Title: Green Bonds for the Transition to a Low Carbon Economy

Note: Our presentation combines the work of 2 documents:

1. Basic policy considerations of green fiscal policies as well as modeling exercise of fiscal policies under different business cycle regimes in a recently published World Bank report titled "Fiscal Policies for a Low-Carbon Economy" (**part 1** of this document, **pp 2-120**). The relevant modeling part is based on chapter 6 (pp 42-51), as well as
2. Modelling and empirical analysis of green vs conventional bond performance of a current working paper (**part 2** of this document, **pp 121-148**).

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Abstract:

Climate change imposes big challenges and demands an active fiscal and financial policy response. Climate disasters and global warming can move economies onto a lower-growth path with a rise of 'stranded assets' and financial instability. The effectiveness of the financial market for the transition to a low carbon economy depends on attracting investors and removing financial market roadblocks. The analysis in part 1 of our submission showed that fossil fuel energy prices co-vary with the business cycle, impact financial market and asset returns, and that green bonds can protect investors and governments against oil price volatilities. In part 2 of our submission we investigate the comparative performance based on a recent dataset of fixed income securities of green and conventional bonds. Many recent studies have focused on yield differential between green and conventional bonds but do not consider what is implied in asset prices and portfolio models with externalities, do not sufficiently highlight the heterogeneous feature of green bonds, and have not addressed various risk-return measure scenarios sufficiently. We focus on both yields and volatility and thus on the risk-return performance (Sharpe ratio) of the two types of bonds. Using an aggregate cross-sectional analysis, bond pairing estimations as well as regression tree methodology, and an energy sector specific analysis we find that green bonds show a negative green premium in the primary, mixed yield results in the secondary market (effects depend on issuers, maturity, sectoral, and currency aspects and vary for different volatility horizons), lower volatilities especially in the energy sector, and generally deliver superior Sharpe Ratios. The improved risk-return performance of green bonds supports the results of our previous analysis in part 1 and promotes the argument that green bonds form an attractive and secure financial vehicle that protects governments and investors from oil price and business cycle fluctuations, and stabilizes portfolio returns.

JEL classification: C610, G120, 0380, Q580
Keywords: green bonds, innovation, climate finance, dynamic portfolio decisions.

Fiscal Policies for a Low-Carbon Economy

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June 2021

WORLD BANK GROUP

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Acknowledgments

Fiscal Policies for a Low-Carbon Economy was prepared by a team led by Miria Pigato and composed of Willi Semmler, Joao Paulo Braga, Andreas Lichtenberger, Marieme Toure, and Erin Hayde. The team worked under the overall guidance of Chiara Bronchi and Marcello Estevao.

The team would like to thank Dirk Heine and the reviewers Diego Rivetti, Fiona Elizabeth Stewart, Martijn Gert Jan Regelink, Stephane Hallegatte, and Robert Johann Utz for their insightful comments. The authors are also thankful to Alexander Vasa, Ana Paula Gorini, Björn Schlebach Caroline Horbruegger, Guilherme Studart, Josef Haider, Monica Arevalo, Maria Netto, Marius Cara, Claudia Kemfert, Dorothea Schaefer, Jürgen Zattler, Nicoletta Batini, Prakash Loungani, Ian Parry, Tom Krebs, Andre Semmler, Timo Teräsvirta, Kira McDonald, and colleagues and students at The New School for discussions, comments, and important insights.

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Foreword

Climate disasters are occurring with ever higher frequency, threatening the lives and livelihoods of millions of people worldwide. Climate risks not only cause sudden economic and social destruction, but can push countries onto a lower-growth path characterized by greater financial instability, fiscal constraints, and poverty traps. This is especially true for more vulnerable developing countries, many of which have been hardest hit by the economic impacts of COVID-19.

In responding to the threats of global warming and climate risks, governments must use a full suite of tools. Fiscal policy can play an essential role. This report makes an important contribution to our understanding of which fiscal policies work best and can be a guide to policy makers as they consider the most effective ways to achieve a low-carbon future. The report finds clear evidence that green bonds can support carbon taxation by acting as a bridge financing instrument, smoothing the path toward a low-carbon transition and overcoming financial market practitioners' and governments' short-termism.

These findings are particularly timely as governments worldwide are looking for ways to recover and rebuild from the devastating impacts of COVID-19. In preparing for a post-COVID world, it is essential for countries to achieve lasting economic growth without degrading the environment or aggravating inequality. Making the right investments now through stimulus and recovery programs can lay the foundation for a sustainable, inclusive, and resilient recovery. The World Bank Group is working closely with partner governments in this essential effort, linking short- and long-term solutions with the opportunity to build a greener future.

The need for green fiscal policy solutions is clear. Though much empirical research is still ahead, I hope this report will provide a good foundation for understanding the potential of complementary fiscal instruments in building a green, resilient, and inclusive future for all.

Marcello Estevão
Global Director, Macroeconomics, Trade & Investment
World Bank

Executive Summary

Global warming, climate disasters, and climate transition risks can move the economies of both advanced and developing economies onto a lower-growth path with greater financial instability and volatility of returns, and a rise of stranded assets (Carney, 2018; Bolton et al., 2020). This is especially true for more vulnerable developing countries. Climate-related disaster risks, such as extreme weather events, may cause not only sudden economic and social destruction but also long-lasting poverty traps and major challenges for fiscal policy. Climate change may also impact financial markets in the medium term by increasing the volatility of commodity and asset prices and creating the potential for "stranded assets" (Carney, 2018). In particular, carbon-intensive securities like fossil fuel energy-based assets may likely affect stock prices, bond markets, and the stability of the banking system. Oil prices are now—and likely to become again—extremely volatile, covary with important macroeconomic variables, and impact financial markets (Hamilton, 1983, 2010; Kilian, 2009).

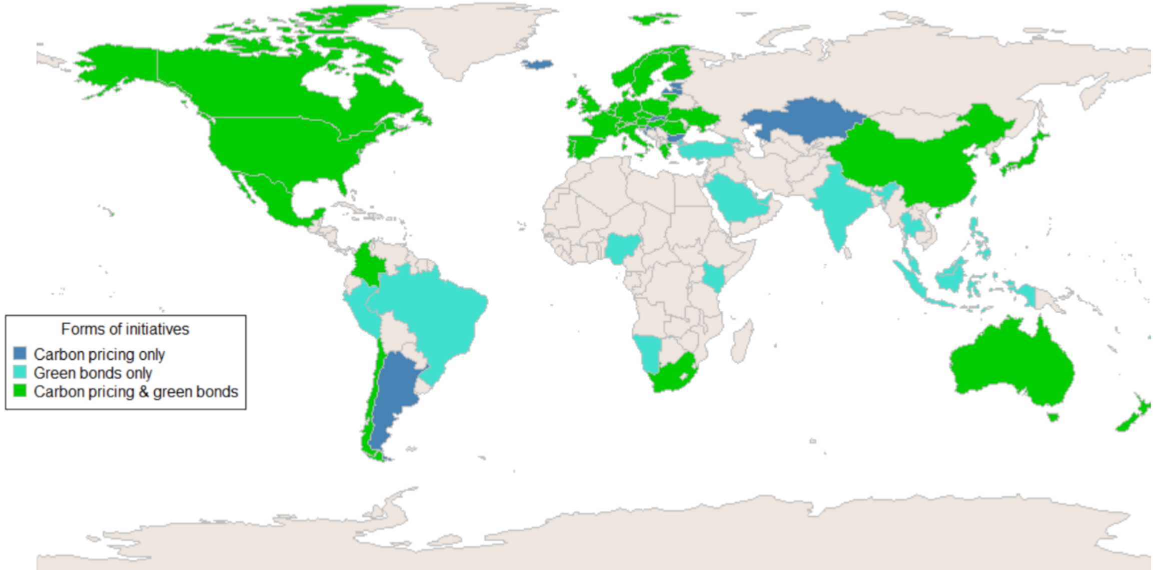
One way to avoid such disruptions is to use fiscal, monetary, and climate policies that allow for a smoother transition to low-carbon economies. It is by now well known that some long-run negative externalities associated with carbon-intensive sectors and assets are frequently not priced into the cost of these goods and services. Conversely, there are positive externalities associated with active climate policy and green investments that impact production and employment potentials and may affect long-run asset returns and investors' behavior and preferences (Semmler et al., 2020).

Fiscal policy tools have recently come to the forefront of climate policy discussions, in particular carbon taxation and green bonds. A vast amount of literature has discussed the benefits of both instruments; this report builds on this literature and argues that it is advisable to use them in combination. The use of Pigouvian carbon taxation addresses negative externalities associated with high-carbon activities, but it also generates other social and macroeconomic co-benefits (Nordhaus, 2008; Acemoglu et al., 2012; Parry, Heine, & Veung, 2014). However, carbon taxation at its current scale is not sufficient to generate the amount of resources and incentives required for the climate transition (Lagarde & Gaspar, 2019). Green bonds can provide supplemental resources that allow the scale-up of low-carbon operations and permit a fairer, Pareto-improving approach to fiscal policy, with future generations benefiting from green investments as well as sharing in their costs (Sachs, 2015; Flaherty et al., 2017).

Figure ES.1. Monthly Annual Oil Price Changes, January 2011–March 2020 (in percentage points)

Source: Author calculations based on International Energy Agency data.
Note: The blue line indicates changes in annual oil price (based on the European Brent oil spot price). The red line indicates harmonic estimations of oil price changes, which capture low frequency movements before and after oil price shocks.

Figure ES.2. Countries Where Carbon Pricing Initiatives* Were Implemented and/or Green Bonds Were Issued



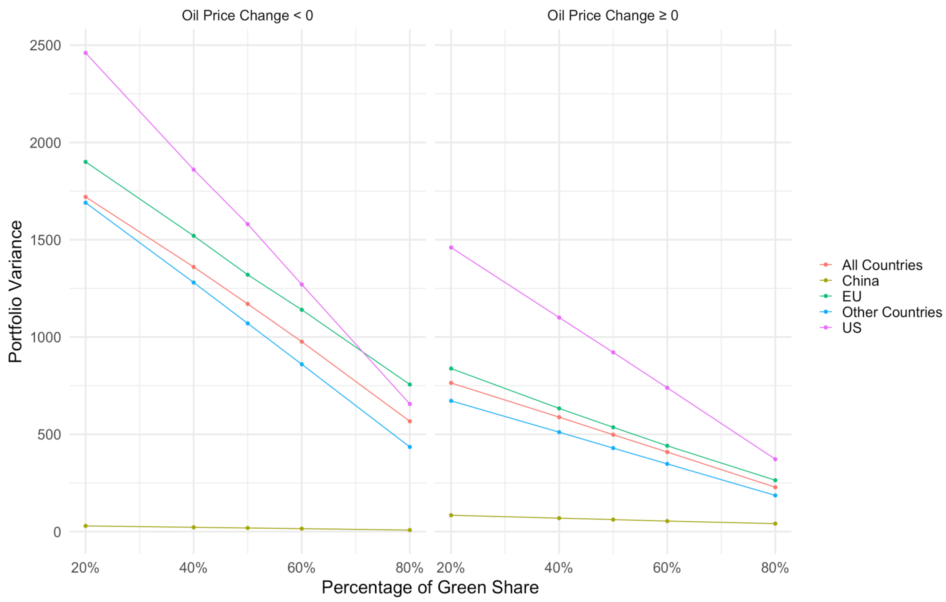
Source: Bloomberg Terminal data and World Bank Carbon Pricing Dashboard.
Note: Carbon pricing initiatives implemented as of October 2020. Green bonds issued between January 2017 and October 2020.
*In the United States, carbon pricing initiatives were implemented in several states, but not nationally. In certain countries, carbon pricing initiatives were implemented on national and subnational levels (for example, Canada, China, and Mexico).

The use of carbon taxation in combination with green bonds creates additional positive interaction effects, particularly in financial markets (Gevorkyan et al., 2017; Heine et al., 2019). Recent macroeconomic theories provide us with important guidance for climate policy and point out the relevance and benefits of combining carbon taxation with green bonds. While carbon taxes can facilitate a low-carbon structural change of the economy in the long run, they also face political hurdles; green bonds can mobilize resources and provide complementary incentives for low-carbon transitions when carbon taxes do not rise sufficiently. Mixing green bonds and carbon taxes also makes green debt sustainable, supports the technological development and improved efficiency of renewable energy, increases overall welfare, and helps policy makers avoid poverty traps caused by climate-related disasters.

This report finds that green bonds can support carbon taxation by acting as a bridge financing instrument, smoothing the low-carbon transition path, and overcoming financial market practitioners' and governments' myopic behavior. However, this approach depends on attracting private investors to green bonds and removing financial market roadblocks to green investment (see Semmler et al., 2020). If investors are impatient and discounted future payoffs are below the investment cost, they will not take on green investments. Thus, short-termism and negative externalities not internalized in asset price formation will create roadblocks to better climate protection investments, potentially leading to a "tragedy of the horizon" (Carney, 2018). This prevents green investments from easily taking off, constrains public climate policy, and increases risks for financial market investors. Further analysis of green asset performance is needed for a better understanding of the incentives for and roadblocks to green investment.

Expanding sustainable practices in real economic sectors requires increased climate awareness in the financial sector. As with any borrowing for real investment, there are innovation, market, operational, and credit risks involved in green investment. Though Merton (1974) provides a fundamental theory as to how corporate bonds' risk structure should be analyzed, the practical study and management of corporate and sovereign bond risk have become a wide field of research. Recent theoretical and empirical studies offer preliminary evidence that green bonds can de-risk investments and thus reduce capital costs for the transition to a lower-carbon economy by exhibiting lower yields (see, for example, Kapraun & Scheins, 2019), lower volatilities, and better risk-return profiles (Han & Li, 2020). Furthermore, a larger share of green bonds may lead to a de-risking effect on portfolios, especially when oil prices fall.

Figure ES.3. Portfolio Variance of Different Shares of Green and Fossil Fuel Bonds



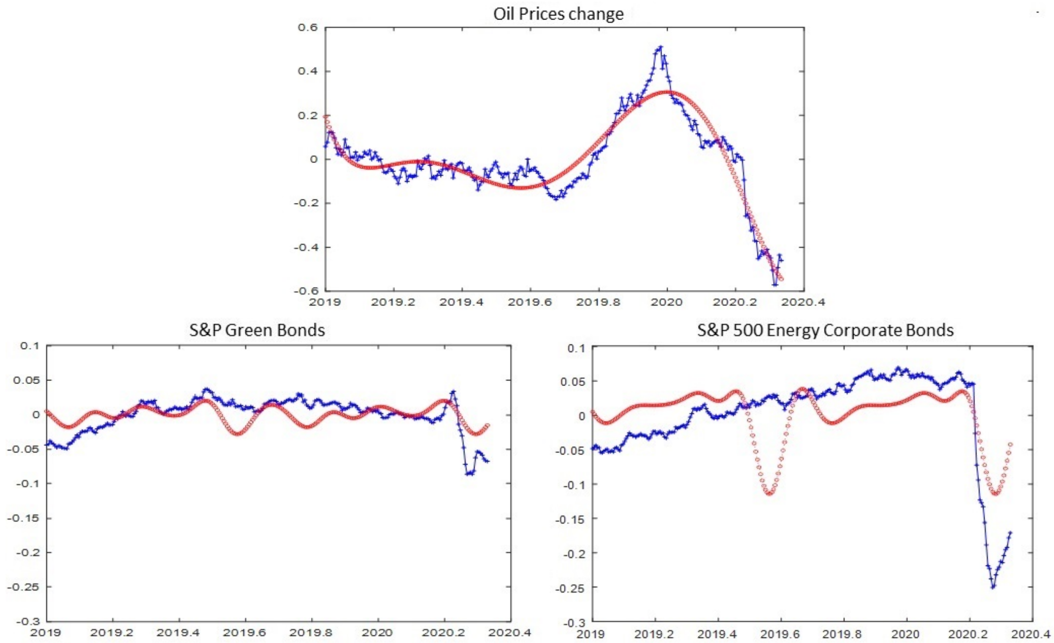
Source: Author calculations based on Standard & Poors data.
Note: As the percentage of green bonds in a portfolio increases, portfolio variance decreases. EU = European Union, US = United States.

This finding is also in line with the tentative results of an analysis of paired green and conventional bonds (see appendix A). Our regression method suggests a negative green premium in the primary market; that is, green bonds tend to have lower yields than conventional bonds and a higher reward-to-risk ratio in the secondary market. However, these findings do not hold for all types of green bonds as different investors, sectors, and currencies show different effects. Furthermore, the analysis of green bonds should be read with care since the market is still small and highly illiquid, which makes the analysis of these market patterns challenging and the results not robust. Further studies are needed and results should be updated as more data become available and as the green market evolves.

Even if green bonds do not experience better market conditions in the present, that does not necessarily mean they are not attractive: Fiscal and monetary policy can influence a securities' attractiveness, and in dynamic portfolios green bonds will likely be socially more profitable in the long run since they fund low-carbon activities. Market externalities and climate risks are exerting a growing influence in investment decisions, with financial market practitioners increasingly taken them into account. Also, in some countries, governments have acted to address these externalities by implementing fiscal and monetary policy tools to change the relative attractiveness of green and fossil fuel assets. Even if investors do not account for climate risks, governments can boost climate finance assets' relative returns with, among other mechanisms, tax incentives for green bond issuance (or for low-carbon projects and sectors) and carbon taxes on carbon-intensive assets (or for brown projects and sectors).

This report finds that green securities are an important fiscal policy instrument that can protect governments and investors in particular against oil price volatility during business cycle fluctuations and against adverse macroeconomic regimes. The analysis shows higher volatility for conventional rather than green bonds, but also that bonds issued by energy sector firms are generally associated with higher volatilities than bonds from other sectors. The correlation of macroeconomic regimes and oil prices also raises the question of whether green bonds are better than conventional instruments to fund a green recovery plan. Oil prices are dependent on macroeconomic regimes and thus are drivers of financial markets—and even sovereign risk—and those fluctuations strongly impact fiscal space. Our analysis finds that swings in the volatility of oil prices spill over to conventional and fossil fuel–based securities, while green securities are relatively insulated from such impacts. Green assets can thus help investors hedge against risk from oil price volatility.

Figure ES.4. Oil Prices and Bond Index Returns, January 2019–April 2020 (in percentage points)



Source: Author calculations based on Standard & Poors data.
Note: These figures compare the volatility of returns for each index with oil price changes. For more details on the relationship between each index's volatility and oil prices, see appendix D.

These findings provide us with reasonable lessons for not only private investment but also fiscal policy under different economic regimes, including the current scenario of a COVID-19 pandemic-driven recession. Issuing green bonds, in conjunction with carbon taxation, is especially important to fund a green stimulus under the current business cycle regime, which is characterized by negative growth rates associated with very low sovereign bond yields (Kemfert et al., 2019; Blanchard, 2019). The economic scenario following the COVID-19 crisis was also characterized by a strong decline in oil prices accompanied by great losses in the value of fossil fuel–related assets. We argue that a green recovery plan, focused on green investments that impact production and employment potentials and possibly affect asset returns and investor behavior and preferences in the long run, could also help improve governments' financial debt profile and tackle both climate-related risks and the risk of moving on to a long-term, low-growth path. This policy combination also has advantages for private small-scale financial investors and large institutional investors, who can include green bonds in their portfolio as a hedging instrument against possible future stranded assets.

The challenge is how to balance green bonds, carbon taxation, and other instruments. Some countries face less fiscal space or more constraints to accessing the credit market. Such countries are also more vulnerable to climate risks and are already more severely affected by the COVID-19 crisis. Since they must have access to funding for rescue and recovery policies, there is a need for early debt forgiveness, debt restructuring, and new financial instruments such as green convertible bonds or climate-to-debt swaps. Though much empirical research is still ahead, as appropriate data slowly emerge, we hope to provide a better landscape of the fiscal policies required for the transition to a low-carbon economy.

Acronyms

BICS	Bloomberg Industry Classification Systems
BNDES	Brazilian Development Bank
bps	basis points
CAPM	capital asset pricing model
CART	classification and regression tree
CO_2	carbon dioxide
DICE model	dynamic integrated model of climate and the economy
EIB	European Investment Bank
ESG	environmental, social, and governance
ETS	emissions trading system
EU	European Union
GDP	gross domestic product
GHG	greenhouse gas
HCIS	high-carbon-intensive sector
IAM	integrated assessment model
IPCC	International Panel on Climate Change
KfW	German Development Bank
LVSTAR	logistic vector smooth transition autoregressive
NDC	Nationally Determined Contribution
NMPC	nonlinear model predictive control
PM2.5	fine particulate matter
R&D	research and development
SAR	special administrative region
SUR	seemingly unrelated regression
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
VaR	value at risk
VAR	vector autoregression
YTD	yield to date

All dollars are US dollars unless otherwise indicated.

1 Introduction

Global warming, extreme weather events, and climate disasters can not only cause sudden economic and social destruction; they can also cause long-lasting poverty traps, move the economy toward lower-growth regimes, and create major challenges for fiscal policy. Climate disaster risks and extreme weather events affect production, employment, and household welfare, as well as create climate-related financial risks. At the same time, the transition to a low-carbon economy entails economic and financial instability risks. It is thus imperative to find macroeconomic climate policy approaches to facilitate the transition to a low-carbon economy while minimizing economic and financial instability and improving resiliency against climate risks.

