ambiguity and signaling value of ESG scores, proposing an informative and distorted signal-based approach. This analysis shows that while ESG

ratings can provide valuable information, they are also prone to inconsistencies and noise. Misaligned or ambiguous ratings can distort capital allocation and risk assessment, underscoring the need for greater methodological transparency and convergence in ESG scoring frameworks.

We then turn to the analysis of water scarcity, a key source of physical climate risk, and of potential methods of water risk mitigation. The issue is studied from two perspectives. First, novel physical and financial hedging are introduced, which are able to mitigate water shortage impacts. These instruments can address the growing need for targeted financial instruments in vulnerable regions and sectors. The second perspective is that of risk management, and the work illustrates the use of weather derivatives as a hedging tools to manage cash flow volatility linked to climate-related water stress, under a number of climate change scenarios described by the RCP pathways. Empirical modeling supports the effectiveness of these instruments for utilities, agriculture, and water-intensive industries. Next, the impact of climate risk — both transition and physical — in equity and debt markets is evaluated. The analysis shows partial but increasing integration of transition risk into corporate valuations, while the pricing of physical risk is more pronounced in the fixed income sector rather than in equity. This suggests significant room for improvement in climate risk transparency and valuation methodologies across capital markets.

Afterwards, to enhance hedging effectiveness in a world dependent on energy, the report introduces an advanced approach to modeling energy commodity futures and futures on the carbon allowances of the Emissions Trading Scheme of the European Union, using realized volatility. Accurate volatility modeling is essential for pricing risk and developing tailored hedging strategies, particularly in energy commodities markets affected by supply-chain disruptions, regulatory shifts, and environmental shocks. The links and transmission channels across commodities are also investigated, to increase the understanding of the complex system of interactions and substitution effects across energy inputs. Finally, once again on the topic of energy, machine learning techniques are applied to analyze how renewable energy generation, electricity prices, and power load

collectively influence CO2 emissions, focusing on France, Germany, and Italy. The objective of the study is to inform policymakers and stakeholders about effective strategies for emission reduction and sustainable energy planning. Ultimately, this analysis contributes to broader efforts aimed at achieving economic sustainability through cleaner energy systems and supports Europe's ambitious targets for reducing greenhouse gas emissions.

Taken together, these analyses highlight the importance of a layered and comprehensive approach to financing sustainable investments. Strategic asset allocation (potentially involving green bonds and accounting for climate risk and ESG ambiguity), novel weather-based risk mitigation tools (weather derivatives), climate risk pricing, and an accurate modelling of energy commodities and CO2 emissions all play essential roles. No single perspective can fully address the complexity of climate risk and sustainable finance, but an integrated combination of hedging tools and analyses offers the most effective pathway toward a resilient and sustainable financial system.

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1. Green bonds

Green bonds are financial instruments designed to fund projects with a positive environmental impact. Since their first introduction in 2007, their market has expanded rapidly, driven by an increased awareness of climate-related risks and by a growing investor sensitivity towards sustainability. Given the significant volatility in traditional financial markets, particularly during crises, green bonds emerge as an alternative asset class that can mitigate risk while aligning with environmental objectives. Over the last few years, a number of studies have focused on the financial properties of green bonds. The positive effect of this asset class on the issuer's stock price as well as on its environmental and financial performances has been highlighted in Flammer (2021) and in Tang and Zhang (2020). The existing literature on the subject of green bond and traditional (non-green) market co-movement includes Reboredo (2018) and Reboredo and Ugolini (2020), that find a strong link with the corporate and treasury bond markets and with currencies, and weak links with a number of traditional commodities, including energy prices.

In Martiradonna et al. (2023), we present a comprehensive analysis of green bond diversification benefits, their co-movement with various market indices, and their implications for portfolio allocation. The research spans a seven-year timeframe, divided into four sub-periods, to examine the dynamic dependencies of green bonds before and during the COVID-19 pandemic.