This report analyzes how two types of fiscal policies—carbon taxation and green bonds[1]—should be combined to enable a smooth transition to low-carbon growth. There are, of course, other policies to protect the climate (such as regulations and standard-setting), but we focus on how these two types of fiscal policies can raise revenues while providing environmental and welfare benefits, improve intergenerational equity, and reduce countries' vulnerability to potential financial disruption. We also provide important lessons for green fiscal recovery policy after recessions, like the current COVID-19 pandemic-driven one.[2]

Climate disaster risks and climate extreme events have wide-ranging impacts across multiple dimensions of the economy. We study climate fiscal policies from a macroeconomic perspective, where success depends on varying macroeconomic circumstances across countries, time, and business cycle regimes. Since carbon taxation and green bonds have complementary interaction effects, these policies should be analyzed together to consider how they can mobilize real and financial investments. It is also important to evaluate to what extent green bonds can be absorbed by the financial market when issued. Such macroeconomic and financial market perspectives are needed to explore how countries can avoid "stranded assets" and other climate-related financial risks.[3]

Green fiscal policy has increasingly relied on carbon taxation and green bonds because of the benefits of combining both instruments. The use of a Pigouvian carbon tax addresses the negative climate externalities associated with private activities, but it also generates other important co-benefits.[4] However, at the current scale, carbon taxation alone cannot deliver the amount of resources and incentives required to meet the challenges of climate protection.[5] The combined use of carbon taxation with green bonds, however, can help meet the financing needs of the green transition as well as create positive interaction effects, and it should be encouraged.[6] The green bond market has sharply increased in recent years, but future strategies should

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[1] Carbon taxation refers to a tax on greenhouse gas (GHG)-intensive goods, services, and activities based on the amount of emissions generated, usually per unit of output. Green bonds are fixed income securities (usually certified by a third party) that leverage large-scale resources through financial markets for investment in sustainable projects. An external certification guarantees that the proceeds are used for sustainable projects only, such as renewable energy, green buildings, and clean transport. The European Union (EU) has provided a classification scheme of green investments (see the EU taxonomy for sustainable finance, http://ec.europa.eu/info/business-economy-euro/banking-and-finance/sustainable-finance_en).

[2] The COVID-19 economic crisis triggered a debate on the importance of building a green recovery plan. Hepburn et al. (2020) performed a survey of government officials and economic experts and find high support for this type of policy. Kemfert et al. (2020) outline a similar proposal for a green deal for Europe under the current crisis. Such a proposal was also included in public sector agendas in organizations like the UNDP (2020), the European Council (2020), and the UN Regional Commissions (ECA et al., 2020).

[3] The financial market is often described as dominated by short-termism (Davies et al., 2014), getting caught by sudden shifts (that is, stranded assets), unpredictable transition risk, and financial instability. See Carney (2018) and Bolton et al. (2020) for more details.

[4] See Nordhaus (2008), Acemoglu et al. (2012), and Parry, Heine, & Veung (2014).

[5] See Lagard & Gaspar (2019) and Mazzucato (2016).

[6] See Heine et al. (2019).

increasingly mix carbon tax implementation and green bond-financed investment with a public sector de-risking strategy to support the continued performance of green bonds in the financial market.[7]

Carbon taxes and green bonds can provide both the incentives and means to make industrial, transport, and service sectors less carbon-intensive, leading toward a low-carbon economy. Most countries can effectively use carbon taxes or feebates[8] combined with green bonds to improve their resilience against future climate disasters. This is true even for countries with a comparative advantage in carbon-intensive industries; this policy combination makes these economies less exposed to real shocks,[9] as well as shocks from the financial side. Such shocks can create not only stranded assets but also "stranded nations."[10] The adoption of carbon taxation today can reduce physical climate risk as well as diminish the macroeconomic impacts of a future fall in carbon-dependent asset prices by helping investors progressively shift to green assets. Thus, for the financial system, proper carbon pricing (that is, through carbon taxation, cap-and-trade schemes, and the removal of fossil fuel subsidies) will lead to a greater uptake of real green investment by making green assets more profitable compared to conventional or fossil fuel bonds and therefore increasing demand for green bonds.[11]

Thus, carbon taxation and green bonds improve the resiliency of not only the real side of the economy but also financial markets. Policy makers can use fiscal policies in such a way to de-risk financial flows, especially through the scaling up of green bond issuance. These instruments also affect the intergenerational distribution of the costs and benefits of climate policies and can allow for a fairer transition to a low-carbon economy. However, the combination of carbon taxes and green bonds might also affect sovereign debt and borrowing conditions; therefore, we analyze under what conditions green debt issuance can be kept sustainable. This is an important issue since some countries have relatively less fiscal space than others.

There is initial evidence that green bonds have certain advantages in terms of stability over other securities that are closely linked to fossil fuel energy prices. We find preliminary empirical evidence of co-movements between oil price fluctuations and fossil fuel–related security returns. Those shocks and co-movements are associated with lower-growth regimes and exert spillover effects on financial markets and portfolio performance. They have a particularly strong impact on oil-producing countries. A fall in oil prices tends to decrease these securities' returns and increase risks. Since oil prices are extremely volatile, they covary with the business cycle, have adverse macroeconomic effects, impact financial markets, and require certain countercyclical policy measures.[12] We present theoretical and preliminary empirical studies that show green bonds have lower volatilities than fossil fuel and conventional bonds and can have lower yields[13] and higher Sharpe ratios than conventional bonds, depending on the issuer's and project's profile and sector.[14] This initial empirical evidence should be read

[7] See Braga et al. (2020).

[8] For example, taxes on carbon dioxide (CO_2) emissions combined with output-based rebates, see Parry, Heine, Li & Lis (2014).

[9] On the impact of real disaster shocks, see Mittnik et al. (2019).

[10] Oil-dependent countries may face continuous growth forecast disappointments associated with higher risk and asset volatility; see Cust & Manley (2018) and Cust & Mihalyi (2017) for more details.

[11] We use the term "conventional bonds" to refer to all bonds not labeled as green according to our Bloomberg data set. We use the term "fossil fuel" (or "carbon-intensive") to refer to securities issued by firms in the energy sector, based on the Bloomberg Industry Classification Systems (BICS) level 1, that mainly operate fossil fuel energy facilities. It includes the following BICS level 2 sectors: coal operations, exploration & production, integrated oils, pipeline, and refining & marketing.

[12] See Hamilton (1983) and Killian (2009).

[13] We add to burgeoning research that has already found evidence of the benefits in issuing green bonds, evaluating variables such as asset price, yields, and the demand from long-term environmental, social, and governance (ESG) investors. See Climate Bonds Initiative (2018), Bachelet et al. (2019), Kapraun & Scheins (2019), Zerbib (2019), Fatica et al. (2019), Flammer (2018), Baker et al. (2018), Karpf & Mandel (2018), Partridge & Medda (2018), Nanayakkara & Colombage (2019), and Hachenberg & Schiereck (2018).

[14] See also Wang et al. (2013), Naifar & Al Dohaiman (2013), and Phan et al. (2014).

with some care because of the market's low liquidity; future comprehensive empirical studies will be needed as the market develops and grows.

Initial evidence also indicates that green bonds can protect governments and investors against oil price changes during business cycle fluctuations and low-growth macroeconomic regimes. We run harmonic estimations and regression models for oil prices and various securities,[15] finding strong evidence that the swings in the volatility of oil prices mainly spill over to conventional and fossil fuel–based securities, favoring the holdings of green assets as a more stable security. We use a static portfolio theory and a capital asset pricing model to determine the correlation between green and fossil fuel bond yields when oil prices change. We find that as the percentage of green bonds in a portfolio increases, the variance of returns decreases, allowing portfolio de-risking. We also apply a nonlinear logistic vector smooth transition autoregressive model (LVSTAR) followed by several linearity tests and impulse responses. We observe that regime changes significantly impact conventional energy bond returns far more than green bond returns. These findings are especially relevant given the current economic downturn triggered by the COVID-19 pandemic. This latest recession and the price crash of oil and related assets suggest that there is space for additional climate-oriented fiscal policy embedded in an economic recovery program.

This report is structured as follows: Chapter 2 presents a global overview of the current state of climate policies, including countries' experience in implementing carbon taxation and green bonds. Chapter 3 discusses the role of carbon taxation and the additional importance of green bonds as complementary and as a bridge finance instruments. Chapter 4 focuses on how those issues are included in existing macroeconomic models, and to what extent recent macro models can be used as guidance for climate policy decisions. Chapter 5 discusses whether the financial market can be seen as a roadblock to green investment or can instead support the issuance of green bonds for policy makers and climate-oriented investors. We present empirical literature reviews of green bonds and their performance compared to conventional bonds in volatility, yields, and Sharpe ratios, among other indicators.[16] We also explore whether green bonds are useful to constrain portfolio risks. Chapter 6 looks at the proper mix of carbon taxation and green bond issuance with respect to business cycle regimes, in particular the importance of green bonds as a countercyclical tool to overcome the 2020 pandemic-driven recession. Chapter 7 offers some concluding remarks. An extensive set of appendixes provides the technical background of our modeling and statistical work.

[15] We use (a) conventional stock market indexes (S&P 500 Index and S&P Energy Select Sector; the latter includes only the S&P 500 firms that operate in the energy sector), (b) a green equity index (S&P Global Clean Energy), (c) a conventional energy bond index (S&P 500 Energy Corporate Bond Index), and (d) a green bond index (S&P Green Bonds Index).

[16] In appendix A, we provide preliminary empirical evidence on green bond market performance measures based on our suggested framework, which could be used by an interested researcher on those or similar topics. Since the green bond market is still evolving and illiquid, these studies should be updated as the market grows, and the current results should be read carefully.

2 Global Overview of Carbon Pricing and Green Bond Policy

The world is increasingly aware of the potential risks and impacts of rising atmospheric concentrations of greenhouse gas (GHG) emissions.[1] Tackling climate change will demand an extensive amount of financial, human, and technological resources for investments in mitigation and adaptation worldwide.[2] Since the establishment of the Kyoto Protocol in the 1990s, many countries have committed to emission targets and implemented carbon pricing mechanisms. After these initial developments, the United Nations Framework Convention on Climate Change (UNFCCC) brought climate finance to the forefront of international discussions. The UNFCCC was followed by a new wave of international climate agreements to mobilize the public and private sectors and develop new financial tools.

This wave of international agreements resulted from increasing concerns that climate change would lead to social welfare losses and negative impacts on the private sector and financial markets. If economies and financial sectors are strongly carbon-dependent, major structural changes and disasters can generate substantial losses and create instabilities and constraints for financial markets and the larger economy, creating a "climate Minsky moment" (Carney, 2018). While the COVID-19 pandemic cannot be classified as a climate disaster, it nonetheless represents an example of a natural disaster that helps us understand the potential future economic and social impact of climate-related negative externalities (Pereira da Silva, 2020). Indeed, climate change may lead to even more extreme financial, physical, and transition risks (TCFD, 2017).

The risk of substantial losses and instability from climate-related impacts is especially relevant if we consider the extreme volatility of oil prices, which can strongly impact oil-dependent businesses, exports, and securities. Governments have increasingly used climate policy instruments like green bonds and carbon pricing to mitigate these and other risks. In this chapter, we review country experiences in implementing carbon pricing and green bonds and present an initial discussion on the global use and benefits of issuing green bonds for fiscal policy and financial markets.

2.1 Carbon Pricing and Green Bonds across Countries

Policy makers have already begun to respond to the risks imposed by global warming by implementing climate policies such as carbon pricing and green bonds. This movement has been supported by international organizations that provide technical information on the urgency of mitigation and adaptation policy and facilitate international agreements and policy recommendations.[3] Carbon pricing and green bonds are important components of prescribed policies to mitigate climate change and scale up green investments. Carbon pricing initiatives internalize carbon emission costs into private decisions and can be implemented by a tax on carbon emissions and/or a cap-and-trade scheme.[4] Green bonds are fixed income securities (usually certified by

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[1] See the Intergovernmental Panel on Climate Change (IPCC) for an overview of some of these effects.

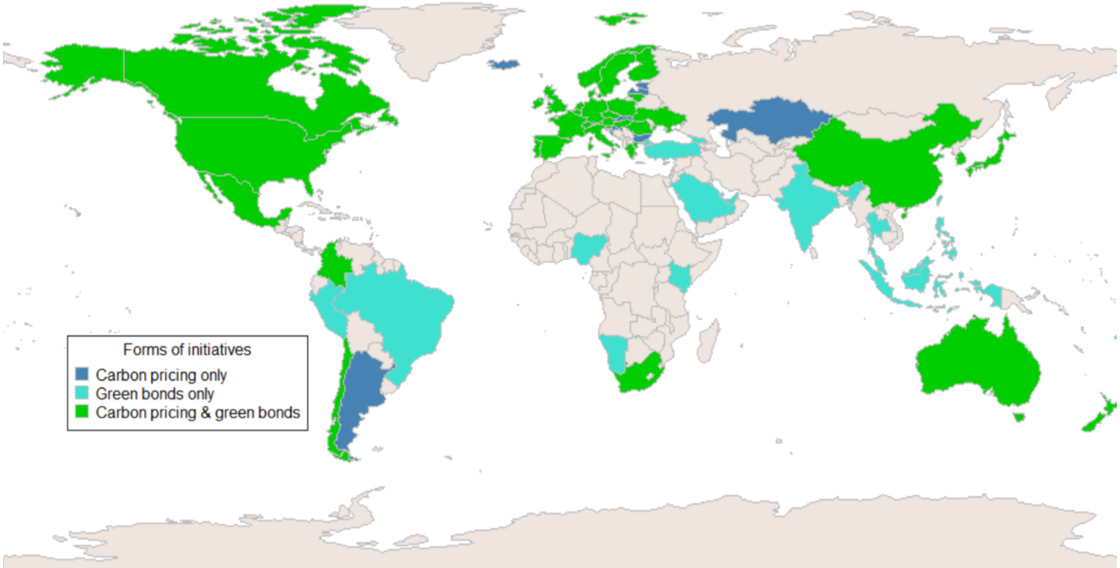
[2] Mitigation refers to efforts to mitigate global warming. Abatement refers to efforts to decrease carbon emissions. Adaptation refers to a preventive policy to avoid or manage the effects of climate disasters.

[3] We should emphasize the role of the UNFCCC in fostering domestic and multilateral climate policy through Nationally Determined Contributions (NDCs). For a better understanding of the timeline of international climate initiatives, see https://unfccc.int/timeline/. Furthermore, the IPCC provides key scientific information for policy makers on the risks of global warming and the need for mitigation policy; see https://www.ipcc.ch/reports/.

[4] Carbon taxation imposes a tax on GHG-intensive goods, services, and activities. An emissions trading scheme (ETS) works as a cap-and-trade policy, under which a cap is set on the maximum amount of emissions allowed, allowances are allocated to private agents, and emissions rights are sold in a carbon market.

a third party) that leverage large-scale resources through financial markets for investment in sustainable projects.[5] The use of both carbon pricing and green bonds has increased (Heine et al., 2019; see also figure 1); however, the price of carbon, the number of green bonds issued, and emission coverage differ between countries.[6]

Figure 1. Countries Where Carbon Pricing Initiatives* Were Implemented and/or Green Bonds Were Issued



Source: Bloomberg Terminal data and World Bank Carbon Pricing Dashboard.
Note: Carbon pricing initiatives implemented as of October 2020. Green bonds issued between January 2017 and October 2020.
*In the United States, carbon pricing initiatives were implemented in several states, but not nationally. In certain countries, carbon pricing initiatives were implemented on national and subnational levels (for example, Canada, China, and Mexico).

Many countries worldwide have implemented carbon pricing,[7] using different approaches, including distinct operational models and coverage and price levels. Historically, governments have tended to prefer an emissions trading system (ETS) (see table 1). Among high-income countries, ETSs cover around 13 percent of global GHG emissions, while carbon taxation covers 3.6 percent. These efforts are mostly concentrated in Europe and Central Asia or North America—continents responsible for more than 30 percent of annual global emissions and 50 percent of the cumulative GHGs in the atmosphere (Ritchie & Max, 2019). Of note, although we find that North America has a relevant number of regional ETS initiatives, carbon taxation among European countries and the European Union ETS has a greater impact in terms of coverage and price level.[8]

Table 1. Carbon Taxation and ETS Initiatives by Country Income Level: Share of Initiatives and GHG Emissions Covered, 2020

	Carbon taxation	ETS	Total*

[5] The external certification guarantees that the proceeds are used for sustainable projects only, such as renewable energy, green buildings, and clean transport.

[6] For example, among high-income countries, only 16.7 percent of global emissions are covered by carbon pricing initiatives, but these countries represent more than 30 percent of global emissions, leaving a coverage gap of 13.38 percent.

[7] Since the 1990s, 41 countries and the European Union have implemented 84 carbon pricing initiatives at the federal and regional levels, as reported by the World Bank Carbon Pricing Dashboard.

[8] The European initiatives cover 5.8 percent of carbon emissions, while the initiatives in North America operate on a smaller scale, covering only 2.3 percent of emissions. The European Union ETS alone represents 67 percent of this coverage. Europe also has a greater number of carbon taxation initiatives, for example, in Portugal, Spain, Sweden, and Switzerland. Lichtenstein, Sweden, and Switzerland have carbon tax of around $100 per ton of carbon equivalent. North America has a greater number of ETS schemes because of several regional initiatives in Canada (for example, Alberta and Quebec) and in the United States (for example, California and Washington). In North America, the highest carbon price is observed in British Columbia, Canada, at around $30, but this initiative is regionally limited and thus has a very local impact.

Country income classification	Number of initiatives (%)	GHG emissions covered (%)	Number of initiatives (%)	GHG emissions covered (%)	Number of initiatives (%)	GHG emissions covered (%)
High income	32.14%	3.6%	36.90%	13.18%	69.05%	16.76%
Upper-middle income	4.76%	1.50%	16.67%	2.60%	23.81%	4.19%
Lower-middle income	3.57%	0.53%	3.57%	0.00%	7.14%	0.53%
Total	40.48%	5.60%	57.14%	15.80%	100.00%	21.49%

Source: World Bank Carbon Pricing Dashboard.

Note: ETS = emissions trading system; GHG = greenhouse gas.

* 2.38 percent of the initiatives were classified as "Undefined" and are not included in the "Carbon taxation" and "ETS" columns. This table uses the World Bank's country classification by income level. Low-income countries were not included owing to a lack of data.

Among middle-income countries, carbon pricing initiatives cover a relatively large portion of GHG emissions but are concentrated in a few upper-middle-income countries. Among developing countries, carbon pricing initiatives are at initial stages and still rely on low prices. As shown in table 1, lower- and upper-middle-income countries are responsible for around 31 percent of carbon pricing initiatives, which covers about 5 percent of global GHG emissions.[9] Half of this effort is implemented in China, with regional ETS initiatives in places like Beijing, Shanghai, and Hubei.[10] Carbon taxation initiatives in the developing world, while not numerous, are responsible for almost half of the emissions covered by world carbon taxation initiatives, demonstrating a greater relative effort in these countries. However, carbon taxation is still very concentrated in a few countries and initiatives rely on relatively low carbon prices.

Carbon taxation is usually considered the most efficient carbon pricing mechanism, and it can be more easily implemented across a wider range of countries than other pricing mechanisms. Economic models show that carbon taxation is the most efficient carbon pricing mechanism (for example, Nordhaus, 2008; Uzawa, 2003; Hansen, 2015; and Greiner & Semmler, 2008). First, the generated public revenues can be further used to increase positive externalities and address the potential inefficiencies of tax increase (Atolia et al., 2018; Nell et al., 2009; Acemoglu et al., 2012; Parry, Heine, & Veung, 2014). Second, well-designed carbon taxation can make it easy for governments to monitor and tax emissions using existing infrastructure (Heine et al., 2019).[11] This approach may also be easier to manage than a cap-and-trade system based on allowances (Parry, Heine, Li, & Lis, 2014). An ETS is more appropriate for countries with highly developed administrative capacities. The system requires costly investments to establish and maintain, is associated with high volatility of carbon prices, and

[9] Carbon tax initiatives are seen in upper- and lower-middle-income countries with lower emissions levels in Latin America (Argentina and Mexico), Europe (Ukraine), and Africa (South Africa). Mexico's initiative was one of the first in developing countries, starting in 2014. The tax was set at around $3 per ton and covers 0.5 percent of the global carbon emissions, while Mexico emits 1.3 percent of this total (implying an emissions coverage gap of 0.8 percent). Ukraine also pioneered carbon taxes among developing countries: It implemented the reform in 2011, adding a carbon tax of 0.38 percent, which is very low by global standards. South Africa and Argentina implemented the most recent initiatives. In South Africa, the initiative was effectively implemented in 2019 and was set at a higher level (around $8 per ton); it covers around 0.8 percent of the global GHG emissions, while the country represents roughly 2 percent of this total (implying an emissions coverage gap of 1.2 percent). The Argentinian carbon tax initiative was implemented in 2018 and covers 0.15 percent of global emissions (the country's contribution for GHG global emissions is only 0.56 percent) with an effective price of $6 per ton. As these initiatives are recent, it is hard to evaluate their effectiveness. See https://climateactiontracker.org/countries for more details.

[10] This position is compatible with the Chinese emission pattern since China is one of the largest emitters in the world (for example, China was responsible for around 26 percent of global emissions in 2016), but the effort is still incipient. China has been implementing ETS pilots since 2013 with different results among provinces and sectors. On their effectiveness, we should note that like other ETS initiatives, the carbon market activity level varies across regions, implying price volatility and disparities. Furthermore, the effectiveness in reducing carbon emissions also differs because of distinct sectoral coverage and the lack of enterprise participation in certain regions: In these terms, Beijing and Guangdong have been the most successful (Zhang et al., 2019; Liu & Zhang, 2019). Sectors with higher ETS coverage seem to have decreased emissions, while no impact was found on carbon intensity (Haijun et al., 2019); although several firms in China are engaged in carbon trading, few firms are motivated to sell carbon above the legal obligations (Deng et al., 2018). The Chinese experience at a regional level has been used to support the implementation of an initiative at the national level.

[11] Carbon taxes can be collected using the fuel tax systems that most countries already have, reducing the implementation and transaction costs of the policy (Parry, Heine, Li, & Lis, 2014).

relies on political decisions that might generate rent-seeking behavior.[12] Indeed, an ETS demands a strong and complex public structure for allowance management, emission controls, and market regulation that might be costly for middle- and low-income countries. Third, the price volatility associated with an ETS reduces the benefits from combining green bonds with carbon pricing as well as the ability of this policy combination to smooth the transition to a low-carbon economy. In the present report, therefore, our primary focus is on carbon taxation as the carbon pricing mechanism.

Firms and policy makers are increasingly using green bonds to fund green investments, although these efforts represent only a small share of the global fixed income security market and have been restricted to high- or middle-income countries with access to financial markets. Since 2017, green bonds have leveraged more than $800 billion ($269 billion in 2020). This market is growing (see figure 3, in section 2.2) but represents less than 1 percent of the total debt market. Our data also show that most of the issued green bonds are classified as investment grade and short term (table 2).[13] Investment-grade issuers in high-income countries are responsible for the majority of green bond issuance. However, China is also a relevant issuer, and upper-middle-income countries are playing an increasing role in this market.

Table 2. Share of Green Bonds Issued per Country Income Level, January 2017–September 2020

Country income classification	Total bonds	Investment grade share	Long-term bonds share
High income	75.0%	91.8%	95.8%
Upper-middle Income	21.9%	7.1%	3.5%
Lower-middle income	3.0%	1.1%	0.7%
Total	100.00%	51.5%	37.1%

Source: Authors own calculations based on Bloomberg Terminal data.
Note: This table uses the World Bank's country classification by income level.

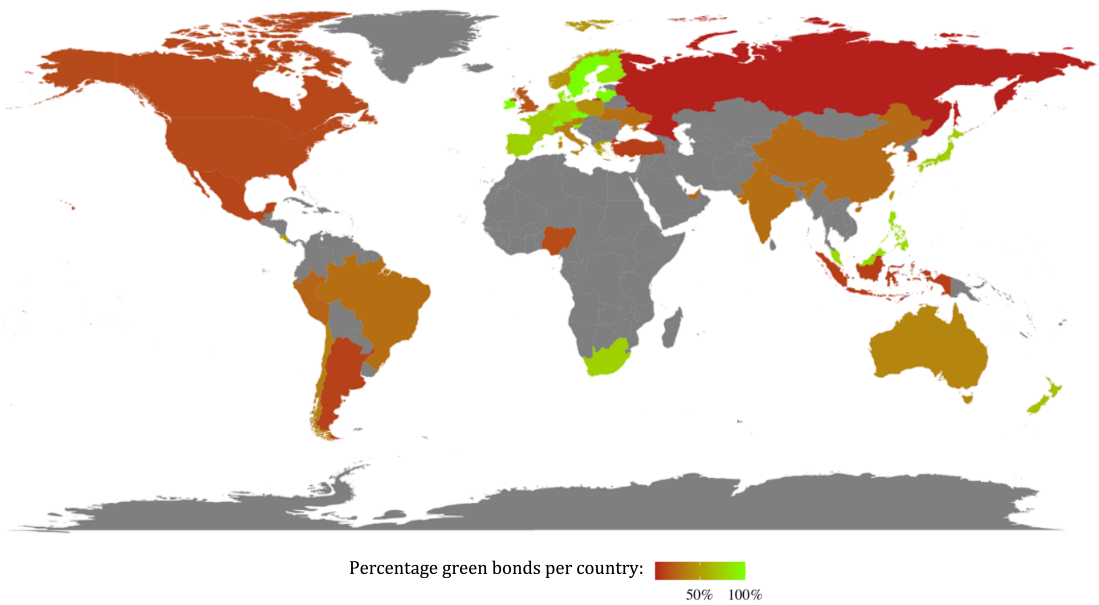
There are also differences in the geographical distribution of green bonds and the relative share between conventional carbon-intensive bonds and green bonds. Figure 2 shows that, besides European countries like Germany, Sweden, and Switzerland (which issue three times more green bonds than fossil fuel bonds), emerging economies such as Malaysia, Mauritius, and South Africa are also issuing a high share of green bonds compared to fossil fuel bonds (that is, twice the amount of green compared to fossil fuel bonds in the countries mentioned). Among developing countries, China is the biggest player in absolute number of green bonds issued; however, figure 2 shows that China still issues four times as many fossil fuel bonds as green bonds.[14]

Figure 2. Global Map of Green Bond Issuance: Relative Share of Green Bonds Vis-à-Vis Fossil Fuel Bonds, January 2010–February 2020

[12] Experiences with ETSs show a high volatility of carbon price associated with speculative investments (Nell et al., 2009; Friedrich et al., 2020). This presents a challenge in contexts of limited administrative capacity, as financial markets within these countries are smaller and less developed. Finally, a cap-and-trade scheme has a high risk of corruption and elite capture in the definition and allocation of allowances, presenting a particular challenge for governments with low governance capabilities. Quantity-type systems like an ETS are more susceptible to such corruption than price-type regimes like carbon taxation, as argued by Nordhaus (2008).

[13] Private firms have issued 55 percent of the total amount; governments at the federal and local level, 35 percent (being sovereign bonds, only 10 percent of the total); and multilateral organizations, 10 percent.

[14] See appendix A, for the total number of green and conventional bonds issued per country.



Source: Author calculations based on Bloomberg Terminal data.
Note: The relative shares of green bonds are calculated by taking the ratio of the total green bonds issued by a country to the total number of green and fossil fuel bonds (that is, non-green energy bonds) issued by that country. Bonds not classified as either "green" or "fossil fuel" are not considered in this total.

There is room to expand the role of the public sector in green bond issuance. An increase in and diversification of the number of green bonds issued by the public sector can expedite the low-carbon transition. Although we observe an increase in the number of green bonds issued by the public sector, we find that green sovereign bonds represent roughly 10 percent of the total market, concentrated in only 10 high- or middle-income countries plus the economy of Hong Kong, SAR, China.[15] Federal governments have also joined this market through development agencies and public banks, representing an additional market share of 10 percentage points.[16] Furthermore, market agents expect 10 more countries to be added to the list of green sovereign bond issuers, including Germany and Spain and oil producers like the Arab Republic of Egypt, Mexico, and Nigeria.[17] In section 2.2, we discuss, based on case studies, how green bonds have been implemented in practice and how they drive real green investment. In section 2.3, we present initial evidence that issuing green bonds may benefit a country's debt profile and financial stability.

2.2 Green Bonds in Practice

Now we turn to some of the challenges and benefits observed as green bond implementation has evolved. We argue that the green bond surge is associated with an increase in green investment and seems to benefit issuers, though this appears to be concentrated in a few sectors and types of projects. Thus, efforts from policy makers are still needed for the wider use of green bonds in different sectors. Obstacles to green bonds' scalability still

[15] According to the Bloomberg green bonds database, from 2010 to February 2020, Belgium, Chile, Indonesia, Ireland, France, Lithuania, Netherlands, Nigeria, Poland, and the Republic of Korea, plus the economy of Hong Kong, SAR, China, have issued green sovereign bonds. The Climate Bonds Initiative also reports green sovereign bond issuance by Fiji and the Seychelles (see https://www.climatebonds.net/2020/02/sovereign-green-bonds-club-mexico-egypt-spain-set-join-who-else2020-pipeline-and-who-else).

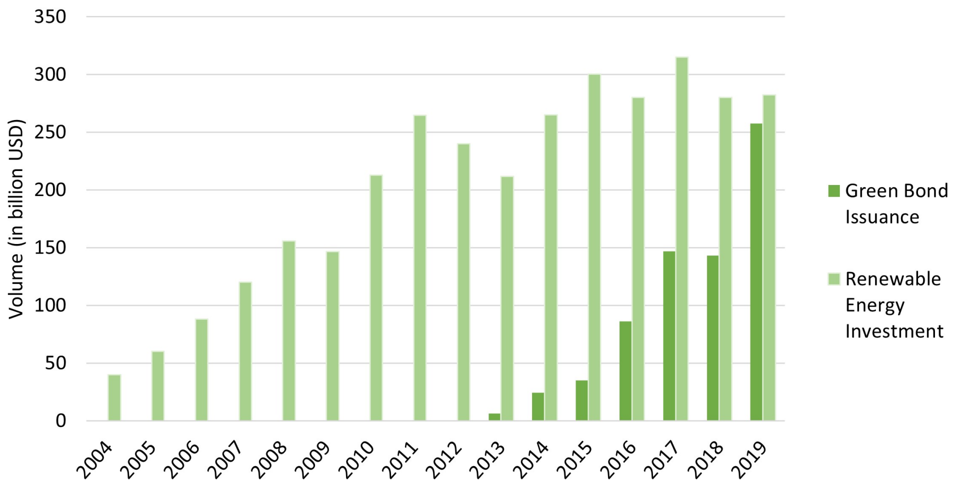
[16] This list includes issuers such as the KfW (Germany), the AFD (France), the China Development Bank (China), the Brazilian Development Bank (Brazil), the Korean Development Bank (Republic of Korea), and export agencies from countries like Canada, China, India, the Republic of Korea, and Sweden.

[17] According to the Climate Bonds Initiative, the prospective green sovereign bond issuers include Colombia, Côte d'Ivoire, Denmark, Egypt, Germany, Italy, Kenya, Mexico, Peru, and Sweden.

exist,[18] but the development of a common green bond framework, improved transparency and market available data (as well as impact assessment and reporting patterns), better definition of the market borders to reduce the risk of greenwashing, and fostering issuance in emerging economies can help address these challenges (Deschryver & de Mariz, 2020). Depending on how policy makers define green projects, green bond issuance may be impacted; adopting broad definitions—such as those found in the "Green Bonds Principles"[19]—can help green bond diffusion. Currently, energy efficiency and renewable energy initiatives appear to be more widely accepted as green projects than clean transport or other investment categories (Kapraun & Scheins, 2019).

Although green bonds are not the only source of funding available for green investments, their wider use should be incentivized. Green projects can rely on a mix of conventional or green funding sources (equity, debt, or tax revenues, for example), and in general funding diversification is beneficial for both lenders and borrowers.[20] Using green bonds to fund green projects is increasing in popularity as investors realize the benefits of these instruments, but green bonds represent less than 1 percent of the total debt market. Since the first green bond was issued in 2008, the green bond market has consistently increased, reaching levels close to total global renewable energy investment (figure 3).

Figure 3. Global Renewable Energy Investment and Green Bond Issuance, 2004–2019



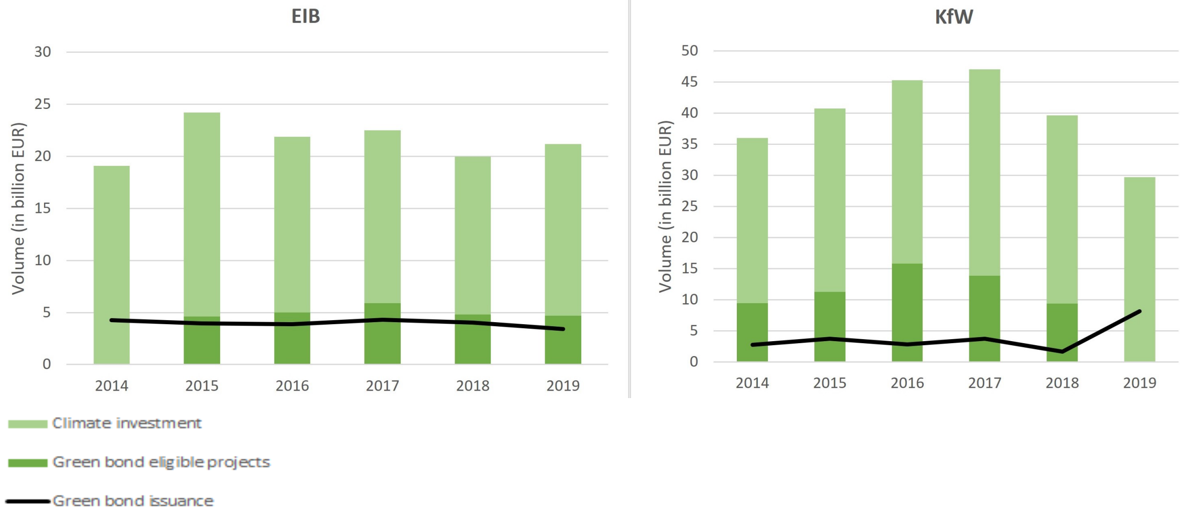
Source: Bloomberg and Bloomberg New Energy Finance.
Note: This plot compares the amount of green bonds issued in financial markets and the level of investment in renewable energy from 2004 to 2019.

The implementation strategy for green bonds varies between issuers. Diversified development banks typically allocate loans based on a more comprehensive or general concept of green investments, but some have narrowed the use of green bond proceeds to specific climate transition programs (see figure 4). The European Investment Bank (EIB) and the German Development Bank (KfW) are two of the largest and most successful issuers in Europe. Since 2014, the KfW has issued €21 billion in green bonds. The proceeds are allocated toward two programs: one for renewable energy investments, the other for energy efficiency projects. These programs provide better loan conditions in comparison with conventional ones. Since 2007, the EIB has issued around €31 billion in "Climate Awareness Bonds." Initially, these bonds were focused only on renewable energy and energy

[18] For example, Deschryver & de Mariz (2020) mention a lack of harmonized global standards, the risk of greenwashing, the perception of higher costs for issuers, the lack of supply of green bonds for investors, and the overall infancy of the market.
[19] See https://www.icmagroup.org/assets/documents/Regulatory/Green-Bonds/Green-Bonds-Principles-June-2018-270520.pdf.
[20] As discussed in Semmler (2011), investors look at return and risk (volatility) but also want to diversify, whereas borrowers need to diversify funding sources when investment needs to increase.

efficiency. In 2019, they included low-carbon technology innovation initiatives and electric transport among the eligible projects. In Latin America, a similar strategy was implemented by the Brazilian Development Bank (BNDES), which focused on the initial use of green bonds in energy projects while setting a diversification strategy for the use of proceeds in the long run.[21]

Figure 4. EIB and KfW: Climate Loans and Green Bond Issuance, 2014–2019



Source: European Investment Bank (EIB) and German Development (KfW) green bond and annual reports.
Note: The data for projects eligible for green bond resources are not available for the EIB in 2014 or for the KfW in 2019. "Climate investment" refers to the total amount of climate projects funded; "Green bond eligible projects" refer to the total amount of eligible projects to be funded by green bonds; "Green bond issuance" refers to the total amount of issued green bonds.

These cases represent a global trend of using green bonds mostly to fund renewable energy and energy efficiency projects, but a diversification effort is also under way. In 2019, 61 percent of green bond proceeds were used for renewable energy or energy efficiency projects (31 percent for renewables and 30 percent for green buildings), 20 percent for transport, and 9 percent for water projects (Climate Bonds Initiative, 2020). However, major issuers have implemented a strategy to allow for investment in diversified projects. In September 2020, the German Treasury issued a €6.5 billion sovereign green bond; among the sectors approved for investment are transport, international cooperation, research and development (R&D), energy and industry, and agriculture and forestry. Since 2017, the French government has leveraged €25.3 billion through green bonds, for use in sectors such as agriculture, clean transport, and energy.[22]

Data for the ex post use of green bond proceeds are still not widely available, which constrains the ability to precisely monitor this trend. In 2020, the Intra-American Development Bank (IDB) released the Green Bond Transparency Platform,[23] which will address this lack of information for Latin America. This type of platform can ease information constraints between investors and issuers and diversify the allocation of green bond proceeds. For the European Union, a diversification trend is likely to follow the release of the EU taxonomy for sustainable finance in 2020.[24] This taxonomy helps issuers and investors select investments with a substantive contribution (and with no significant harm) toward environmental objectives, based on a list of climate-related infrastructure,

[21] In 2017, BNDES issued a $1 billion green bond fully allocated to wind energy projects. In 2020, an additional green security issuance also focused on energy projects, but, according to plans, the next issuance may target additional sustainable objectives.

[22] See the French sovereign bond report: https://www.aft.gouv.fr/files/medias-aft/3_Dette/3.2_OATMLT/3.2.2_OATVerte/Agence%20France%20Tresor_Green%20OAT%20UK.pdf.

[23] See http://greenbondtransparency.com/.

[24] The EIB reports that the new EU taxonomy for sustainable finance influenced their decision to diversify the use of green bonds.

sectors, technologies, and climate performance indicators. As these projects and technologies should be eligible for green bond funding, new issuers are likely to be attracted to the green bond market.

We should note that an increase in and diversification of green bond issuing does not necessarily imply a capital cost reduction in comparison with a similar conventional bond option. This trend is influenced by a variety of other factors, as will be discussed next and later in chapter 5. In 2020, the German Treasury green bond market debuted a twin bond structure: A green bond was issued together with a conventional sovereign security with the same term and coupon to compare their market performance. The green bond was five times oversubscribed; this larger demand implied slightly lower yields at issue (-0.43 basis points [bps], or 1 bps lower than the conventional yield).[25] For other sovereign bonds, the Climate Bonds Initiative (2019) also consistently observes an oversubscription for developing country issuers but does not find a negative green premium at issue for all issuers. For example, they found a green premium for the French and Chilean sovereigns but not for Belgium and Indonesia.

In middle-income countries, there is an increasing number of sovereign green bond issuers and cases for which green bonds have been beneficial in green investment capital costs. In 2019, the Chilean sovereign bond interest rate reached 3.53 percent, the lowest rate for a sovereign Chilean bond with a similar term to maturity.[26] In 2020, Egypt's $750 million sovereign green bond was five times oversubscribed with a yield at issue of 5.25 percent, or 50 bps lower than the opening target.[27] In the past few years, other countries (such as Indonesia, Mexico, and Nigeria) have also issued sovereign green bonds. The potential advantages of green bonds for fiscal policy are further discussed in section 2.3 and chapter 5.

2.3 Improving Financial Market Stability with Green Bonds

Issuing green debt can provide financing for the transition toward a low-carbon economy, generating positive externalities associated with green investment while tackling the negative externalities of carbon-intensive assets (Semmler et al., 2020). There are benefits from investing in green assets even if differences in asset returns are not clearly observed, but supporting the pace of portfolio shifts from carbon to green assets requires a new mindset in financial markets as well as a supply of profitable green securities to investors. On the financial side, there is initial evidence that issuing green bonds may have favorable effects on risk control for asset and portfolio holdings as well as broaden and diversify the investor base.[28] On average, green bond yields might be lower than conventional bond yields, but they are also less volatile, which can increase the attractiveness of green bonds for investors (figure 5). Although views differ on the topic, a growing number of empirical studies confirm those initial findings, but these empirical findings should be interpreted carefully. As the green bond market is still small (particularly for green sovereign bonds—an asset class that has a low probability of default) and highly illiquid (bonds are not heavily traded in the secondary market), empirical analysis of these market movements is challenging. Further analysis of this issue is warranted as the market grows and develops. However, even if green bonds are not priced differently in general, the positive externalities of green investment can benefit investors in the long run (Semmler et al., 2020), as discussed in chapter 5. These features of green

[25] See https://www.bloomberg.com/news/articles/2020-09-02/germany-to-sell-debut-green-debt-as-it-seeks-to-dominate-market.

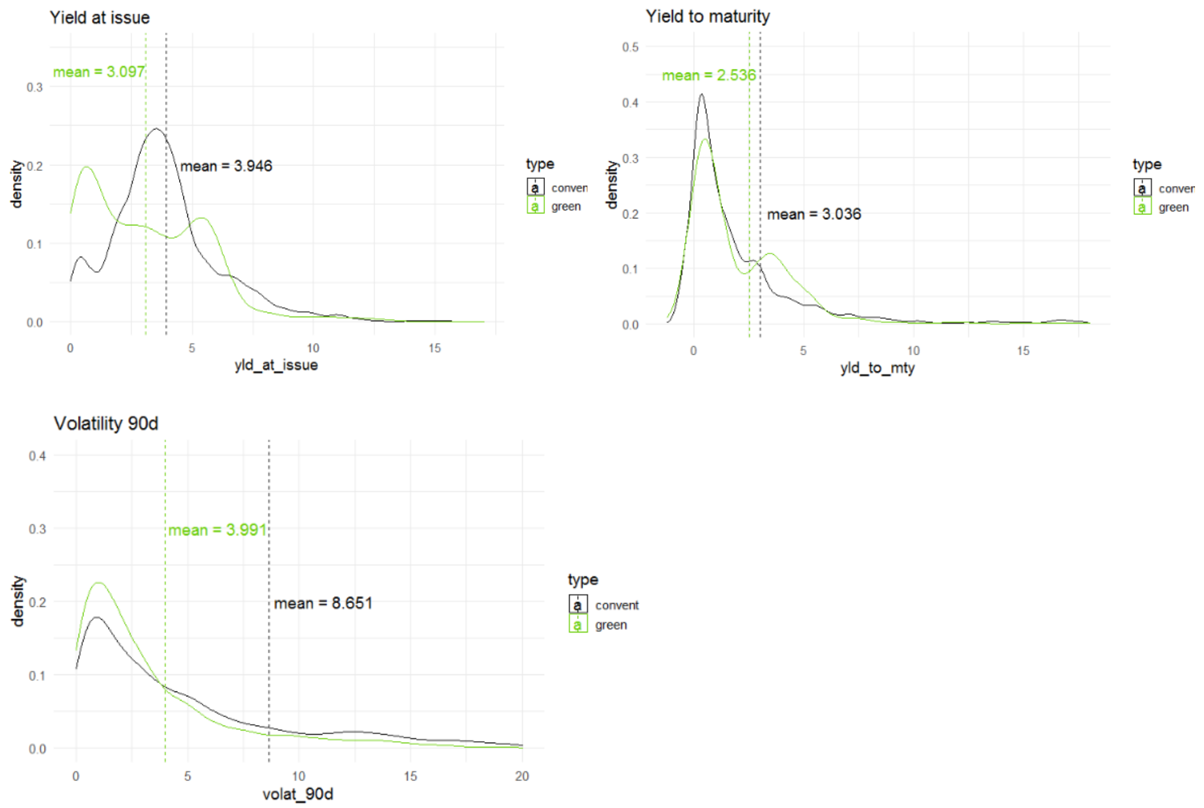
[26] See http://blog.investchile.gob.cl/chile-obtains-historically-low-interest-rate-in-successful-placement-of-its-first-green-bond#:~:text=In%20the%20placement%20of%20Chile's,its%20first%20sovereign%20green%20bond.