Key results indicate that the two green-bond indices considered, the Bloomberg Barclays MSCI Green Bond Index and the Solactive Green Bond Index, show a significantly positive dynamic conditional correlation with the traditional corporate bond market in all sub-periods. They thus do not appear to be particularly helpful for diversification in this sector, but their even lower volatility makes them an appealing new asset class for conservative investors. The Solactive Green Bond Index provides greater diversification benefits compared to the Bloomberg Barclays MSCI Green Bond Index, as it negatively co-moves with all remaining sectors of the analysis: the global stock market, the energy commodity index, the airline industry, the healthcare sector, and the IT index. This diversification effect is particularly pronounced during market downturns, when green bonds act as a stabilizing asset.

When considering a variety of portfolio allocation strategies and of risk and performance measures, the difference between the two green indices was confirmed by the weights attributed by the various allocation strategies. As the Bloomberg Barclays MSCI Green Bond Index is slightly preferable to Solactive in terms of volatility, more weight was attributed to the Bloomberg Barclays MSCI Green Bond Index by strategies which prioritized variance reduction, while the Solactive Green Bond Index was selected exclusively when the aim was diversification maximization. This suggests that the diversification potential associated with the other green-bond index was absorbed by Solactive and by the non-green assets. However, the Bloomberg Barclays MSCI Green Bond Index displays a weak positive co-movement with the sectors which had an outstanding positive performance during the pandemic.

Afterwards, two types of portfolios were constructed and compared: "green portfolios", which included green bond indices together with a variety of traditional market indices, and "non-green portfolios", which did not include green bonds. Green portfolios consistently outperformed non-green portfolios in terms of risk across all periods and for all investment strategies. They also exhibited lower losses during market downturns, across nearly all strategies, and delivered positive but relatively lower returns than non-green portfolios, during phases of market expansion. The performance gap between green and non-green portfolios was particularly pronounced under strategies that prioritized risk minimization over return maximization, as these strategies allocated greater weights to the least risky assets, namely the two green bond indices. However, in the pre-pandemic period, incorporating green bonds enabled portfolios to achieve returns that were either superior to or on par with non-green portfolios, while incurring less risk. During the pandemic, strategies that focused exclusively on minimizing portfolio variance, without considering returns, led to a significantly better performance of non-green portfolios in terms of value. Conversely, the mean–variance optimization strategy, which aims to maximize returns per unit of risk, resulted in substantially higher returns for green portfolios. When an additional risk measure was introduced to account for behavioral factors such as investor risk aversion, green portfolios once again proved to be consistently preferable to their non-green counterparts, all else being equal. The risk-reduction and diversification advantages offered by green indices remained robust

across all strategies and time periods, including the extreme market conditions brought by the Covid-19 pandemic.

Overall, these findings underscore the critical role of green bonds in supporting financial stability and sustainability objectives. Policymakers and investors should take into account the strategic importance of green bonds in achieving both economic resilience and environmental goals.

More information on this research is available in the GRINS Policy brief by Romagnoli and Santini (2025).

2. ESG rating and ambiguity

In recent years, ESG considerations have played an increasingly significant role in investment decisions. ESG ratings influence capital flows, corporate strategies, and policy decisions at both national and international levels. Investors rely on these ratings to assess corporate sustainability performance, making them a crucial component in financial markets. However, a major challenge facing ESG assessments is the lack of standardization in data disclosure and rating methodologies. One of the primary concerns is that the lack of a clear taxonomy set by the different governments led the agency to use varying criteria to evaluate companies, leading to discrepancies in ESG scores. The absence of a universal framework results in the same company receiving different ratings from multiple agencies, making it difficult for investors to make informed decisions, as reported in Inderst and Stewart (2018) and Berg et al. (2019).

This inconsistency not only reduces trust in ESG assessments but also creates uncertainty in financial markets, as investment decisions based on conflicting ratings can lead to misallocation of capital. Another critical factor contributing to ESG rating ambiguity is the quality of corporate disclosures. While some companies provide extensive, verifiable ESG data, others offer limited or selectively curated information. This variation in transparency makes it difficult to compare firms accurately, as rating agencies rely heavily on self-reported data. The lack of a standardized reporting framework exacerbates this issue,

allowing companies to present their ESG performance in a way that may not fully reflect their actual sustainability efforts. Market sentiment and subjective interpretations further complicate ESG assessments. Investors and analysts may weigh certain ESG factors differently based on prevailing narratives, leading to potential biases in how ESG performance is perceived. This subjectivity introduces an additional layer of ambiguity, making it challenging to establish a reliable and objective ESG rating system.

Addressing these inconsistencies is crucial for improving the reliability and effectiveness of ESG ratings. A structured, information-based approach that enhances transparency, standardizes reporting practices, and reduces subjectivity in evaluations can help mitigate these challenges. Establishing clear guidelines for ESG disclosures and harmonizing rating methodologies will strengthen the credibility of ESG assessments, ultimately fostering greater trust among investors and encouraging responsible corporate behaviour.

In Bongermino and Romagnoli (2025), a structured framework is presented, developing an information-based distortion model, which integrates an information matrix assessing data reliability and a garbling matrix capturing subjective market biases. By applying this approach, it is possible to evaluate the effects of policy shocks on the companies' ratings, evaluating the sentiment of market participants towards the different ESG scores. Key findings indicate that ESG ratings are susceptible to systematic distortions, leading to inefficient capital allocation. Under scenarios of increased regulatory scrutiny, firms with low transparency experience greater rating volatility, highlighting the importance of standardized disclosure and a clear regulatory framework. Furthermore, adjusting for ambiguity significantly enhances the predictive power of ESG scores in assessing long-term financial performance. These findings underscore the need for policy interventions aimed at improving ESG rating consistency and reliability.

More information on this research is available in the GRINS Policy brief by Bongermino and Romagnoli (2025).

3. Water scarcity risk

Climate change, combined with water mismanagement and overuse, is intensifying droughts and water shortages worldwide. These challenges threaten public health, disrupt agriculture, and exacerbate food insecurity. Particularly in agriculture, water scarcity reduces crop yields and endangers food supply chains. Effective water resource management now requires innovative approaches beyond traditional engineering. Within a water market system, it is possible to define hedging instruments to manage the volumetric risk associated with low rainfall and water scarcity when basin levels fall below a specified threshold. This approach has significant implications for addressing the insurance gap and for the development of policy instruments aimed at managing environmental risks. Using California as an example, we illustrate the practical application and benefits of these strategies, particularly in agricultural water management, where inefficient irrigation and over-extraction of water resources are critical concerns. Agriculture consumes around 70% of global freshwater, and effective management of these resources is key to mitigating the risks of water scarcity. By incorporating such financial tools, the agricultural sector can better hedge against water-related risks, ensuring more resilient food production systems and sustainable resource use.

More precisely, in Bartolini et al. (2024), we introduce two new weather derivatives that enable hedging strategies based on the specific location of the protection buyer (the option buyer), even if the contract is set for a different location. These weather derivatives are designed to be flexible and cater to the unique needs of various stakeholders in the water market. They are:

- Rain Quanto Options, or RQOs, with payoff $\left(K - R_T\right)^+ AS_T$, where R_T represents average rainfall in millimeters, A denotes the area of interest in square meters, K is the strike rainfall level in millimeters, and S_T is the water price expressed in dollars per cubic meter
- Basin Level Cash or Nothing options, or BLCONs, with payoff $QS_{T1_{\left(Y_T \leq K\right)}}$, where Q represents the water amount in cubic meters and Y_T is the basin level. In this

contract, the payment corresponds to the price of water at maturity, multiplied by the quantity Q, if the basin level is below a certain threshold K.