[27] See https://renewablesnow.com/news/egypt-issues-1st-sovereign-green-bond-in-usd-750m-deal-715514/.

[28] These benefits are discussed in more detail in chapters 5 and 6.

bonds make them beneficial in particular for fossil fuel–dependent countries because of the high volatility of oil prices and the lower volatility of green securities.

Figure 5. Density Plots for the Yield at Issue, Yield to Maturity, and 90-Day Volatility for Green and Conventional Bonds, 2017–February 2020



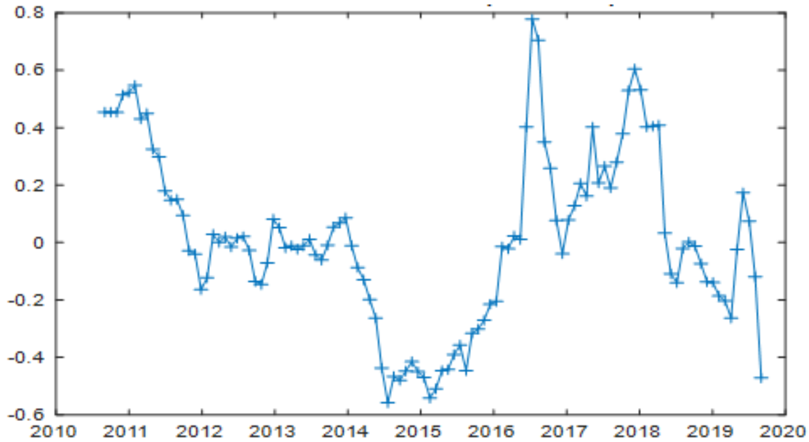
Source: Author calculations based on Bloomberg Terminal data.
Note: This plot shows the distribution of yield at issue, yield to maturity, and volatility for our sample of all green and conventional bonds downloaded from the Bloomberg Terminal. The 90-day volatility is measured with the standard deviation of a bond yield time series for the past three months (from July to September 2020). For volatility measures for 30 and 260 days, see appendix A.4, figure A.3. For a descriptive overview by maturity and rating, see appendix A.4, tables A.5 and A.6.

The oil price is extremely volatile, covarying with the business cycle and impacting financial markets**.** Figure 6 shows how volatile the oil price has been over the past 10 years. Exogenous positive oil shocks can explain recessions since World War II (Hamilton, 1983); however, oil prices are also endogenous to economic growth because increasing oil demand is connected with higher growth rates (Kilian, 2009). These oil price shocks spill over to financial markets and have a particularly strong impact on oil-producing countries and firms: A fall in oil prices tends to decrease security returns and increase risks (Wang et al., 2013; Naifar & Al Dohaiman, 2013; Phan et al., 2014). This macroeconomic effect can create not only stranded assets but also "stranded nations": oil-dependent countries that may face continuous growth forecast disappointments associated with higher risk and asset volatility (Cust & Manley, 2018; Cust & Mihalyi, 2017).

Green bonds can help governments promote productive structural change, improve their access to financial markets, and decrease sovereign bond volatility due to oil price shocks. As oil price shocks spill over to financial markets, climate-related securities outperform fossil fuel assets, at least in recent years. In 2020, after the

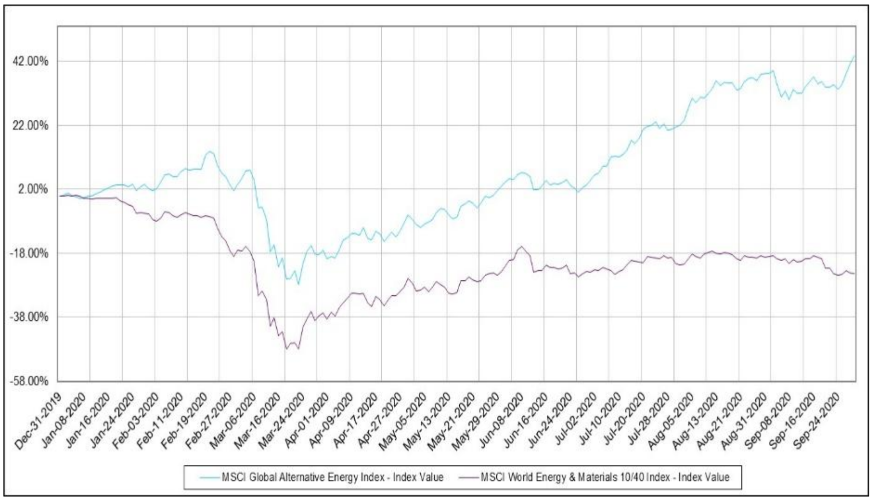
COVID-19 outbreak and a rapid decline in oil prices, green assets seem to have outperformed carbon-intensive assets: The MSCI Global Alternative Energy Index, for example, increased its value by 43.7 percent, while the MSCI World Energy and Materials index lost 24.3 percent of its value (figure 7).[29] This analysis, further elaborated in chapter 6, seems to be associated with the fact that green bonds attract long-term horizon investors, such as pension funds (Cochu et al., 2016; Flammer, 2018; Deschryver & de Mariz, 2020). Green bonds appear to have performed better as a debt instrument with regard to resilience against market fluctuations such as oil price movements. Oil producers' sovereign risks are more affected by these fluctuations as well. In March 2020, non-oil producers' sovereign debt was less impacted by the oil price collapse. On March 24, when the oil price monthly decrease reached 57 percent, the 10-year sovereign bond yields' positive variation was significantly higher for oil-producing countries.[30] These pandemic-driven economic impacts, having a large effect on oil demand, highlight important lessons for climate-oriented fiscal policy in pursuit of both low-carbon consumption and production activities.

Figure 6. European Brent Oil Spot Price Monthly Annual Changes, 2010–2020 (in percentage points)



Source: International Energy Agency.
Note: The y-axis shows annual price changes represented in percentage points (for example, 0.2 represents 20 percent).

Figure 7. Market Performance of Two MSCI Financial Market Indexes, 2020 (%)



Source: S&P Capital IQ.

[29] The MSCI Global Alternative Energy Index includes developed and emerging market companies that derive 50 percent or more of their revenues from products and services in alternative energy. The MSCI World Energy and Materials Index is designed to capture segments across 23 developed markets in the energy and materials industry.

[30] For a sample of 57 countries, including nine oil producers (Brazil, Canada, Colombia, Mexico, Nigeria, Norway, Qatar, the Russian Federation, and the República Bolivariana de Venezuela), we run a t-test to assess the differences between the 10-year sovereign bond yield variation mean for oil producers and non-oil producers. We find a statistically significant difference, as the mean for non-oil producer bond yields is equal to 0.5 percent, and 1.2 percent for oil producer bond yields.

The growing experience in the implementation of carbon taxation and green bond issuance is an important asset to help reshape fiscal policy. Policy makers already have the expertise and tools to move toward green fiscal policy. Conventional bonds seem to be more volatile than green ones and create additional risks for oil-producing countries. Extensive literature points out that a shift toward more green bonds can potentially bring macroeconomic, climate, and financial benefits. Going forward in this report, we improve upon this discussion, providing additional literature, reporting policy experiences, and adding further empirical evidence. In the next chapter, we discuss the key advantages of combining carbon taxation and green bonds.

3 The Benefits of a Mix of Climate Policies

Carbon taxation plays a key role in macroeconomic climate policy approaches. Carbon taxation has been advocated by economists as one of the most effective fiscal mechanisms for addressing climate change because of its ability to affect economy-wide incentives for climate mitigation as well as green innovation.[1] The carbon tax itself aligns economy-wide incentives to cost-effectively steer economic decision-making toward low-carbon alternatives by incorporating negative climate externalities into the costs of private economic agents. Carbon tax revenues can then be used to generate additional positive externalities, such as investments in green innovation.[2] Carbon taxes also create spillover effects in green innovation by ensuring stable low-carbon investment climates and increasing potential returns of low-carbon innovation.

However, carbon taxation should be nested within a comprehensive macroeconomic climate policy package to adequately address other market and governmental failures relating to climate change. Carbon taxation—at the current scale—cannot provide all the necessary climate mitigation and adaptation funding (especially if carbon taxes remain at current low rates).[3] Carbon taxes should be used with complementary policy mechanisms, particularly to promote green innovation and ensure stable fiscal environments. Both of these complementary goals can be achieved through green bonds.

Combining carbon taxation with green bonds allows policy makers to leverage key synergies to speed up the low-carbon transition. When used in combination with carbon taxation, which addresses negative externalities, green bonds may create positive externalities and increase the effectiveness of both policies in lowering the cost of overall mitigation (Heine et al., 2019). Combining carbon taxation and green bonds leverages private sector decision-making to make the transition to a low-carbon economy in a more stable and effective way. This chapter discusses the role of carbon taxation and how policy makers can improve the associated climate and macroeconomic policy outcomes by simultaneously implementing green bonds.

3.1 The Role of Carbon Taxation

The main role of carbon taxation is to correct a key market failure and enhance overall market efficiency. Efficient markets require that prices accurately reflect all costs of a good or service, including the negative externalities generated by these products (Heine et al., 2019; Pigato, 2019). In regard to climate change, burning fossil fuels has global externalities not captured in prices.[4] These climate change impacts carry significant economic costs: Certain estimates place the costs of climate change without mitigation policies between 3 and 10 percent of global gross domestic product (GDP) by 2100 (Kahn et al., 2019; Burke et al., 2015; Tamirisa, 2008;

[1] The fundamental role of carbon taxation is to address market failure and improve market efficiency through better-tuned price signals. Carbon taxation thus provides incentives on multiple frontiers in the economy (for example, investment, production, consumption, and technology), reducing mitigation and future adaptation costs, while at the same time speeding up the transition to a low-carbon economy.

[2] The macroeconomic impacts of carbon taxation will depend on the market structure of the economy in question. For example, depending on the industrial structure of an economy, carbon taxation may positively or negatively impact international competitiveness (Pigato, 2019). Policy makers should be cognizant of managing all the various impacts of carbon taxation through critical design choices, such as decisions regarding the use of revenues.

[3] For example, the International Monetary Fund (IMF) estimates that the gap between current carbon tax levels and the level required to internalize the costs of climate change amounts to more than $5 trillion per year (Lagarde & Gaspar, 2019).

[4] Burning fossil fuels releases gases into the atmosphere that trap heat, contributing to global warming and other physical climate impacts like sea level rise and changes in precipitation.

Stern, 2014). Carbon taxation internalizes these external costs of carbon emissions into the private costs faced by both producers and consumers.

Carbon taxation creates economy-wide incentives for the low-carbon transition by internalizing the external costs of climate change. Carbon taxation places an explicit price on a unit of carbon emissions; goods and services are then taxed based on the amount of carbon embodied in their production. Carbon taxation thus makes carbon-intensive processes and products more expensive than low-carbon substitutes. The new relative prices between carbon-intensive and low-carbon products then create incentives for economic agents to move from carbon-intensive (and therefore more expensive) products to low-carbon alternatives.[5] An upstream tax on the carbon content of fuels, for example, creates incentives for power plants to switch to cleaner inputs and production processes and for consumers to switch to cleaner fuels or more efficient appliances.

Box 1. Carbon Taxation Co-benefits and COVID-19

Carbon taxation provides important development co-benefits alongside its impact on climate change mitigation—in particular, improved health outcomes. As many pollutants are emitted simultaneously with carbon dioxide during production processes, a carbon tax may impact other pollutants beyond carbon. For example, coal combustion produces CO_2, as well as fine particulate matter (PM2.5), sulfur dioxide (SO_2), and nitrogen oxides (NO_X); therefore, a carbon tax that reduces coal combustion leads to cleaner air as fewer local airborne pollutants are emitted. Carbon taxes thus simultaneously reduce the welfare costs from both CO_2 and other, local pollutants (Pigato, 2019). These welfare savings can be substantial and may even outweigh the climate benefits of carbon taxation (Parry, Heine, Li, & Lis, 2014; Parry, Heine, & Veung); for example, Silva et al. (2013) estimate the value of air pollution co-benefits from avoided mortality alone amount to \$50–\$380 per ton of CO_2—a figure above the estimated marginal abatement costs through 2050. A similar mechanism works between carbon taxation and clean water: Carbon taxes reduce both carbon and local pollutants from coal production (such as mercury, lead, cadmium, and arsenic, among others), so fewer pollutants enter the water supply. Because of cleaner air and water, mortality (that is, premature deaths) and morbidity (that is, heart disease, cancer, asthma, birth defects, and stroke, among others) are reduced. Thus, health outcomes are improved and the costs of the health care system in each country are reduced compared to a scenario without carbon taxation.

Carbon taxation also reduces the welfare impacts from pandemics like COVID-19. Many of the preexisting conditions that make people more susceptible to COVID-19 are also affected by long-term exposure to air pollution. One study found that a small increase in long-term exposure to PM2.5 leads to a large increase in the COVID-19 death rate (Wu et al., 2020). Another study found a positive association between air pollution and SARS 2002–03 fatalities: In China, people living in regions with moderate air pollution rates had an 84 percent increased risk of dying from SARS compared with people from regions with low air pollution rates (Cui et al., 2003). Carbon taxation can thus reduce the risk of death from pandemics by improving air pollution and reducing associated morbidities. Carbon taxation can also mitigate the risk of other infectious diseases with increasing occurrences due to climate change (Altizer et al., 2013). For example, GHG emissions and global warming have already begun to increase the geographic spread of diseases into temperate areas, like the 2012 dengue outbreak in Portugal (Liu-Helmersson et al., 2016). Therefore, using carbon taxation to mitigate emissions can also reduce the risks associated with future potential outbreaks.

Furthermore, the development co-benefits of carbon taxation extend beyond health outcomes (Parry, Heine, Li, & Lis, 2014). For example, motor fuel taxes reduce overall vehicle use, lowering congestion and road accidents and leading to significant benefits for local business, households, and government (Weisbrod et al., 2003; Hansson et al., 2011; Hoehner et al., 2012; Santos et al., 2010; Parry, Heine, Li, & Lis, 2014; Pigato, 2019). Other potential development co-benefits include welfare gains via a reduction of the informal sector and tax evasion effects (Pigato, 2019). Furthermore, using carbon tax revenues to invest in development projects through well-designed expenditure policy can increase the social benefit spillovers from carbon taxes. Especially when combined with complementary policies (like expenditures and energy subsidy reforms), carbon taxation can improve outcomes in health and safety, welfare, nutrition, shelter and sanitation, water and energy access, education, and rights and freedoms (Pigato, 2019; Parry, Heine, Li, & Lis, 2014; Parry, Heine, & Veung, 2014).

The impacts of carbon taxation depend on the economies' industry structure and characteristics. In labor markets, carbon taxation will integrate the costs of high-carbon sectors and can generate employment opportunities in low-carbon sectors when subsidized with the tax revenue. Structural changes will look different

[5] If low-carbon alternatives exist and are readily available. See section 3.2 for more details.

in high-income countries than in lower- and upper-middle-income countries because of differences in the share of employment and output in carbon-intensive sectors. Changes in aggregate employment will be greater in Asia and the Pacific region, where 53 percent of workers are employed in carbon-intensive sectors, compared to about 20 percent of workers in industrialized countries (Esposito et al., 2017).[6] Climate policies, therefore, need to help workers transition from the primary sectors to non-resource-intensive decent work in other sectors of the economy. Each jurisdiction should examine its own economic and emissions profile to make the best choice for achieving the combined goals of reducing GHG emissions without negatively affecting industry competitiveness or aggregate employment.

Carbon taxation can provide dynamic incentives for cost-effective, low-carbon transitions across the economy. Carbon taxation helps achieve climate objectives[7] while minimizing negative effects on the economy and is in many cases more cost-effective than direct regulation (Pigato, 2019). For example, mandating the adoption of a specific technology or performance standard creates costs for firms (like the costs of improving machinery). Larger firms will face lower relative costs than smaller firms when implementing new abatement technologies because of economies of scale (Cohen & Keppler, 1996). In contrast, carbon taxation allows firms that find abatement costs cheaper than the tax to cut emissions more than firms that find abatement more expensive than the tax. Thus, the marginal costs of emissions abatement are equalized across all producers and climate mitigation is achieved at an overall lower cost to the economy.[8]

Carbon taxation is also cost-effective in its ability to cause spillover effects to low-carbon innovation. At the microeconomic level, carbon taxation creates dynamic incentives for individual firms to continually invest in low-carbon technologies. The technological challenges and required capabilities to innovate change over time and between sectors: Carbon taxation offers a flexible and dynamic incentive for continuous innovation that fits different types of firms. Under a carbon tax, firms face an incentive not only to implement abatement technologies but to develop cheaper technologies themselves (Pigato, 2019). This increases the efficiency of voluntary mitigation efforts and the availability of low-carbon technologies, and further reduces the overall costs of the low-carbon transition. At the macroeconomic level, carbon taxation accelerates and guides overall investment in low-carbon directions over the long term (Grubb et al., 2014). By channeling R&D investment onto a new, low-carbon route, carbon taxation thus helps firms avoid lock-ins associated with path dependence on carbon-intensive technologies, creating new green technological paths (Arthur, 1989). Over time, this reduces the cost and other barriers to low-carbon options.[9]

Carbon taxation policies can affect these economy-wide changes while generating significant domestic revenues. The transition to a low-carbon economy will take virtually unprecedented levels of investment and governments across the world are increasingly interested in climate policy instruments like carbon taxation that can help raise the necessary funding.[10] At the current scale of implementation, carbon taxation cannot raise all

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[6] The high share of employment in carbon-intensive sectors in low- and middle-income countries is due to the high share of overall employment in the agriculture, forestry, and fishery sectors, whereas in high-income countries the high-carbon sectors (that is, heavy industry and energy) have relatively small employment shares (Esposito et al., 2017). For country differences, see also Nadel (2016) on the lessons learned from 19 countries and Criqui et al. (2019) on Canada, France, and Sweden.

[7] Such as mitigation targets or NDCs agreed to under the Paris Agreement.

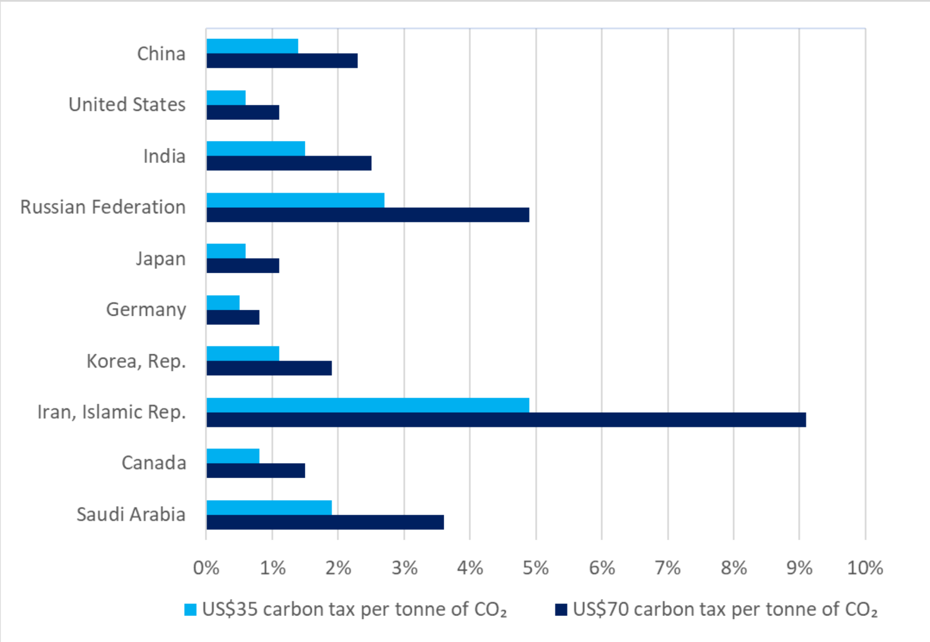
[8] Additionally, carbon taxation is also a more cost-effective way of raising revenues when compared with broad-based taxes, as carbon taxes are less distortionary and can be designed to cover the informal sector (Heine et al., 2019).

[9] This enabling environment for low-carbon investment can be further strengthened by complementary policy instruments, for example, strategic public investments or subsidies to R&D in green technologies (Acemoglu et al., 2012). Complementarities between particular policy instruments are discussed in more detail below.

[10] In carbon pricing mechanisms, the potential revenue generation is higher for carbon taxes than for ETSs; however, significant revenues can be generated with an ETS if allowances are auctioned (Heine et al., 2019).

the funds required for the low carbon transition;[11] nevertheless, it can provide significant revenues that governments can use to generate positive externalities (Parry, Heine, & Veung, 2014; Atolia et al., 2018; see figure 8). If appropriate, carbon tax revenues can be put toward multiple objectives,[12] including redirecting innovation toward cleaner technologies (Acemoglu et al., 2012).

Figure 8. The Revenue-Raising Potential of Carbon Taxation Among the Biggest Carbon Emitters, % of GDP



Source: Author calculations based on IMF (2019).
Note: The largest emitters in percent of GDP were selected using data from the International Energy Agency (IEA). See http://energyatlas.iea.org.

Revenues from carbon taxation can also be used for redistribution purposes and to compensate "left behind" households in the low-carbon transition. Carbon taxes may have distributional and international competitiveness impacts (Yip, 2018; Zhong et al., 2018; Hansen, 2015; Pigato, 2019).[13] Any carbon tax policy should be evaluated from the perspective of fair transition and designed to avoid regressive impacts. Policy makers can account for any distributional effects by rebating revenues back in the form of lump-sum payments (Vona, 2018; Pigato, 2019). Compensating for the effects of climate policies on left-behind households appears to be the key priority to increase the political acceptability of such policies (Vona, 2018). Residual adverse impacts on domestic industry, if any, can also be managed with output-based rebates to affected firms.

[11] Discussed in more detail in section 2.2.

[12] Some evidence indicates that if carbon tax revenues are used to reduce existing labor and capital taxes, countries can achieve a "double dividend" of reduced carbon emissions and increased employment and growth, especially in low- and middle-income countries (Pigato, 2019; Heine et al., 2019; Parry, Heine, Li, & Lis, 2014; Kirchner et al., 2019; Markandya et al., 2013; Landa et al., 2016; He et al., 2019; Goulder, 1995; Bovenberg, 1999; Bento & Parry, 2000; Freire-Gonzalez, 2017). For example, using carbon tax revenues to lower social security contributions or other payroll taxes reduces the cost of labor and may therefore increase overall employment (Pigato, 2019).

[13] For example, under certain circumstances, carbon taxes may have regressive effects on income distribution (for example, by negatively affecting low-income households relative to their income more than wealthier households or by taxing away jobs disproportionately held by less-educated workers [Yip, 2018]). Localized contextual effects, such as peer group pressure, and politico-economic factors, such as weak unions and tight government budgets, amplify the strength and the persistence of the "job killing" argument. Regarding the impact on international competitiveness, developing countries' industrial structures are more dependent on carbon-intensive exports (Zhong et al., 2018), and so carbon taxation might create competitive imbalances between countries and incentivize the implementation of import taxes on countries without carbon taxes. However, this mechanism can also create incentives for carbon-exporting countries to implement carbon taxes domestically to increase their tax revenues (as proposed in Hansen [2015]). Additionally, carbon taxation may have positive effects on firm productivity and so may positively affect international competitiveness (Pigato, 2019).

While carbon pricing has been recognized as the first-best option for mitigating climate change for decades, it has not been implemented at a level sufficient to induce change at the scale needed to meet the goals of the Paris Agreement. In theory, carbon pricing could entirely meet the financing requirements for a low-carbon transition.[14] However, in practice carbon pricing initiatives, though widespread, are limited and carbon prices are still too low (Heal & Schlenker, 2019). Among high-income countries, the amount of emissions covered by carbon pricing is still lower than their contributions to global GHG emissions.[15] Carbon prices are also still too low in most countries: Model simulations show that carbon prices should be much higher because climate effects can only be expected at a minimum carbon price of $40 per ton of CO_2-equivalent (Carbon Market Watch, 2017).[16] Thus, carbon taxes alone are inadequate for climate change mitigation, and other instruments—such as green bonds—are needed (Mazzucato, 2016).[17]

Given the current state of carbon taxes, policy makers need to enact complementary mechanisms to speed up the low-carbon transition. Carbon taxation has not been implemented at the necessary scale (both in coverage and price level) in part because of political and international coordination failures (BIS, 2020). Given the deficiency of international responses, it is more likely that climate change will significantly impact the global economy and even lead to irreversible losses for the financial and other sectors (Bolton et al., 2020; Cœuré, 2018). Responding to climate change thus requires complex policy mixes that combine fiscal, monetary, regulatory, and other instruments (Krogstrup & Oman, 2019). Policy makers can increase the effectiveness of carbon taxation by implementing well-designed, complementary policies to tackle other various government and market failures (such as credit market failures). For example, by implementing complementary mechanisms alongside carbon taxation, the same level of emissions reduction can be achieved with lower carbon prices (Stern & Stiglitz, 2017). By using a comprehensive approach with multiple policy instruments, governments can ensure that the transition to a low-carbon economy is encouraged through multiple dimensions in a cost-effective and macroeconomically stable way.

3.2 Combining Carbon Taxes with Green Bonds

Well-designed carbon taxation policies are effective, but they have certain drawbacks that can be improved upon by using complementary instruments like green bonds. As discussed above, carbon taxation is a necessary component of climate policy as well as an efficient and cost-effective mechanism for affecting economy-wide low-carbon transitions. However, evidence shows a gap of greater than $5 trillion between the current global level of fossil fuel taxation and the one justified by the externality costs (Lagarde & Gaspar, 2019). Furthermore, the required investments for the climate transition are large, between 5 and 7 percent of global GDP, or $5 to $6 trillion (OECD, 2017). However, the introduction of sufficiently high carbon taxes is often politically contentious and has been one of the least favored climate policy approaches by politicians and the general public (Grubb et al., 2014).[18] Therefore, carbon tax initiatives likely will not be implemented at the necessary

[14] According to one estimate, limiting global temperature rise in accordance with the Paris Agreement requires $790 billion, or triple the annual amount of low-carbon investment (IEA, 2014). Another estimate places the number closer to $1.5 trillion over the next decade (King et al., 2015). These figures are far below the over $5 trillion per year that could be raised if carbon pricing rates were set at levels justified by externalities (Heine et al., 2019).

[15] See section 2.1 for more details.

[16] Furthermore, if low-carbon technologies are unavailable and the implementation of climate policies is delayed, higher carbon prices in the range of $80–$100 per ton of CO_2-equivalent between 2020 and 2030 will be necessary (Stern & Stiglitz, 2017).

[17] There are also efficiency, political, and equity arguments to use a combination of policy tools; see Heine et al. (2019) for more details.

[18] Indeed, political economy considerations are key: A carbon taxation policy's successful implementation depends on the political and institutional environment, including trust in politics and corruption perception (Funke & Mattauch, 2018).

speed and scale to meet all funding requirements for the low-carbon transition; other mechanisms will be needed to unlock various sources of public and private low-carbon finance.[19]

The combination of carbon taxes and green bonds represents an attractive policy, as green bonds are a politically attractive solution able to address important carbon taxation limitations.[20] Carbon taxation operates on a specific economic dimension.[21] Responding to climate change requires a combination of policies that provide a diversity of incentives for low-carbon pathways. Low-carbon innovation and climate-related infrastructure investment will face constraints without additional public policies beyond carbon pricing (Grubb et al., 2014). As an effective climate change response requires immediate measures, it is "better to use second-best policy instruments than to do too little too late" (Heine et al., 2019, 6).

Green bonds can increase the effectiveness of carbon taxation by expanding available energy choices and therefore unlocking carbon price elasticities. The success of carbon taxation depends on the carbon price elasticity—in other words, the responsiveness of economic agents to carbon price incentives. So, the effectiveness of carbon taxation to affect emission reductions depends on whether economic agents are willing and able to switch from carbon-intensive goods and services to low-carbon alternatives. Carbon price elasticity is positive but varies between countries (Andersson, 2019; Nadel & Kubes, 2019; Hu et al., 2015). However, if low-carbon alternatives are unavailable, carbon taxation policy will be less effective at mitigating emissions. The issuance of green bonds can raise the price elasticity of demand for fuels, increasing the supply of low-carbon alternatives so the same rate of carbon taxation achieves greater mitigation outcomes.

Green bonds can function as bridge financing for green investment, increasing the effectiveness of carbon taxation. Carbon taxation will be more effective people can turn to low-carbon alternatives; however, currently, carbon taxation by itself cannot raise the necessary funds to immediately supply these alternatives. Green bonds can provide bridge financing for the necessary green investments to provide these low-carbon alternatives, complementing the (future) role of carbon taxation in driving changes in both supply and demand. The bridge financing role of green bonds is especially important in climate-related infrastructure investments that do not respond to price signals and should be led by the public sector (Stern & Stiglitz, 2017). Using green bonds in this way can reduce political barriers to climate policy: Citizens' resistance to carbon taxation tends to be greater when alternatives are not available. For example, the recent protests against the increase in motor fuel taxation in France were partly motivated by a perception that citizens living in the outskirts of Paris had no alternative but to continue using their cars because public transport systems were insufficiently developed. In this case, the literature suggests that countries should first invest in improving their public transport systems before introducing (or raising) carbon taxes on motor fuels. Green bonds can fulfill this role.

The positive interactions between carbon taxation and green bonds can also increase returns and decrease risks of green investments. Carbon taxation increases the relative returns of green investments, improving the efficiency and decreasing the relative cost of capital for green bonds (Heine et al., 2019).[22] The combination of

[19] In other words, carbon taxation is therefore mainly a mitigation tool and requires additional instruments to adequately fund adaptation initiatives. While carbon taxation revenues can be used for climate adaptation purposes, they will not be large enough to fund all the necessary expenditures.

[20] For example, Acemoglu et al. (2012) show that in an optimal climate policy combination, subsidies for green technologies (a function that could be fulfilled through green bonds) accompany carbon taxation.

[21] For example, carbon taxation can instigate better decision-making by and engagement of individuals, as well as accelerate and guide the direction of low-carbon innovation and infrastructure investment (Grubb et al., 2014).

[22] Both taxation and an ETS, by integrating negative externalities through carbon pricing, level the playing field between low- and high-carbon investments and promote the efficiency of green bonds. However, the positive interactions between an ETS and green bonds are more ambiguous since mitigation projects funded by green bonds reduce the scarcity of emissions allowances under the ETS cap. This

carbon taxation and green bonds can also lead to lower price volatilities for green investments (Gevorkyan et al., 2017): A stable carbon price creates more stable returns on green investments, including green bonds. Less volatile returns on green bonds can attract more investors and create a better business environment. Importantly, the stability of carbon prices is not observed in countries with an ETS (Nell et al., 2009; Friedrich et al., 2020), indicating that the combination of carbon taxation with green bonds is a better policy arrangement in terms of macroeconomic stability and policy complementarities.

Macroeconomic climate models have evaluated the role of green bonds and their interaction effects with carbon taxes and find that this policy combination speeds up the process of climate mitigation, increases welfare, and promotes greater intergenerational fairness. Mitigation policies that occur in the present increase the social welfare of future generations. In contrast, when those policies are funded through carbon taxes only, the current generation shoulders all the cost and therefore accepts a lower level of welfare (Orlov et al., 2018). Sachs (2015) defends bond issuance instead as a strategy to share current climate policy costs between current and future generations. Because future generations will enjoy the benefits of a climate policy, green bonds allow policy makers to share the costs of climate policies more equitably across generations.

Green bond issuance also helps overcome policy makers' myopic behavior and brings a necessary intergenerational approach to fiscal policy. Green bonds allow governments to properly fund long-term green investment and increase overall social welfare while keeping a sustainable debt trajectory. In chapter 4, we explore the results and methodologies of various climate models, including those that take into account the use of debt to fund climate policy (Flaherty et al., 2017; Orlov et al., 2018). We also explore models that evaluate the effects of mixing debt and tax instruments and show that combining carbon taxation and green bonds is a superior choice in terms of aggregate welfare (Heine et al., 2019).

reduction in the scarcity of ETS allowances reduces the price of those permits and further allows for the displacement instead of the reduction of net emissions (Heine et al., 2019). Tightening the ETS cap would then be politically necessary to counterbalance such an emissions displacement (and would also be in the interest of green investors).

4 Macroeconomic Climate Models as Guidance for Public Policy

Developments in macroeconomic modeling can support policy makers in determining appropriate macroeconomic climate policy approaches. In decision-making processes, policy makers need to have an understanding of the mechanisms through which policies operate. Macroeconomic modeling results supporting major climate policy decisions have changed over the years with advancements in modeling approaches. These modeling improvements incorporate approaches that balance short- and long-term costs and benefits. Policy makers should rely on the lessons learned from advanced macro models like extensions made to the original DICE model as well as the inclusion of further environmental macro policy. This chapter discusses advancements in and different types of macroeconomic modeling that deal with carbon emissions and macroeconomic policy tools like green bonds and carbon taxation. A summary of the main learnings from these macroeconomic models is listed here:

- Carbon taxes can lead to a structural change in the economy in the long run. However, due to political hurdles, carbon taxes may not rise sufficiently and the transition to a low-carbon economy may be too slow (Orlov et al., 2018). Thus, other policy tools—like green bonds—are needed.
- Subsidizing low-carbon products can have positive effects on aggregate output and employment, whereby the best results are achieved when carbon tax revenues are recycled and used to subsidize the development of low-carbon products (Kato et al., 2015).
- Investments should be fully tailored to the improvement of renewable energy sources instead of making fossil fuel energy sources more efficient, pointing to the need for policy instruments (like green bonds) that can fulfill this role (Semmler et al. 2018).
- Green bonds benefit both current and future generations and are a good policy instrument to finance climate stabilization and address intergenerational fairness in fiscal policy (Bonen et al., 2016; Flaherty et al., 2017).
- Mixing green bonds and carbon taxes is Pareto superior to other policy choices, increases welfare, makes the green debt sustainable, and helps policy makers avoid poverty traps caused by climate-related disasters (Heine et al., 2019; Orlov et al., 2018; Semmler et al., 2019; Mittnik et al., 2020).

The following model reviews compare the basic Nordhaus DICE model with extended integrated assessment models (IAMs), macro policy augmented models, and a synthesis type model. The groundwork for the first IAM was laid by Nordhaus in 1975, which he further developed into the dynamic integrated model of climate and economy (DICE) (Nordhaus, 2008). This report categorizes macroeconomic climate models into four typologies (table 3), beginning with the Nordhaus DICE 2008 model as type 1. The DICE model entails several shortcomings, but it is a useful foil for the explanation and development of further macroeconomic climate models that allow for the investigation of combined mitigation and adaptation policies as well as models that include interaction effects between carbon taxation and green bonds. Type 2 models extend the classical Ramsey growth model welfare function (used in the Nordhaus DICE model) and allow for policy analysis regarding public investments for growth-enhancing infrastructure and mitigation or adaptation efforts. Type 3 models do not include the same extensions as type 2 models, yet they allow for a more climate-specific macroeconomic analysis because they either include carbon taxation, green bonds, or both in their approaches. Macroeconomic models that are technically advanced (like type 2 models) and combine macroeconomic policy features (like type 3 models) are synthesized as type 4 models.

Table 3. Basic Macroeconomic Climate Model Typology

Model type	Model features							
	Extended welfare function	Mitigation policy	Adaptation policy	Renewable and nonrenewable energy sources	Nonlinearities and tipping points	Carbon tax	Green bonds	Multi-phase*
Type 1: Basic IAM (DICE 2008)		✓				✓		
Type 2: Extended IAMs	✓	✓	✓	✓	✓			
Type 3: Macro policy augmented models		✓		✓		✓	✓	✓
Type 4: Synthesis models	✓	✓	✓	✓	✓		✓	✓

Note: A gray checkmark indicates that only some models of this model type include the mentioned model feature. For a more comprehensive table including the individual studies, see table 6 in section 4.4.
*Multiphase models allow for more policy dynamics—for example, enabling credit issuance for mitigation efforts in an initial phase and debt repayment in a later phase.

4.1 Type 1 Model: Nordhaus DICE 2008

The Nordhaus DICE macro-climate model enjoys a central position in the literature and policy analysis but has shortcomings with major consequences for policy analysis and implementation. The Nordhaus model updates a conventional Ramsey model to include interaction effects with climate variables. The main equations of the DICE model include (a) temperature-based climate dynamics, (b) carbon cycle dynamics,[1] (c) capital dynamics based on changes in the economic capital stock, (d) population dynamics, (e) total factor productivity dynamics, and (f) emissions dynamics of industrial and land use activities (Kellet et al., 2019). These equations allow for interactions and feedback effects, yet for climate policies essential shortcomings in the basic model setup exist:

- **Narrow perspective to emission impacts:** Emissions and mitigation functions only affect output and capital accumulation through a damage function but don't show any direct impact on households. Households are only indirectly affected by a decrease in consumption because of lowered production. Yet climate change has a huge impact on households beyond impacts to the consumption of industrially produced commodities, such as on living conditions, habits, and health. Furthermore, the damage from carbon dioxide is only modeled via the temperature channel; however, we know that higher CO_2 levels also cause damages through other channels, by impacting health, living, and ecological conditions.[2] As the original DICE model does not comprehensively consider the impact of emissions, policies relying on this framework may, for example, underestimate the amount of financing needed to address climate change risks or the number of redistributive policies needed to address welfare impacts on households.
- **Source of emissions:** The Nordhaus model considers the effect of industrial emissions in increasing carbon stocks and temperature; however, the main driver of carbon emissions is fossil fuel–based energy production and consumption. Hence, the pollution and externalities from fossil fuel extraction, production, and consumption matter and need to be included (Hotelling, 1931; Greiner et al., 2014).

[1] Carbon cycle dynamics are based on carbon concentration dynamics in the atmosphere and lower and upper ocean.

[2] For example, increased carbon uptake by oceans leads to acidification, causes the extinction of marine life, and further disrupts ecological services. Most of these effects are neglected by the narrow way that GDP is calculated.

Furthermore, models should also address the feasibility and challenges of replacing fossil fuels and phasing in renewable energy, including public and financial policies for this purpose. Thus, policy analyses relying on the DICE model may not emphasize the need to address fossil fuel extraction, production, and consumption, or renewable energy production.

- **Adaptation policies:** Nordhaus includes mitigation policies through a mitigation effort determined by an emission control rate and an abatement cost function. However, disaster-resilient infrastructure built up in the present can increase future welfare by reducing vulnerability to extreme climate events.[3] Policy analyses using the basic DICE model may, therefore, miss key dynamics involving both mitigation and adaptation policies.
- **Intergenerational costs and benefits:** There is a fairness problem in the DICE model due to temporal and intertemporal inequality of costs and benefits.[4] In the Nordhaus model, welfare is higher for future generations under the mitigation scenario than under a scenario absent mitigation policies. Future generations also receive a greater benefit from mitigation policies than do current generations, as the current generation accepts lower welfare when optimal mitigation policy is implemented, compared to the no mitigation scenario (Orlov et al., 2018). Using the basic DICE model may lead to policy prescriptions that do not balance intertemporal equity (for example, through debt issuance).
- **Nonlinearities and tipping points:** Climate change will generate ecological tipping points because of disruptive climate impacts (for example, sudden melts of ice shields, increased frequency and severity of weather-related disasters, and heat waves, among others) that will generate nonlinear trajectories in economic variables like growth rates, productivity, welfare, or risk premia. The Nordhaus model is based on linear equations and so may mischaracterize the amount of risk or instability associated with different policy packages (see Greiner et al., 2010).

4.2 Type 2 Models: Extended IAMs

The model of Bonen et al. (2016) is a more refined IAM than the basic DICE model and allows for context-specific calibration of climate policies. This IAM model can be calibrated to country- and institution-specific circumstances to determine the optimal budget allocation[5] between growth and climate-related infrastructure.[6] Calibrated to country-specific parameters, the model setup shows how to optimally allocate funds between infrastructure for production, for mitigation of GHG emissions, and infrastructure against extreme events to ameliorate local damages from such events. Results suggest that a high share of public investment should be attributed toward growth-enhancing infrastructure and only 5 to 20 percent toward climate-related infrastructure.[7] Compared to the Nordhaus model, which did not include adaptation measures, Bonen et al. (2016) includes a completely new policy recommendation about how to implement adaptation measures.[8] The

[3] Countries or regions can fall into poverty traps because of climate disasters (see Mittnik et al., 2020).

[4] For temporal inequities and how they can be compensated, see Marron & Morris (2016).

[5] Mainly focusing on developing countries, this paper also considers financial support received as part of the public budget.

[6] Each type of investment is included as a control variable, which reflects the fact that countries can invest in non-green capital to increase growth at the same time as they are investing in climate policies. The model solves a nonlinear system iteratively over a receding finite horizon. The iteratively updated short-term projections reflect the fact of climatological uncertainty and a lack of perfect foresight. This approach expands the complexity of the dynamic optimization problem while maintaining significant analytical traction.

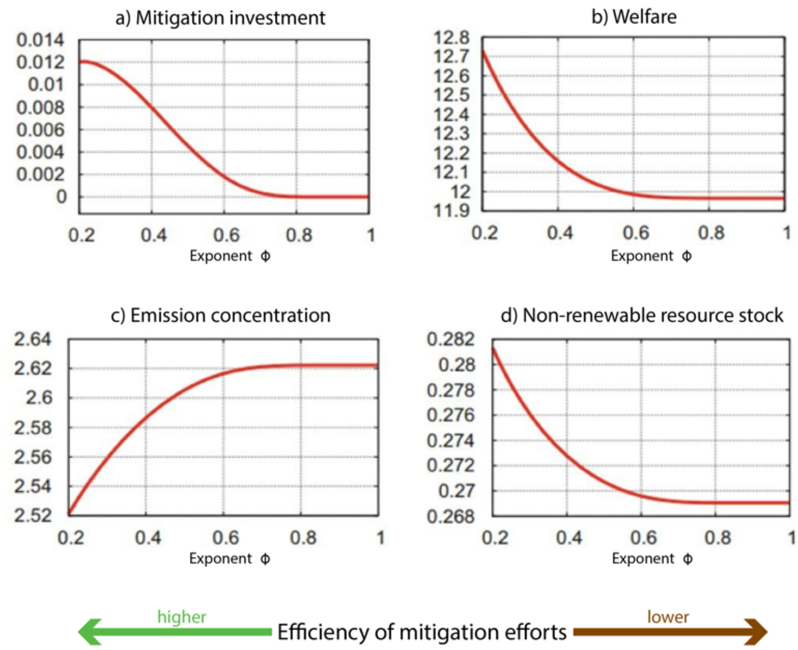
[7] This can be considered as climate change–adaptive since (in the context of developing countries) increasing productivity-enhancing infrastructure also increases climate resilience by protecting communities from natural disasters.