By leveraging these instruments, protection buyers can hedge against the risk of water scarcity more effectively than through traditional insurance contracts. This is because the costs associated with the contract can be distributed among all market participants protection buyers and sellers rather than being borne solely by the protection buyer. The structure of the weather derivatives market offers additional advantages over traditional insurance contracts. Specifically, it facilitates the dissemination of information about water scarcity, as this information will be reflected in the prices of water and options. An increase in the value of the water resource will be immediately reflected in prices, enabling all operators (both private and public) to promptly observe and take necessary actions to mitigate the negative economic impact of water scarcity. Such a mechanism cannot be achieved solely through insurance contracts, as these are client-specific and their value is private. This public dissemination of risk information through market prices can be a powerful tool for policymakers, as it provides real-time data on water scarcity and can inform more responsive and adaptive water management policies.

In addition to addressing the volumetric risk associated with low rainfall and water scarcity, in Bartolini et al. (2025b) we show the hedging effectiveness of these instruments, particularly when there is a geographical mismatch between the contracts specified location and the location of the hedger. This aspect is crucial for filling the insurance gap, as traditional insurance products often fall short in providing adequate coverage for such geographically mismatched risks. The model-independent nature of the proposed procedure allows it to be applied to real market data as the market develops. This flexibility extends its use to various sectors, including agricultural water management, where water scarcity caused by factors like inefficient irrigation or over-extraction represents significant risks. By leveraging these financial tools, farmers can safeguard their operations against water-related losses, promoting more sustainable agricultural practices and mitigating the effects of climate-induced water shortages.

We then introduce an example of scenario analysis on the mitigation of water risk through the use of an RQO, by basing rainfall scenarios on four different Representative

Concentration Pathways (RCPs). These pathways allow us to capture a range of plausible climate outcomes and evaluate the sensitivity of RQO prices and hedging potential to future environmental conditions. We restrict this analysis to RQOs and not BLCONs, as scenario projections for the basin under study are not currently available. The scenarios are used for two types of analysis: first, the price sensitivity of the RQO is evaluated with respect to variations in the parameters of the rainfall process corresponding to the different climate scenarios. Then, the hedging effectiveness of an RQO is assessed, under realized rainfall conditions corresponding to each RCP pathway. We find that the RQO provides perfect coverage under all scenario-based realizations of rainfall, limiting losses to its purchase price. The risk incurred by an unhedged position is instead great, as it depends on the realized rainfall scenario and on the market price of water at maturity. Finally, the option premium varies according to the scenario, reflecting the exercise probability implied by each setting.

We conclude by emphasizing how the introduction of weather derivatives within the water market system represents a significant advancement in risk management for water scarcity. By providing a mechanism for hedging volumetric risks and disseminating information about water scarcity, these instruments can help close the insurance gap and serve as valuable tools for both private sector participants and policymakers. The ability to distribute risk costs among market participants and to use market prices as indicators of water scarcity enhances the overall resilience of the water market and supports more informed and proactive water management policies.

The results of this analysis are presented in Bartolini et al. (forthcoming).

4. Climate risk in equity and fixed-income markets

We then move to an analysis of how climate risk affects the European equity and fixed-income markets, currently presented in the working paper Bartolini et al. (2025c). In light of the efforts on the part of the EU towards a green transition, identifying reliable indicators for the assessment of climate risk has steadily grown in importance. Climate

risk, however, is of a complex and multifaceted nature, and therefore difficult to capture via a limited number of observable variables. The current scientific consensus is that there are two main components of climate risk: physical and transition risk.

Physical risk encompasses financial losses caused by extreme weather events, which are increasing in frequency due to climate change, and by gradual alterations in local climate. Its direct impact on infrastructure, production, and overall business operations can lead to higher costs and lower profitability. As for transition risk, it is caused by uncertain regulatory changes that restrict or ban certain technologies, which can impact the profitability of companies and therefore their ability to repay debts. It is also driven by technological updates, which drive up costs, and by changing consumer preferences, which move towards greener options. Transition risk causes significant alterations in the business environment, requiring fast adaptation on the part of companies.