[8] Whereas the DICE model includes carbon emission through the carbon intensity of production in general, the Bonen et al. (2016) model uses emissions exclusively from the extraction of nonrenewable resources (in other words, fossil fuels; fossil fuel extraction is

results suggest that policy makers should increase the share of adaptation versus mitigation programs as climate change impacts become more severe and increase the need for adaptation measures.[9] Additionally, though the possibility of debt issuance in the Bonen et al. (2016) model allows for intergenerational fiscal policy (not considered in the Nordhaus model), carbon taxation or green bonds are not specifically included or analyzed.

Semmler et al. (2018) build on the model of Bonen et al. (2016) and yield similar results. According to them, efficiency improvements of nonrenewable energy sources are not beneficial for the environment. Instead, investment is needed to improve green technology to move from nonrenewable energy sources, increase mitigation efforts, and increase welfare. Their modeling shows that if green capital becomes comparatively more efficient, this will lead to less extraction of fossil fuels, increased investment in mitigation projects, and lower emissions.[10] This suggests that investments should be fully tailored to the improvement of renewable energy sources instead of making fossil fuel energy sources more efficient. The results for changes in the efficiency for mitigation efforts are depicted in figure 9. These findings support the argument that instead of subsidizing and incentivizing fossil fuel energy usage, technological investments need to target the green technology sector. This updated model provides new policy recommendations, in particular that the efficiency of renewable energy sources and mitigation technologies should be improved, pointing to the need for policy instruments (like green bonds) that can fulfill this role.

Figure 9. Impact of Mitigation Efficiency on Key Variables in Semmler et al. (2018)



Source: Adapted from Semmler et al. (2018).
Note: The graphs show that a lower efficiency of mitigation efforts (higher ϕ) will lead to (a) less investment in mitigation projects, (b) lower terminal welfare, (c) higher terminal emission concentrations, and (d) lower stock of nonrenewable resources. An improvement in mitigation efficiencies (parameter ϕ becomes smaller) will lead to inverse results: More public capital will be invested into mitigation efforts, terminal welfare will be higher, terminal emission concentration will go down, and more fossil fuels will be left in the ground. Decreasing mitigation efficiency will lead to less investment into mitigation efforts, will decrease welfare, will increase terminal emissions, and will run down the total nonrenewable resource stock.

The findings of Atolia et al. (2018), the final type 2 model under analysis, suggest that it is vital to enact mitigation efforts early on and that CO_2 concentration can be steered down even when initial CO_2 levels are above the

then determined using a Hotelling-like resource extraction model); nonpolluting, renewable energy can be phased in by addressing the funding issue of climate change. Compared to the Nordhaus model, in Bonen et al. (2016) carbon emissions act as a direct disutility on the welfare function of households.

[9] One caveat is that an off-target CO_2 path could accelerate physical climate risks and therefore change the schedule of optimal funding allocations.

[10] This is determined through further analysis of parameter homotopies (for the efficiency index for CO_2-generating resources and the pure discount rate) under a strategy of optimally selecting the allocation shares to traditional, adaptive, and climate change mitigating expenditures.

target level. Atolia et al. (2018) use a similar setup as Bonen et al. (2016) and Semmler et al. (2018) but include an additional type of capital stock and model the transition to a fossil fuel–free green energy infrastructure (see the detailed model comparison in table 6). As with other type 2 models, the optimal public budget is allocated between mitigation, adaptation, and growth-enhancing infrastructure. Thereby, Atolia et al. (2018) show that it is possible to achieve public infrastructure growth with low-carbon sources of production. The dynamics of the model suggest that optimal spending on traditional infrastructure is lower at the beginning with large efforts at mitigation and rising efforts at adaptation. This updated model reinforces the need to find ways to pay for necessary mitigation and adaptation investments, such as through green bond issuance.

4.3 Type 3 Models: Macroeconomic Policy Augmented Models

Type 3 models include macroeconomic environmental policy tools such as carbon taxation and green bonds but do not include all aspects of type 2 models.[11] In these models, carbon taxes penalize the consumption of carbon-intensive goods and incentivize the usage of low-carbon production methods. These models show that carbon taxes can lead to a structural change of the economy in the long run. As argued in chapter 3, carbon taxes alone will not create *enough* additionality for climate protection and another tool—such as green bonds—is needed. Furthermore, because of political hurdles, carbon taxes may not rise sufficiently over time and the transition to a low-carbon economy may be too slow (Orlov et al. 2018). Type 3 models take these considerations into account by incorporating additional climate policy tools beyond carbon taxation into the analysis. The following paragraphs summarize the key features and results of relevant type 3 models.

The budget neutral implementation of carbon taxes in Kato et al. (2015) shows that subsidizing low-carbon products can have positive effects on aggregate output and employment. Kato et al. (2015) set up a model to analyze the effects of carbon taxation on employment and output for nine industrialized countries. Based on the double dividend hypothesis,[12] Kato et al. (2015) investigate the effects of a budget neutral carbon tax, where collected tax revenues are reinjected into the economy.[13] They compare three scenarios: a carbon tax and subsidies on the consumption of low-carbon products; a carbon tax and no subsidy (that is, no reinjection of revenues); and a carbon tax and wage subsidies. The least desirable policy combination according to the results is to implement a carbon tax that is levied on carbon-intensive industries while tax revenues are not used for other subsidizing purposes (such as reducing other taxes).

The most desirable outcome, according to Kato et al. (2015), is achieved when carbon taxes are used to subsidize the development of low-carbon products. The results of their study for the US case are presented in table 4. The response analysis suggests that green policies, which favor the US low-carbon-intensive sector at the expense of the high-carbon-intensive sector, result in both employment and output growth. The study only reports

[11] Despite this advantage over previous model types, the examined type 3 models do not include several aspects found in type 2 models: (a) The models do not include emissions as direct disutility in their welfare functions; (b) since the models do not specifically include separate parameters for mitigation and adaptation, there is no proper differentiation on how mitigation and adaptation measures are promoted (the costs of climate policies are only jointly expressed through abatement efforts (which do not differentiate between mitigation and climate adaptation); and (c) for the models that do not differentiate between brown and green capital (that is, where brown capital produces higher amounts of emissions compared to the green capital), carbon tax revenues support a low-carbon transition yet are based on the total output and do not relate to capital sources of different carbon intensity.

[12] The double dividend hypothesis, briefly discussed in section 3.1, posits that environmental taxation policies could improve an economy's competitiveness by replacing more distorting taxes and reducing the barriers to employment (for example, labor tax).

[13] They differentiate between high- and low-carbon-intensive production sectors and levy a carbon tax on high-carbon-intensive industries. They analyze the effects on industry-specific output and employment via policy shocks on the economy. Their model is based on a four-variable vector autoregression (VAR) model that comprises changes in output and employment rates for high- and low-carbon-intensive industries. The specification of their model is given in appendix B, along with more details.

results for the case of carbon taxation with subsidies for low-carbon products for all nine countries but not for the other scenarios (see appendix B, table B.1). The cross-country results for nine countries suggest a clear decrease of output in high-carbon-intensive sectors and an increase in low-carbon-intensive sectors, and on average a slightly positive effect on aggregate output growth. Employment effects move in the same direction but are not as strong as output effects. Overall, the imposed climate policy does not have a major effect on total gross output and total employment with exceptions.[14] This model shows that when carbon taxes are combined with investments in low-carbon technology and other green subsidies, economic outcomes can be improved—if green fiscal policy is tailored to individual country circumstances like industrial structure.

Table 4. Changes in Real Employment and Output in High- and Low-Carbon-Intensive Sectors Under Three Green Fiscal Policy Scenarios (%)

United States	HCIS employment	LCIS employment	Total employment	HCIS output	LCIS output	Total output
Scenario 1: Carbon taxation & low-carbon products subsidy	0.25%	0.75%	0.47%	-1.00%	2.00%	0.50%
Scenario 2: Carbon taxation & no subsidy	-0.22%	-0.15%	-0.40%	-1.00%	0.60%	-0.40%
Scenario 3: Carbon taxation & wage subsidy	0.10%	0.33%	0.20%	-0.50%	0.80%	0.50%

Note: Results for the three modeling scenarios in Kato et al. (2015) for the United States. Changes in real employment (%) and output effects (%) relative to the business-as-usual 5 years after the introduction of a budget neutral carbon tax with subsidies. HCIS = high-carbon-intensive sector; LCIS = low-carbon-intensive sector; total = aggregate effects.

The Flaherty et al. (2017) model evaluates the intergenerational benefits of green bonds, finds that the use of bonds is a Pareto-improving strategy,[15] and shows the theoretical possibility of financing climate stabilization. Flaherty et al. (2017) argue that tax increases, cap-and-trade systems, and fees and regulations are often seen as too costly as well as difficult to implement and not sufficiently scalable. Therefore, they use green bonds in their model as the preferred environmental policy tool. They generalize the Sachs (2015)[16] model for green debt in continuous time and study three subsequent stages, starting with a business-as-usual scenario. Through bond issuance during the second stage, debt is built to finance abatement efforts and hence increase capital accumulation and output. An income tax for bond repayment is introduced in the final stage and subsequently debt is reduced so the economy reaches a low level of debt. The model shows that green bonds benefit both current and future generations and are a good policy instrument to finance climate stabilization. Money generated by green bonds supports the advancement of green investments and improves the environmental well-being of future generations while not compromising the financial situation of the current generation.

Heine et al. (2019) examine the policy mix of green bonds and carbon taxes and show that green bonds can be repaid and that the debt is sustainable.[17] In this model, carbon taxes are used as a funding source for mitigation policies and adaptation efforts. They investigate three different scenarios that are similar to the stages in the Flaherty et al. (2017) model. Especially interesting is the third scenario, which applies a carbon tax as a semi-flat tax rate on output as long as the GHG level is higher than a specified amount.[18] Carbon tax revenues, channeled

[14] Australia, for instance, has a heavy extractive industry and strong manufacturing sector, which yields a strong negative employment effect.

[15] Pareto improvement means that total welfare can be improved without making anyone worse off.

[16] Sachs (2015) argues that sharing costs between different generations through bond issuance is a strategy to address intergenerational environmental justice.

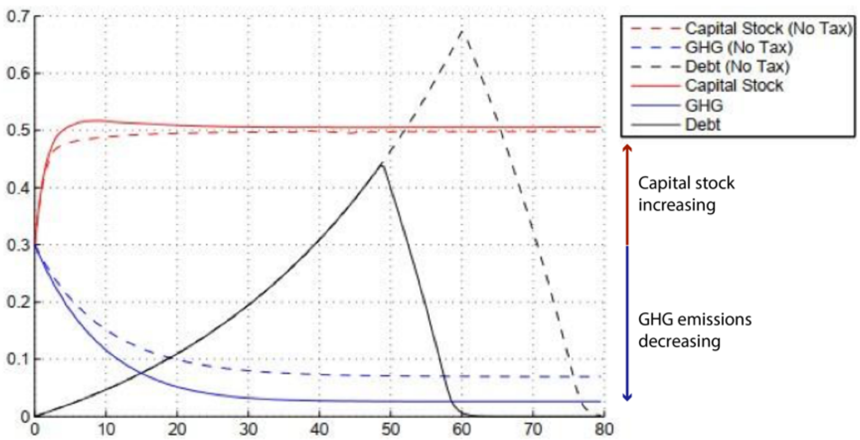
[17] Heine et al. (2019) use a more developed version of the model that was also proposed by Gevorkyan et al. (2017).

[18] Since this model does not differentiate between the types of capital with different amounts of carbon intensities, only capital as a whole is taxed.

back into the economy together with the revenue from green bonds, are solely spent on mitigation and abatement efforts; the green bond debt is paid back by taxing the income generated at a later stage.

The results show that green bonds can be repaid, the debt is sustainable, and that carbon taxes should complement green bonds to expedite the transition to a low-carbon economy. Figure 10 compares the results of the second and third scenarios: The combination of a carbon tax and green bonds (solid lines) accelerates mitigation and GHG levels reach equilibrium faster. This faster adjustment means less accumulated debt, less accumulated interest, and faster repayment. Hence, a scenario that uses a mix of carbon taxes and bond financing is superior to other policy choices. The main conclusion of the supporting econometric panel study is that a mix of policies should be used that give weight to green bonds as viable financial instruments for climate policies as well as for shifting energy production to large-scale renewable energy generation.

Figure 10. Sustainable Green Debt Repayment in Heine et al. (2019)



Note: The figure shows that the interaction effect scenario of carbon tax and bond issuing (solid lines) is superior to the second scenario where only bond issuance is used to finance mitigation and adaptation efforts (dashed lines) because GHGs decline faster, capital stock reaches a higher level (capital stock), and debts are repaid faster (debt).

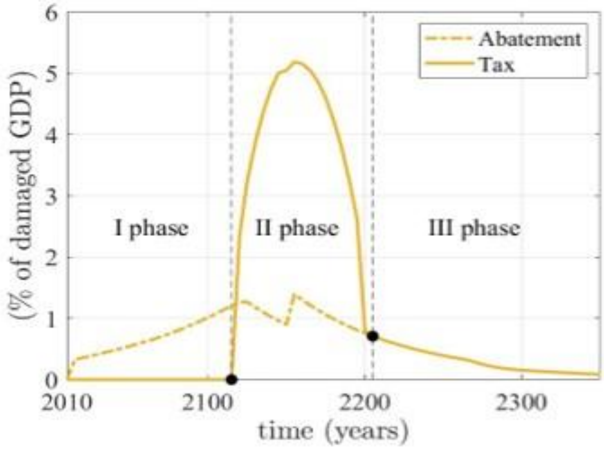
Orlov et al. (2018) introduce green bonds into their model and yield similar results: The combination of green bonds and a carbon tax can indeed enhance climate change mitigation and simultaneously spread out debt over time. Orlov et al. (2018) build off the DICE growth model and examine a scenario where a policy maker decides on the investment/saving rate and abatement policies by maximizing the integrated and discounted welfare derived from per capita consumption.[19] Figure 11 shows the model's three phases: (I) bond issuance (2010–15); (II) bond repayment (2120–2200); and (III) taxation for mitigation (2205 onward).[20] Overall, the results roughly replicate and validate the structure and benefits of the inter-temporal fiscal policy introduced by Sachs (2015) and further investigated by Flaherty et al. (2017). The three phases, which emerge endogenously, illustrate that the introduction of green bonds accelerates climate investments, the issued debt is sustainable, and there is a positive effect on welfare from the policy combination.[21]

[19] The model uses the Nordhaus-type Cobb-Douglas production function from which industrial emissions are derived, a damage function that depends on the surface temperature of the earth, and an abatement function. The net output of the model is GDP net of damages and abatement.

[20] The study does not set up regime changes manually but is able to show that in the optimum case, three distinct phases emerge endogenously when allowing for green bonds and tax repayments throughout the entire simulation period.

[21] The authors also note that a further compensation mechanism is needed to reallocate consumption across generations to make it Pareto efficient and that green bonds in their model are only issued by an external creditor; Orlov et al. (2020) pick up on that and model the results for green bonds that are issued internally by households. Orlov et al. (2020) integrate green bonds into the DICE model where bonds were assumed to attract finances from outside of the economy (which Tobin called "external debt"); hence, their model

Figure 11. Sustainable Green Debt Repayment



Source: Adapted from Orlov et al. (2018).
Note: Abatement efforts (dashed line) and income taxes (solid line) as fractions of the net output over time. In the optimal scenario, taxation is delayed until 2120 and abatement is positive (reaching 1.2 percent of GDP by 2115). Green tax rates increase in phase II to finance mitigation efforts and the repayment of green bond debts. Hence, the tax rate must be higher than the abatement rate, reaching up to 5 percent of the GDP. By the end of phase II, bonds are fully repaid. Abatement efforts in the last phase are purely financed by tax revenues. The endogenous emergence of these phases mirrors the results that were obtained by other type 3 models that include the issuance of green bonds and their later repayment.

4.4 Type 4 Models: Synthesis Models with Regime Changes

Semmler et al. (2019) show welfare improvements and enhanced intergenerational equity when green bonds are used in comparison to a baseline model without green bonds. Developing a multiphase model with green bonds for climate mitigation and adaptation, they build on the single-phase model of Semmler et al. (2018) and introduce different phases (as in Flaherty et al., 2017) that include the issuance and repayment of green bonds. Their results suggest that a multiphase model with both green bonds and income taxation is Pareto superior[22] and shows enhanced intergenerational equity compared to a scenario with only income taxation. Table 5 shows that social welfare over multiple periods is more than double that of the single-phase model. The model provides evidence that green bonds smooth consumption levels over the modeling period, which is in line with a more equitable intergenerational distribution of welfare and also reflects the general results of this report (see section 5.2 and chapter 6). The following paragraph summarizes the key features and results of additional, relevant type 4 models.

Mittnik et al. (2020) show that even in the presence of active fiscal and financial policies, consumption may fall because of climate-related externalities from economic activities. The authors include large-scale disasters, capital losses, and risk premia into the framework of Semmler et al. (2019) by making a connection between climate-related disasters and CO_2 emissions. The modeling shows that disasters decrease capital stocks and consumption levels. Because of lower growth and a smaller increase of capital stocks, the extraction and use of fossil fuels also decrease, which leads to a decline in total CO_2 emissions. With a stronger disaster shock,

investigates the optimal amount of climate finance that needs to be attracted over time. They show that the needed investment could be financed via internal debt and portfolio decisions of households. Policy makers should thus consider how households can be incentivized to reallocate part of their savings to green bonds and whether the inclusion of bonds in investment portfolios might mobilize extra funds for more aggressive mitigation actions.

[22] Pareto superiority is a qualifier for a reallocation where the total welfare can be improved without making anyone worse off.

consumption, capital stocks, and debt levels stay low. This outcome is in line with empirical results[23] that show that emissions decline in times of a negative output gap. A negative output gap is also visible with the COVID-19 crisis, which mimics a natural disaster in its effect on output (Pereira da Silva, 2020).

However, a green recovery can be accelerated through the support of climate bonds, reduced credit constraints, and risk premia, according to Mittnik et al. (2020). The issuance of green bonds can raise output, private and public capital, and consumption when a disaster phase has occurred. Bond issuing—along with relaxing credit constraints and risk premia—has significant benefits since it helps scale up mitigation, adaptation, and recovery policies, as we've seen from the previous models under discussion. Sufficient financing measures will support a green transition and may also aid in preventing poverty traps[24] and sudden climate-related financial market instabilities.

Table 5. Beneficial Impact of Taxes and Green Bonds on Key Variables in Semmler et al. (2019)

Single phase model with no green bonds and no additional taxes	**Average**	**Terminal**	**Total**
Consumption	**2.82**	6.45	
Private capital	19.49	15.33	
Public capital	1.53	1.92	
Carbon emissions	2.36	**2.53**	
Social welfare	--	--	***6.0***
Multiphase model with green bonds and debt repayment through a special income tax	**Average**	**Terminal**	**Total**
Consumption	**3.09**	4.84	
Private capital	19.00	15.00	
Public capital	1.91	1.79	
Carbon emissions	2.35	**2.20**	
Social welfare	--	--	***13.4***

Note: The table compares the results of Semmler et al. (2019) for the single-phase and multiphase model with regard to consumption, capital stocks, emissions, and social welfare. Social welfare (last rows) for the multi-regime model is more than double that for the single-phase model, which makes the multi-regime model Pareto superior. Terminal consumption, private capital, and public capital accumulation are slightly lower, but also carbon emissions are lower compared to the single-phase case.

The development of newer macroeconomic climate models helps policy makers better incorporate long-term outlooks into decision-making. With the support of carbon taxes, green bonds can achieve a low-carbon economy that steers down emissions and enhances social welfare. The presented modeling improvements can support policy makers in their decision-making by incorporating long-term approaches that balance short-term benefits with long-term costs. Modeling results show that incorporating green bonds into the policy mix improves total welfare, drives down emissions, and enhances intergenerational burdens. The achievement of a low-carbon transition (for example, building up renewable energy sources) through green bonds was explained in section 3.2 and carried out in this chapter through macro policy augmented and synthesis models (see model types 3 and 4 in table 6) that showed the feasibility of repaying the additional debt with revenues from carbon taxation. Table 6 gives a detailed comparison of advancements in IAMs and other climate models that were discussed in this chapter, with regards to several modeling features. Policy makers should rely on the most comprehensive models to address climate change and improve social welfare by using a policy mix of green bonds and new tax regimes to finance green technology, mitigation, and adaptation measures. A long-term investment perspective instead of short-termism can lead to higher total wealth accumulation and green investments through the incorporation of environmental perspectives, reduce negative externalities, and

[23] See Cohen et al. (2018).

[24] Note that type 4 models (like type 2 models) introduce emissions as having a direct (damaging) effect on welfare. This better encapsulates the multitude of economic, health, migration, and intrinsic environmental losses expected from insufficiently abated climate change.

enhance private wealth accumulation. The relevance of environmental concerns for public decision-makers as well as private investors is addressed in the next section.

Table 6. Detailed Comparison of Macro Model Types Regarding a Set of Model Features

Model type	Individual models	Model features: Extended welfare function	Mitigation policy	Adaptation policy	Renewable and nonrenewable energy sources	Nonlinearities and tipping points	Carbon tax	Green bonds	Multiphase
(1) DICE 2008	**Nordhaus (2008)**		✓				✓		
(2) Extended IAMs	**Bonen et al. (2016)**	✓	✓	✓	✓	✓			
	Semmler et al. (2018)	✓	✓	✓	✓	✓[a]			
	Atolia et al. (2018)	✓	✓	✓	✓[b]	✓			
(3) Macro policy augmented models	**Kato et al. (2015)**		✓[c]		✓		✓		
	Flaherty et al. (2016)		✓[c]					✓	✓
	Heine et al. (2019)		✓[c]				✓	✓	✓
	Orlov et al. (2018)		✓					✓	✓[d]
(4) Synthesis models	**Semmler et al. (2019)**	✓	✓	✓	✓	✓		✓	✓
	Mittnik et al. (2020)	✓	✓	✓	✓	✓[e]		✓	✓

a. Their modeling results include homotopic analysis of parameters as efficiency indices and mitigation efforts.
b. Besides a renewable (green) energy source and a fossil fuel–based, nonrenewable (brown) energy source, this model has a third input for the production function, which is private physical capital (non-CO_2 intensive and with its own capital depreciation rate).
c. Combined policies: Policy efforts for mitigation and adaptation are not separately modeled.
d. The multiple phases of this model emerge endogenously, whereas the regime changes in the other models are introduced manually.
e. Inclusion of disasters as tipping points of climate change that inflict capital losses and lead to jumps in risk premia.

5 Financial Markets and Green Bonds: A Survey and Tentative Assessment

Theoretical and empirical studies have shown that the financial market can be both a roadblock and a bridge to a low-carbon economy. Thus, we next elaborate on some of the modeling of financial markets and green assets and assess some empirical work on the performance of green bonds in the financial markets, using measures suggested by finance theory. We want to note that the green bond market is still small, though quickly growing. Green bond market participants on both the supply and demand sides are heterogeneous and in a learning phase. Moreover, the interaction of green bonds with other sections of the financial market and asset classes is quite complex. For example, arbitrage trading tends to quickly eliminate differences in the performance of different asset classes, often by subjectively assessing future returns and risks of the different assets.

Since the currently scarce supply of green bonds has not been able to meet climate finance needs, green bonds should be transformed from a niche product into a more liquid asset. In particular, since 2017, more than 3,000 green bonds have been issued worldwide, mobilizing more than $800 billion. Green bonds are now being issued rapidly (see figure 3, in section 2.2), and a variety of issuers in the private as well as the public sector use them. The OECD (2017) estimates that the necessary level of investment for the climate transition is 5–7 percent of global GDP, or roughly between $5 and $6 trillion—much larger than current green bond issuance despite recent increases. While there are short-run obstacles to green bonds' scalability,[1] improving the transparency and availability of market data (including impact assessments and reporting patterns) as well as developing a common green bond framework, better defining market borders to reduce the risk of greenwashing, and fostering issuance in emerging economies can help address these challenges (Deschryver & de Mariz, 2020).

In addition to discussing the theoretical studies on green finance in this chapter, we also analyze the empirical side of green bond studies. In section 5.2, we present empirical literature reviews regarding green bonds and their performance compared to conventional bonds in terms of volatility, yields, and Sharpe ratios, among other indicators. (Appendix A provides preliminary empirical evidence on green bond market performance measures based on our suggested framework, which could be used by an interested researcher on those or similar topics.) The initial empirical evidence outlined in section 5.2 should be read with care; future comprehensive empirical studies are needed as the market develops and grows.

5.1 Financial Markets as a Roadblock to Green Investment: A Survey

As discussed in earlier chapters, climate change creates financial market risks that can cause shocks in the stock market, banking system, and portfolio holdings and trigger financial market instability if investors continue to rely on carbon-intensive assets. Indeed, climate change will lead to multiple financial, physical, and transition risks (TCFD, 2017).[2] If economies are still strongly carbon-dependent (and thus dependent on stranded assets),

[1] Deschryver & de Mariz (2020) mention a deficit of harmonized global standards, risks of greenwashing, the perception of higher costs for issuers, the lack of supply of green bonds for investors, and the overall infancy of the market.

[2] Physical risks are associated with climate disasters that might cause financial losses for firms, households, and investors. Transition risks are political, legal, reputational, technological, and market risks associated with the sudden change in asset value(s) because of the transition to a low-carbon economy.

structural changes will generate losses and create instabilities in financial markets, creating a "climate Minsky moment" (Carney, 2018).

The implementation of long-term climate investment depends on overcoming myopic and short-term decision-making behavior and on attracting private investors to long-term green securities. Both private investors and governments exhibit myopic behavior and short-termism[3] in their decision-making. The provision of long-term funding sources reduces policy trade-offs and allows for a necessary intergenerational approach to fiscal policy planning. Green bonds can fill such a role for investors and governments. We now turn to the role of myopic behavior and short-termism as has been observed in investment decisions, asset pricing, and portfolio models.

A short-term-oriented investment approach constrains long-term investments like low-carbon infrastructure and does not place enough value on climate-related assets. Investors follow conventional, not climate-oriented, targets and usually prioritize liquidity and greater capital expenditure, channeling this behavior with executive bonus incentives and stock buybacks (Warren, 2014). An empirical analysis of financial market discount rates shows that private investors' short-termism and myopia have increased in recent times and that investment decisions are especially biased toward carbon-intensive energy firms (Davies et al., 2014). If short-termism behavior dominates, investors cannot adequately assess long-term climate change risks, which might lead to a "tragedy of the horizon" (Carney, 2018). This perspective omits the transition risks of holding stranded assets that will likely lose value in the long run, impacting investors' portfolio and entrepreneurs' physical production.[4]

While loss-averse investors are likely to account for low-likelihood events that lead to great losses (such as climate disasters), conventional financial models do not capture these events. Weitzman (2007) argues that big losses are rare events observed in the thick tail of the distribution of certain variables. In the climate field, these events have been termed "green swan" events (Bolton et al., 2020): a highly unlikely event that has a massive impact on human lives and investments, but the timing of occurrence is uncertain.[5] Climate scientists have alerted us to the likelihood of these events, but economic and financial studies tend not to capture them. Often conventional models do not account for these events even though investment studies where investors exhibit loss aversion pointed out this likelihood (see Gruene & Semmler, 2008). This oversight can constrain the development of green financial markets and impact long-term green investment funding.

To induce private investors to consider green assets in portfolio decisions, analyses should move beyond conventional static models and toward dynamic portfolio models.[6] In financial markets, investment decision models are also still highly influenced by modern portfolio theory,[7] such as the well-known capital asset pricing

[3] Here, we use "short-termism" and "myopic behavior" to refer to decision-making that is not based on long-term time horizons. Short-termism and myopic behavior are not equivalents: Myopic behavior involves decisions that consider only the very short term (that is, only during the current period), while short-termism includes decisions that consider more than one period but are still short term oriented. In this chapter, we use short-termism for roadblocks to long-term climate-oriented investment and use myopic behavior for government short-term decision-making. In section 5.2, we define long-term bonds as bonds with a maturity equal to or greater than 10 years.

[4] Dietz et al. (2016) find the climate value at risk (VaR) of global financial assets is on average 1.8 percent (or $2.5 trillion), but most of the risks are concentrated in the distribution tail, 16.9 percent for the 99th percentile ($24.2 trillion). *The Economist* Intelligent Unit (EIU, 2015) estimates that the VaR of global financial assets due to climate change is around $13.8 trillion for private assets (about 10 percent of total global assets). For public assets, losses are estimated at about $43 trillion.

[5] One example of this kind of disaster is the COVID-19 pandemic. While it cannot be classified as a climate disaster, it has evolved as a "black swan" event and helps us understand the potential future economic and social impact of climate-related negative externalities (Pereira da Silva, 2020).

[6] See the "Principle for Responsible Investment," the "Climate Action 100+," and the "Investor Group on Climate Change." In the United States, financial assets whose managers apply ESG criteria for portfolio selection have increased 13.6 percent per year since 1994, reaching $11.6 trillion in 2018—that is, 25.7 percent of the total managed assets in the country (US-SIF, 2019). Globally, this amount reached $30.7 trillion in 2018 (GSIA, 2018).

[7] The Markowitz mean-variance model (Markowitz, 1952), followed by Tobin's mutual fund theorem (Tobin, 1958), states that investors make decisions based on the expected returns (mean) and the risk (variance) of various portfolios.

model (CAPM), a static model in which investors choose between risky and risk-free assets based on a mean-variance approach (Sharpe, 1964; Lintner, 1965).[8] However, these models are poor instruments to address climate-related risks since they do not induce investment in long-term bonds or consider the nonlinear dynamics of climate variables. Dynamic portfolio models are a better instrument for including climate risk dynamics in investor decision-making.[9]

Semmler et al. (2020) use an adjusted dynamic portfolio decision model and find that investors' short-termism and myopic behavior are obstacles to green long-term investment. Their baseline model examines two assets: a risk-free bond and an equity asset that displays time-varying returns, with and without shocks. Under this framework, the effects of short- versus long-term investment strategies are considered, specified by the decision horizon.[10] The model shows that if investors exhibit more impatience (namely by having a high discount rate), the value of the discounted future payoffs and the present value (in other words, the sum of these discounted future payoffs) will be reduced below the investment cost (see table 7) and the green investment will not be undertaken.

Table 7. Change of Present Value due to Change in the Discount Rate in Semmler et al. (2020)

N = 6	T = 40	T = 40	T = 40	T = 40	T = 40
ρ	0.01	0.015	0.03	0.07	0.15
PV	138.1 ≥ Inv	133.3 ≥ Inv	126.1 ≥ Inv	109.5 ≤ Inv	85 ≤ Inv

Note: Increasing discount rates reflect increased short-termism, which harms investment and the creation of long-term values. This is indicated by a lower present value for higher discount rates. Semmler et al. (2020) assume an investment cost of Inv = 110. If the PV, given the high discount rate, is lower than 110, the investment (green investment) would not be undertaken, this is the impact of short-termism on green investments. ρ = discount rate; PV = present value; Inv = investment.

Thus, short-termism expressed through high discount rates is an obstacle to the development of renewable energy and a low-carbon transition. If short-termism and shareholder nearsightedness dominate, projects with higher risk or information constraints are not taken on. This is true for low-carbon-intensive energy firms, as Davies et al. (2014) show through their empirical analysis of discount rates. Thus, renewable assets might not attract enough investors. Of course, marginal investment projects with lower discount rates could also be affected; for instance, the value of fossil fuel energy assets that are originally seen as profitable could suddenly collapse when the discount rate swings up, as studies of the years 2008–09 have shown (Cochrane, 2011).

Carbon-intensive assets can also decrease welfare; model results show that the substitution of fossil fuel investments with green investments can improve wealth accumulation, creating positive externalities and reducing negative externalities. Semmler et al. (2020) examine the impacts of channeling a fraction of investor wealth into either green or fossil fuel–based innovation.[11] The results on asset formation for different decision horizons and asset types (that is, renewable versus nonrenewable assets) show that portfolio decisions with

[8] There are, however, some initiatives worldwide of the implementation of new climate assessment models that overcome traditional risk modeling. See, for example, UNEP FI (2019), Almeida & Braga (2020), KfW (2020), and Cambridge Centre of Sustainable Finance (2016).

[9] For dynamic portfolio models, see Campbell & Viceira (2002) and Chiarella et al. (2016). Static CAPM models do not consider several key factors included recently by dynamic portfolio models: Decisions are made under constraints, returns are not fixed over time, and asset profiles and time horizons are not the same for every investor. Yet those improvements still do not consider additional constraints, such as myopic behavior and externalities associated with certain asset types.

[10] The technical details of the model are explained in appendix B.

[11] The investment of a fraction of wealth into innovation has a time-varying return re(t) that can be positively or negatively affected by the investment decision. The value of an investment that does not create long-term negative externalities (such as renewable energy) will be positive, whereas the value of an asset that creates long-run adverse effects on the economy through negative externalities (such as CO_2 emission) will be negatively affected.

long decision horizons yield superior asset formation. By looking at portfolio allocation paths with the same decision horizon, the results show that portfolio decisions that promote green innovation yield higher asset returns and wealth than investment decisions that fund nonrenewable technology, as the latter induce negative environmental externalities usually not directly reflected in the asset return.[12]

Short-termism and negative externalities not internalized in asset price formation will prevent green investments from easily taking off, constraining public climate policy and increasing risks for financial market investors. Investment projects with higher uncertainty (like renewables) are often viewed as receiving lower short-term gains and may not attract sufficient investment; thus, the portfolio holdings of this type of asset will decline. This decline prevents the quick generation of renewable energy investments and yields inferior wealth outcomes over time, as demonstrated by Semmler et al. (2020). Neglecting to invest in green technologies can lower asset returns in the long run because of negative externality effects resulting from CO_2 emissions (for example, stranded assets and disrupted production processes due to environmental damages).

While green market awareness develops, public policy can help internalize negative externalities into asset price formation by de-risking green investment and imposing carbon taxation. First, the ability to attract investors and the feasibility of green projects can be enhanced if the public sector supports the de-risking of green bonds. Braga et al. (2020) discuss the increasing role of governments and multilateral organizations in the green bond market and show that public green bonds have lower yields, risks, and volatility, and so may be a particularly attractive investment to loss-averse investors with a risk-constrained portfolio. Second, the implementation of Pigouvian carbon taxation can decrease the profitability of carbon-intensive sectors, which also impacts financial markets. The introduction of carbon taxes can thus increase relative returns for green bonds and decrease returns for fossil fuel–related assets. In particular, carbon taxation decreases the costs of green bonds and leads to lower volatility for green investments (Heine et al., 2019; Gevorkyan et al., 2017). In practice, pricing mechanism effects can also be amplified by coordination efforts between economic agents to internalize pollution as well as nonmonetary disutility from holding polluter stock (Baker et al., 2019).

We should note that negative externalities from carbon emissions are likely to affect assets' relative risk and return even if investors do not take them into account when pricing green bonds, given the existence of positive externalities associated with low-carbon investment and the negative externalities related to carbon-intensive ones (see appendix C). However, green investment could benefit if green assets are also more attractive to private investors in terms of risk or return, whether induced by public policy (for example, carbon taxation and de-risking) or not. Next, we present a literature review and discuss the existent and tentative empirical evidence on the performance of green bond markets vis-à-vis conventional bond markets and how financial innovation and climate policy can benefit green asset returns.

[12] Short-termism can be expressed by high discount rates or short decision horizons. The model compares dynamic portfolio allocation for three different decision horizons (looking 8 time steps, 6 time steps, or 2 time steps ahead) and for the possibility of the environmental impact of portfolio decisions on wealth accumulation (either a positive impact due to environmental investments, a negative impact due to further fossil fuel investments, or no externalities feedback effect). The model outcome shows that the curve with a long decision horizon (N = 8) has the highest wealth accumulation; curves with the same decision horizon (N = 6) differ because of negative externality effects that come from investment into nonrenewables, which drive a lower asset formation; the curve with the shorter decision horizon (N = 2) exhibits a rapid decline in assets. More detailed model explanations are given in appendix C.

5.2 The Performance of Green Bonds in the Financial Market: A Literature Assessment

The OECD (2017) estimates that climate investment needs vary from $5 to $6 trillion, while institutional investors hold around $120 trillion in assets not channeled yet to climate investments (Bielenberg et al., 2016). Attracting this finance will require a shift in investor preferences, both as a result of private initiatives as well as fiscal and other policy interventions. Some studies have already mapped investor preferences, evaluating the performance of green assets vis-à-vis conventional securities. To measure this performance, the studies use indicators such as yield, asset volatility, liquidity, and Sharpe ratio (table 8). Keeping in mind that green security markets are still small and face obstacles such as those discussed in section 5.1, we next review some of these studies. Additional empirical evidence should be considered, revisiting these conclusions as the market evolves and the available data set expands.

Although there does not yet seem to be clear-cut empirical evidence for a (negative) premium for green bonds, a growing body of literature shows that under certain conditions green bonds can face better market conditions than conventional bonds, thus lowering capital costs and volatility. Green bonds attract long-term investors who value environmental gains and follow a buy-and-hold strategy, such as pension funds (Cochu et al., 2016; Flammer, 2018, Deschryver & de Mariz, 2020). Green bonds induce ESG-sensible investors to diversify their portfolios, allowing for new issuers and diversifying risk (Climate Bonds Initiative, 2018; Moody's, 2018). It implies lower volatility and, as new investors enter the market, green bonds' relative prices increase, lowering yields and capital costs. Zerbib (2019) finds a significant green bond premium related to investors' pro-environmental preferences, especially if the bond is issued in the financial sector or by low-rated issuers. Baker et al. (2018) find that US corporate and municipal green bonds have been traded with a premium as well (on average, 6.3 bps lower than conventional ones). Nanayakkara & Colombage (2019) find a similar result for a global sample.

However, as noted before, this market is at an early stage and growing. Some authors argue that the context matters and that market conditions for green bonds have recently improved. Partridge & Medda (2018) find that yield differences for green bonds have been increasing over time: In 2017, they found a yield difference of roughly 5 bps, while in 2014 there was no relevant difference. Febi et al. (2018), based on liquidity indicators such as the bid-ask spread and the LOT liquidity measure, find that the impact of liquidity risks on spreads has become negligible only in recent years. These discussions illustrate the importance of monitoring the market for the next few years before drawing any strong conclusion about the performance of green bonds vis-à-vis conventional bonds.

Furthermore, green bond performance in financial markets seems to also depend on issuer characteristics such as reputation, industry, or risk profile. The issuer's reputation can be measured by its commitment to environmental policy and by the existence of third-party green certification for the investment. Bachelet et al. (2019) find evidence that green bonds issued by institutional issuers (for example, multilateral organizations) are more liquid and have a negative premium. Moreover, private issuers of noncertified green bonds face worse market conditions: lower liquidity and a positive premium. Li et al. (2020) and Fatica et al. (2019) also find that certified bonds have lower interest costs. Nevertheless, empirical studies find that other factors also matter when defining this premium size, such as the issuer industry (Hachenberg & Schiereck, 2018; Gianfrate & Peri, 2019) and the rating (Ehlers & Packer, 2017; Hachenberg & Schiereck, 2018).

Table 8. Bond Performance Indicators in Practice: Description and Potential Data Sources

Performance indicator	Description	Literature reference	Potential data sources
Asset volatility	Measurement of the dispersion of an asset return (given by the standard deviation of the returns or by the beta price). Riskier assets tend to have more volatile returns. The volatility can be measured in a time series for a given asset or a cross-sectional between similar assets.	Horsch & Richter (2017), Reboredo (2018), Nasreen et al. (2020), Bondia et al. (2016), Christoffersen & Pan (2018), Reboredo & Ugolini (2018), Ahmad (2017)	S&P Green Bond Index, S&P 500 index, S&P 500 Bond Index, Barclays MSCI Green Bond Index, Solactive Green Bond Index, Bloomberg (volatility for 30, 90, and 260 days)
Current yield, yield to maturity, and yield at issue	Measures of a bond return. The current yield measures the annual coupon yield in relation to the bond current price. The yield to maturity measures the total return if a bond is held to the maturity date. The yield at issue measures the current yield at the date of the bond issuance.	Zerbib (2019), Baker et al. (2018), Nanayakkara & Colombage (2019), Partridge & Medda (2018), Bachelet et al. (2019), Li et al. (2020), Fatica et al. (2019), Kapraun & Scheins (2019)	Bloomberg Fixed Income search, Mergent, Climate Bonds Initiative, Thomson Reuters Datastream
Liquidity	Liquidity indicators measure how easily an asset can be sold in the market. It depends on the supply and demand conditions in the financial markets. It can be measured by the market size, the bid-ask spread, or the LOT liquidity measure (see Chen et al., 2007).	Bachelet et al. (2019), Febi et al. (2018)	Bloomberg Fixed Income search, Thomson Reuters Datastream
Sharpe ratio	The Sharpe ratio is a risk-to-return measure, whereby the portfolio standard deviation describes the risk of a portfolio (see Sharpe, 1994). The combination of both the yield level and the variation in yields (portfolio volatility and risk) is integrated in the classical Sharpe ratio. We call the classical Sharpe ratio SR_p ("portfolio Sharpe ratio"), indicated by the following formula: $$SR_p = \frac{\overline{R_P} - R_F}{\sigma_p}$$ Where SR_P = portfolio Sharpe ratio, $\overline{R_P}$ = average portfolio returns, R_F = risk free rate, and σ_p = portfolio standard deviation.[a]	Original concept: Sharpe (1994); Application of the Sharpe ratio to green bonds: Ehlers & Packer (2017), Giroday & Stenvall (2019), Kochetygova & Jauhari (2014), Han & Li (2020)	Databases indicated above, from which one can obtain yield and volatility indicators

a. In appendix A.4, we further introduce an asset-specific measure, which we call SR_b ("bond-specific Sharpe ratio"), to be used in the regression analysis. Inspired by the original Sharpe ratio, it carries individual excess bond returns in the numerator and a measurement for a bond return volatility over time in the denominator: $SR_b = (R_b - R_f)/v_b$. Where, for each bond we have SR_b= bond-specific Sharpe ratio, R_b = individual asset return, R_f = risk free rate, and v_b = individual asset volatility measure.

Although several empirical studies find that green bonds have lower yields and face, according to some measures, better market conditions than conventional bonds, there is as yet no consensus on the performance of green bonds. First, as stated above, the market is still small; green bonds are currently evolving from a niche product into a more liquid one. New evidence should be considered as this market develops and increases in size. Second, even with existent data, some empirical studies do not find yield differentials in favor of green bonds (Larcker & Watts, 2019; Kuhn et al., 2018; Hyun et al., 2019;[13] Karpf & Mandel, 2018).