It is difficult to identify specific variables that can be used as measures of climate risk. In our study, we test various potential drivers to understand their effect on the market. We hypothesize that climate risks are already partially reflected in corporate bond spreads and utility stock prices, and our goal is to pinpoint the specific factors responsible for this pricing. To do so, we conduct an econometric analysis focused on European utility equities and the European bond market, with particular emphasis on the more complex and less identifiable dimension of transition risk. We identify two potential proxies of transition risk: the log-returns of futures on the carbon allowances of the European Emissions Trading Scheme and the transition risk index developed by Blasberg et al. (2021), computed on 20-year tenor CDS. The choice for physical risk falls on weather variables: temperature, floods, droughts, wind speed, and an index of wildfire risk.

The analyses reveal that these variables have a different effect on stocks and bonds. Stock returns are only rarely affected by climate risk, and the most frequent among them is flood risk. In contrast, bond z-spreads show statistically significant relationships with both physical and transition climate risks. There is also a distinction between green and non-green bonds: physical risk, on average, rewards the former and penalizes the latter. Interestingly, the two transition risk proxies are found to capture different types of information and to affect different bonds. This suggests that credit default swap-based

index is pricing a transition risk that goes beyond carbon emissions. The ECF is shown to be correlated with traded energy commodities, consistently with its interpretation as a proxy for carbon-related input costs in production. On the other hand, the TRI index could encapsulate broader, longer-term transition risks embedded in corporate creditworthiness. We in fact observe that the TRI is constructed with company CDS having a maturity of 20 years, and therefore reflects longer-term expectations, while the ECF carries information about the emissions produced during the solar year. This temporal misalignment could also be responsible for the difference in the two proxies, in line with the interpretation that ECF and TRI provide different perspectives on transition risk, as ECF could represent immediate market exposures and TRI could instead capture longer-term structural vulnerabilities.

5. Energy commodities

Following the recent crisis in the European energy system, in Bartolini et al. (2025a) we present an analysis of futures contracts on key commodities that represent essential inputs for the EU economy. These are: Dutch TTF gas, Brent crude oil (due to its connection with inflation and overall economic performance), and carbon allowances from the European Emissions Trading Scheme, which reflect a production cost of polluting firms and play a central role in the green transition. We consider the recently developed Heterogeneous Autoregressive (HAR) model, which was originally designed for analyzing equity indices and which was shown to effectively capture their return volatility, and apply it to commodity futures. The model relies on high-frequency trading data to calculate daily realized volatility, which inherently reflects intra-day market activity. We then assess how well this realized volatility predicts daily close-to-close return volatility, aiming to determine whether the model's data-intensive approach offers the same advantages in the commodity market as it does in equities. Our findings suggest otherwise: a Value-at-Risk validation test indicates that the model consistently overestimates volatility for the commodities examined. As a result, we conclude that realized volatility is not a

dependable tool for risk management in this context and recommend against its use for these specific commodities.

We then integrate this advanced approach with traditional financial time-series models, starting with univariate and moving to multivariate frameworks. Realized volatility is introduced as an external regressor in several univariate GARCH(p,q) model configurations, testing different assumptions for the residual distributions. Our results show that while realized volatility consistently enhances model fit and significantly explains close-to-close volatility, it is unsatisfactory in terms of predictive accuracy. In the multivariate analysis, we confirm the statistical significance of realized volatility by incorporating interactions among the variances of all commodities, revealing key channels of simultaneous volatility transmission. For HAR-type models in the univariate case, we find that including cross-commodity effects in the conditional expectation of log-returns yields statistically significant results. In the GARCH framework, we test the explanatory power of each commodity's realized volatility on the conditional variance of others, uncovering several meaningful relationships.

The multivariate analysis is finally performed, exclusively using GARCH models, specifically through the estimation of a Dynamic Conditional Correlation (DCC) model. The ECF and Brent crude oil, on the one hand, and Dutch TTF and Brent crude oil, on the other, exhibit an overall low correlation with each other. The strongest relationship is observed between European Carbon Futures (ECF) and Dutch TTF gas futures, which is generally negative—consistent with the economic logic linking carbon allowance prices to energy market dynamics. In fact, an increase in TTF prices reflects higher demand for natural gas, suggesting it's become more cost-effective than coal. Since natural gas emits less CO2 than coal, this shift results in cleaner production and lowers the demand for carbon allowances, pushing ECF prices down. Conversely, when TTF is sold off, it signals a shift back to cheaper but more polluting coal, increasing the need for carbon allowances and driving ECF prices up. Other inter-commodity correlations fluctuate over time but tend to center around zero.

6. Carbon emissions

In this final project, currently a working paper by Baruah et al., we investigate the relationship between electricity prices, renewable energy production, and carbon dioxide (CO2) emissions, focusing specifically on European countries such as France, Germany, and Italy. Given the availability of annual CO2 emissions data, statistical methods are employed to construct daily emission series that closely emulate actual behavior. Subsequently, machine learning techniques are applied to analyze how renewable energy generation, electricity prices, and power load collectively influence CO2 emissions.

The findings aim to deepen the understanding of how fluctuations in electricity prices and renewable energy availability impact CO2 emissions, thereby highlighting the critical role electricity plays in transitioning towards a more sustainable economy. By identifying these dynamic relationships, the research seeks to inform policymakers and stakeholders about effective strategies for emission reduction and sustainable energy planning. Ultimately, this analysis contributes to broader efforts aimed at achieving economic sustainability through cleaner energy systems and supports Europe's ambitious targets for reducing greenhouse gas emissions.

7. Conclusions

In this report we summarize the analyses carried out to evaluate how financial tools can support sustainable investments and manage climate risk. Across six related studies, we explore ways to tackle sustainable investment from multiple angles: we begin by investigating the potentially beneficial features of green bonds and their attractiveness for investors with different portfolio exposures and allocation strategies. The analysis shows that they offer diversification benefits particularly during times of market stress, including the COVID-19 pandemic. This makes them useful for medium- and long-term sustainable investment strategies. Next, we look at ESG ratings. These scores are often used in investment decisions, but they can be inconsistent and misleading. Our study highlights

the need for clearer, more standardized ESG rating methods to avoid misallocating capital.

Water scarcity is another key source of risk, which requires mitigation for handling sustainable investment. We propose two new weather derivatives, which can provide a financial hedge for agents requiring a steady amount of water in their operations. They help manage risks linked to water shortages, especially in sectors like agriculture and utilities. We also test their performance under different climate change scenarios, described by RCP pathways, showing how they can be effective tools for risk management.

We then study how climate risk in general, including both physical and transition components, affects stock and bond markets. We attempt to fill a gap in the literature by comparing the explanatory power of two different transition risk proxies. Interestingly, we find that they convey different information, as they have different relationships with the same assets. We also find that the climate risk proxies (both for physical and transition risk) have a different effect on stocks and bonds. Stock returns are only rarely affected by climate risk, and the most frequent among them is flood risk. In contrast, bond z-spreads show statistically significant relationships with both physical and transition climate risks. There is also a distinction between green and non-green bonds: physical risk, on average, rewards the former and penalizes the latter.

We then move on to another key aspect of sustainable investment: energy inputs. We investigate the accuracy of new time-series models for the returns of energy commodity futures and of futures on EU carbon allowances. We find that these models help explain past price movements, but fall short in producing accurate forecasts. We also explore the transmission channels across commodity prices, finding useful insight for risk management and asset allocation. Finally, again tackling the energy market, we examine how renewable energy production, electricity prices, and power demand together affect CO2 emissions. The goal is to better understand how changes in energy prices and the supply of renewables influence emission levels. Electricity plays a key role in the shift to a low-carbon economy.

Overall, our findings show that supporting the green requires an approach from multiple angles. From green bonds and better ESG ratings to weather-based risk tools and improved modeling, combining different approaches is the best way to build a more sustainable and resilient financial system.

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