[13] The authors find a premium if the bond is certified by an external reviewer, only.

However, even if there are no price differentials, the literature reports certain benefits in issuing green bonds: positive externalities in financial markets (as discussed in section 5.1) and lower volatility in financial returns. Research has shown that green bonds can protect investors from volatility associated with energy and commodity price fluctuations, which reduces portfolio risks (Horsch & Richter, 2017; Reboredo, 2018). The same conclusion can be drawn from empirical analyses of green stocks (Nasreen et al., 2020; Bondia et al., 2016; Christoffersen & Pan, 2018; Reboredo & Ugolini, 2018; Ahmad, 2017). Green bonds can thus improve the Sharpe ratio of stock-bond portfolios (Han & Li, 2020). On the other hand, studies also find that the financial benefits of diversifying investments to include green securities are not necessarily attained, depending on market conditions and on the success of the new green technologies (Sadorsky, 2012; Henriques & Sadorsky, 2008; Dutta, 2017). We contribute to this debate in chapter 6 by presenting an empirical study of the volatility of green bond returns along business cycles.

Future empirical studies should follow up on green financial market performance across business cycles and examine not only fixed income assets but also equity and hybrid instruments, such as convertible bonds (see box 2). Innovations in green finance can induce lower yields and allow the social return to rise in the long run, facilitating asset accumulation. Convertible bonds, for example, allow both investors to benefit from future capital gains associated with positive climate externalities (and protect against negative externalities from carbon-intensive assets) and issuers to access resources with lower interest rates in the present. The benefits of convertible green bonds and the abovementioned effects on firm value are illustrated by an improved version of the Semmler et al. (2020) model in appendix C, which also provides researchers and policy makers with an additional empirical tool to assess the benefits of green assets over time.

Given that further empirical studies are still needed for a better understanding of green bond performance, appendix A provides an empirical approach to compare the performance of green and conventional bonds and some preliminary results of its application. This analysis can be applied to financial markets' cross-sectional data and help comparisons of yield differentials (yield at issue and yield to maturity), volatility of bonds, and Sharpe ratios for different types of bonds and issuers.

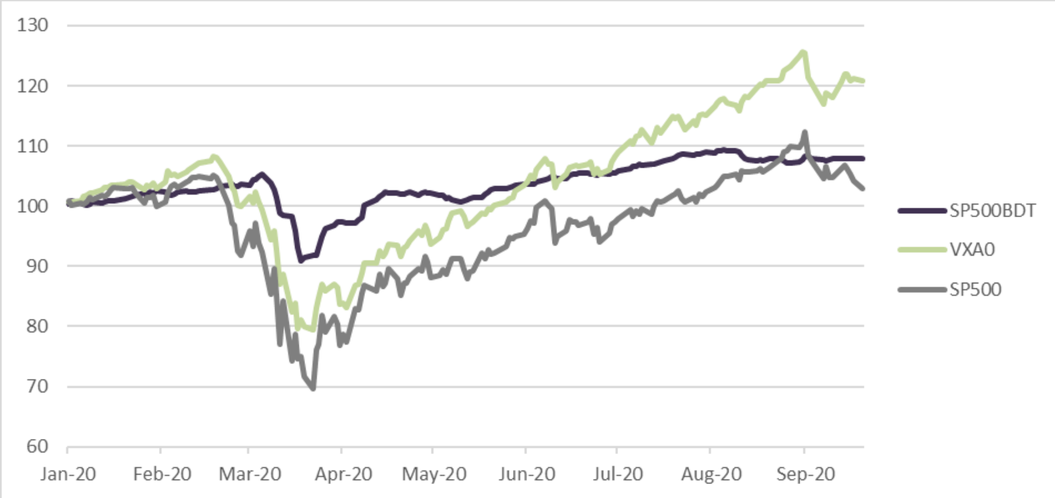
Box 2. Innovation in the Green Bond Market: Convertible Bonds

Convertible bonds have recently been issued with green labels as an alternative to conventional fixed income bonds (Gregory, 2020). Financial instruments should be customized to meet investment needs. Firms tend to pursue the diversification of funding sources when investment needs increase, moving from debt to equity (Semmler, 2011). Also, innovative firms face higher capital costs and market constraints that limit debt access (Hall & Lerner, 2010). A convertible green bond is a solution that can address these challenges and benefit long-term issuers and investors (see appendix C).

Convertible corporate bonds are securities that can be converted into shares of the issuing firms' stock. The condition of convertibility to equity might be tied to an equity price through a strike price, as the Merton model for debt and the Black & Scholes model for derivatives suggest (see section 5.2 and appendix A.1 for further discussion of these models). The existence of this option allows issuers to leverage funding at lower yields in the debt market and investors to gain benefits along business cycles (that is, protection in downturns and gains in upturns). If the issuer succeeds and the stock price increases, the lender has the option to convert bonds into equity and earn capital gains. The benefits are likely to accelerate if the distance to default also decreases. If the issuer fails, the fixed income return is ensured. This hybrid instrument can solve market imperfections associated with asymmetric information regarding a firm's risk and returns (Nyborg, 1996). This is especially true for activities with high externalities and risks, such as innovative and environmental projects.

A surge in the convertible bond market was observed in 2020 following the COVID-19 crisis. In the United States, new convertible bonds totaled $77 billion as of September 2020, an increase of 45 percent over 2019 and 200 percent over 2015.[a] The convertible bond market index (ICE BofA US Convertible Index—VXA0) outperformed other market indexes such as the S&P 500 Bond Index (SP500BDT) and the S&P 500 (SP500). In 2020,[b] the VXA0 yield-to-date returns (YTD) was 20.9 percent; the SP500BDT, 7.85 percent; and the SP500, 2.97 percent (figure B2.1).

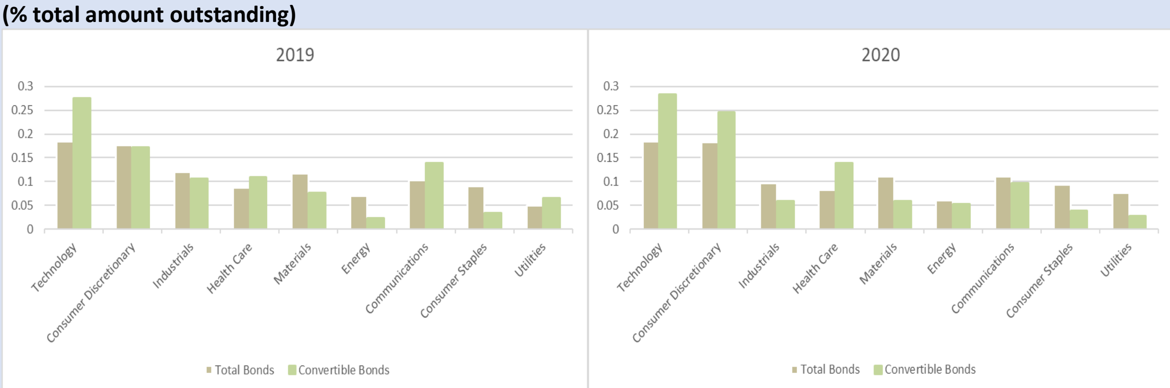
Figure B2.1. Yield-to-Date Returns for Convertible Bond Index Vis-à-Vis Other Market Indexes



Source: Bloomberg and S&P.
Note: Base 100, on 12/31/2019.

This surge is explained by the recent market downturn and by the profile of convertible bond issuers. High-tech, growing firms are more likely to leverage funding through the convertible bond market than fixed income markets (figure B2.2). In 2020, US technology firms such as Okta, Lyft, and Snap accessed this market. In 2019, Chinese technology firms such as the electric car start-up Nio and the streaming platform iQiyi issued a total of $5.3 billion in convertible bonds, four times more than in 2018 (Lockett & Ruehl, 2020). On the issuer's side, higher credit costs for high-tech firms and higher equity market volatility induced firms to access hybrid instruments (Goodwin Procter LLP, 2020). On the investor's side, an explanation for this trend is current low asset prices combined with low interest rates that lead to higher conversion prices.

Figure B2.2. Total and Convertible Corporate Bonds: Sectoral Distribution Excluding the Financial Sector, BICS Level 1 (% total amount outstanding)



Source: Bloomberg.

Given market uncertainties and technology requirements for green investment, convertible bonds should be supported as a sustainable finance instrument. Following this trend, six different issuers from distinct sectors issued green convertible bonds in 2020, for a total amount of $1.1 billion.[c] This represents only 1 percent of global issuance, but a growing trend can be observed.[d] The benefits of convertible green bonds for the climate transition are discussed in more detail in appendix C, as these bonds allow investors to benefit from the positive externalities from green assets and help protect against negative externalities from carbon-intensive sectors.

However, additional solutions must also be implemented to address sovereign debt. Convertible bonds are currently associated with corporate debt, but previously this instrument was used for government debt. During the 1980s, debt-to-equity swaps were implemented in Latin America for debt renegotiation: A large number of swap operations took place in Argentina, Brazil, Chile, and Mexico; however, the schemes were highly criticized for not increasing capital accumulation or promoting development. For example, these debt-to-equity swaps gave foreign investment preference in certain sectors or offered state-owned enterprise stocks as part of privatization programs (Buckley, 1998; Monteagudo, 1994).

For the current crisis and in the context of a green bond market, a forward-looking and inclusive solution to sovereign debt is needed instead. An improved approach to sovereign debt swaps should be able to promote sustainable growth and build additional capabilities in the developing world. One example is the use of a debt-for-development swap associated with climate investment requirements (Degnarian, 2020). But green convertible bonds could also be used for sovereign debt control: Debt is issued at lower rates to implement green infrastructure and can later be converted to project shares after project completion.

a. According to the Fixed Income Security search in Bloomberg Terminal.
b. Cumulative returns by September 2020.
c. Based on the Bloomberg Terminal Fixed Income search. Electricité de France (Utilities, France), Falck Renewables (Utilities, France), Neoen (Utilities, France), Livent (Chemicals, US), Hannon Armstrong (Real Estate, US), Plug Power (Renewable energy, US), and Atlantica Sustainable Infrastructure (Utilities, Spain).
d. In 2014, by Innovatec SpA (EUR 3.8 million). In 2018, by Sumitono Forestry (JPY 88.15 million). In 2019, by Link 2019 CB Ltd (HKD 509.59 million).
e. See https://www.nytimes.com/1989/01/02/business/debt-equity-swaps-draw-latin-criticisms.html.

Our starting point is the methodology and findings from Kapraun & Scheins (2019): The authors do a comprehensive empirical study comparing green and conventional bonds and find a negative green bond premium in the primary markets for euro- and US dollar–denominated bonds, giving rise to lower capital costs for green investment. They run regressions with fixed effects for the issuer name, date of issuance, currency, seniority, maturity, and issuance size but also analyze conventional and green bond pairs to test how significant these differences are. For primary markets, the yield differentials show that green bonds carry a negative premium, giving rise to lower capital costs, especially for bonds issued by more reliable entities such as governments and supranationals. For secondary markets, a negative premium difference is found only for governments and supranationals. In conjunction with this work and previous studies on yield differentials between green and conventional bonds, we provide descriptive statistics and regressions for a group of bonds as well as for pairs of similar bonds (following characteristics such as sector, maturity, risk, currency, and so on).

We combine this approach with the structural bond pricing tradition literature, which aims to explain bond yield and risk premium drivers focused on different firm-specific drivers. It provides us a more comprehensive perspective to bond yield differential drivers. Merton (1974) inaugurated this tradition of credit risk modeling based on a firm value model. From his perspective, modeling credit risk means modeling default probability. It expands the seminal Black & Scholes (1973) model toward a general theory for corporate debt. Merton (1974), taking for granted the Modigliani-Miller theorem (1958), assumes that the value of a firm equals the sum of its debt and equity levels (thus, equity and liabilities are a fraction of the firm’s value). The default premium is caused by both the high leverage of the agent and the high volatility of the asset value.

Our complete methodology and its theoretical background are further detailed and presented with the initial results in appendix A. Just looking at the data (without additional inferences), the initial results show that, on average, green bonds are likely to have lower yields and lower volatility than conventional bonds. On average, green bonds tend to have higher Sharpe ratios as well. Our findings are also reflected in the referred literature, but it is important to mention that these results are not definitive, given the current state of the green bond market. Green bonds have displayed less volatility than the broader fixed income market and seem to have outperformed recently; however, as the market is still small (particularly for green sovereign bonds—an asset class that has a low probability of default) and shows low liquidity (most investors “buy-and-hold” and the bonds are not heavily traded in the secondary market), empirical analysis of these market movements is still challenging. Further analysis of this issue is warranted as this market develops. We thus encourage further studies as this market grows and becomes more liquid.

6 Business Cycles and the Proper Mix of Carbon Taxation and Green Bonds

The use of carbon taxation and green bonds is an important strategy to expedite the low-carbon transition and reduce instabilities in financial markets. Earlier, we discussed how macroeconomic and financial roadblocks can be removed to model a transition more suitably—and give policy advice—to achieve a low-carbon economy. In chapter 5, we assessed whether green bonds are less volatile and less risky than carbon-intensive securities. Evidence proving that would provide us with important lessons for climate fiscal policy, as bond issuance and management are important components of active fiscal policy strategies.

Green bonds and carbon taxation also have a role to play in green economic recovery plans. Both instruments are an essential part of existent climate transition plans in advanced countries. Green investment can be funded through low-cost sovereign debt (Kemfert et al., 2019) and has stronger multiplier effects in both the short and long runs (Batini et al., 2021; IEA, 2020; Vona et al., 2019; Hepburn et al., 2020). In the wake of the 2020 COVID-19 pandemic, governments and academia have discussed how to reshape green economic recovery initiatives against the backdrop of a pandemic-driven economic meltdown. However, in times of crisis and uncertainty forward-looking policy making is difficult and policy makers are generally encouraged to make decisions off present observations instead of forecasts (De Grauwe & Ji, 2020). Furthermore, recessions might constrain the fiscal policy space of countries, as tax revenue decreases and financial market instability increases. Therefore, policy instruments that can fund a green countercyclical policy while maintaining financial market stability are of increasing importance.

Here, we show that there are important benefits from using carbon taxes and green bonds to respond to recessionary business cycle regimes. The proper combination of debt and tax instruments varies with the characteristics of the business cycle regime. During recessions, a carbon tax is likely to be only moderately used, but governments can take advantage of certain green investments' larger job multiplier effects and foster investment funded by green debt. In section 6.1, we discuss the characteristics of business cycles, how they are affected by oil price fluctuations and their impact on financial markets and fiscal policy. In section 6.2, we apply harmonic estimations to oil price changes and green, conventional, and fossil fuel market indexes and add evidence that green assets reduce government's and investor's exposure to riskier carbon-intensive securities. In section 6.3, we analyze the effect of an increasing share of green bonds relative to fossil fuel bonds on portfolio variance and find additional evidence for the de-risking effect of green bonds during periods of oil price declines. In section 6.4, we apply a nonlinear LVSTAR and evaluate the performance of green and fossil fuel securities under different business cycle regimes, confirming the previously obtained results.

6.1 Fiscal Policy Under Different Business Cycle Regimes

Business cycle regimes influence fiscal policy decisions as the effectiveness and constraints of fiscal policy vary according to the regime. Under stable economic conditions, one could argue that fiscal policy does not affect growth rates because fiscal expansion (or contraction) would be followed by a fiscal contraction (or expansion).[1]

[1] This has been called the Ricardian equivalence theorem in economics. Thus, under rational expectations and perfect foresight, agents decide current and future consumption levels based on Friedman's permanent income hypothesis (Barro, 1974).

However, looking at the impact of business cycle regimes shows that regime switching can change expectations, liquidity levels, labor market conditions, credit constraints, and financial stress levels. Regime-switching models (such as multi-regime VARs or threshold VARs) are necessary to capture these nonlinearities that may include non-mean reversion dynamics (Hamilton, 1989). Looking at different business cycle regimes supports a better understanding of the role and dynamics of fiscal policy under different market conditions.

The fiscal policy multiplier varies with the business cycle: The benefits of fiscal expansion increase during economic downturns but also depending on the types of investment projects, as green investments can carry larger multiplier effects. The fiscal expansion multiplier is much higher in a regime with low economic activity than in a regime with higher growth rates (Borsi, 2018; Mittnik & Semmler, 2012; Corsetti et al., 2012).[2] For advanced countries, this effect arising from fiscal expansions is even stronger at the beginning of downturns (Blanchard & Leigh, 2013). However, the spending multiplier also differs by type of project: There is a growing perception that certain types of green investment have higher multiplier effects in the short and long runs (Batini et al., 2021; IEA, 2020; Hepburn et al., 2020). Vona et al. (2019) find that one additional green job creates 4.2 new local jobs in nontradable, non-green activities (higher than the multiplier seen in the mining industry, for example). Furthermore, recession-associated financial instabilities are likely to reduce the effectiveness of monetary policy and so additional policies should be implemented to reduce credit constraints and financial stress levels, as discussed in Mittnik & Semmler (2012).

The perception of fiscal sustainability is also likely to vary as debt levels and fiscal space change according to financial market conditions and GDP growth. Bohn (1998) argues that governments can achieve sustainable debt when the primary surplus to GDP ratio is a positive linear function of the debt to GDP ratio.[3] Blanchard (2019) defends the idea that there is fiscal space for new debt issuance when interest rates are below growth rates, which is actually the case in high-income countries for most of the period after World War II, but not necessarily in middle- and low-income countries. Of course, these conditions vary with the business cycle regime as we observe in empirical studies for advanced and developing countries.[4] In advanced countries, the business cycle regime after the COVID-19 pandemic is characterized by large negative growth rates combined with low sovereign bond yields, high volatility and losses in financial markets, and a deep decline in oil prices. Given the income reduction and the rapid rise of job losses and credit constraints, for a better understanding of how to design appropriate fiscal policy, it is important to understand how financial stress and oil price shocks can be addressed in regime-switching models.

Different financial stress levels strongly impact credit conditions and investor risk appetites, thus affecting fiscal stabilization policy. Blanchard (2019) emphasizes the low cost of debt as a relevant policy decision variable. In the context of high financial stress, credit is constrained while growth rates decrease or become negative. Such regime switching can be captured by financial stress thresholds such as risk premia, asset prices, and overleveraging indexes.[5] During downturns, when the economy is hit by a negative shock, high leveraging in financial markets can be accompanied by more severe credit restrictions and output contractions. As the negative shock affects asset prices, unstable dynamics involving a fire sale of assets and a further decrease of asset prices lead to an increase of credit risk and risk premia, driving up default probabilities and thus risk premia

[2] On the other hand, contractionary fiscal policy has stronger negative effects during recessions (Baum et al., 2012).

[3] Assuming that the response of the surplus to debt remains linear.

[4] For a regime-switching analysis of debt sustainability, see Aldama & Creel (2019) and Reyes-Heroles & Tenorio (2019).

[5] For regime-switching models with financial stress, see Aristei & Gallo (2014), Schleer & Semmler (2016), Semmler & Chen (2014), and Mittnik & Semmler (2012).

again (Brunnermeier & Sannikov, 2014). In this way, financial markets alternate between periods of high volatility, insolvency risk, and risk premia, and periods of low volatility and risk (Hamilton, 1989; Cai, 1994).

The volatilities in financial markets can constrain fiscal policy when accompanied by sovereign risks, limiting access to financial markets, especially in the developing world. Market downturns and uncertainty increase sovereign risks and impact financial market volatility and government bond liquidity, price, and spread.[6] This effect is usually stronger in more fragile emerging markets, in which higher volatility and a lower growth regime are associated with interest rate spikes and sudden stops in external financing.[7] Spillover effects between different markets reinforce these price volatilities as investors move to safer assets, such as fixed income securities and bonds in lower-risk countries such as the United States (Kontonikas et al., 2013; Fratzscher, 2012). However, the current regime is characterized by low sovereign debt costs, which can help overcome the economic recession even with instabilities in financial markets and oil prices.

Business cycles are linked to the volatility of oil prices, which in turn may depend again on the business cycle regime. The seminal Hotelling (1931) model discusses the relationship between resource use and oil prices and finds that prices increase while reserve levels decrease with economic growth. However, empirical facts show that oil prices first declined during the early 20th century then began rising in the 1970s, in a U-shaped curve. In other words, the resource discovery rate matters for resource prices and not only the demand (Greiner et al., 2012; Nyambuu & Semmler, 2014; Pindyck, 1978). In fact, the oil price shock in the 1970s induced a perception among economists that recessions could be caused by increasing energy costs and related supply-side effects.[8] Hamilton (1983; 2010) argues that exogenous positive oil shocks explain almost every recession since World War II. However, this relationship differs depending on a given countries' productive structure, on the interaction between supply and demand factors (Arezki et al., 2017; Greiner et al., 2012), and on the nonlinearities that downturns and upturns generate (Hamilton, 2010; Herrera et al., 2010). Oil prices are also endogenous to economic growth and should not be treated only as an exogenous shock, as increasing oil demand relates to higher growth rates (Kilian, 2009).[9]

Oil prices are regime dependent and drive sovereign risks and fluctuations in financial markets, impacting fiscal policy conditions and asset prices. Oil price shocks are one of the main drivers of stock market return volatilities (Guo et al., 2011; Aloui & Jammazi, 2009). While a high-volatility regime is more likely to occur during recessions (Balcilar et al., 2015), there is evidence of cyclical co-movements between oil prices, output, and stock prices (Ewing & Thomson, 2007). Indeed, volatilities in oil prices spill over to stock markets, as empirical studies show for the S&P 500 Index and the S&P 500 Energy Select Index (Aloui & Jammazi, 2009; Choi & Hammoudeh, 2010;

[6] For empirical studies in advanced countries, see Dufrénot et al. (2014), Gourieroux et al. (2013), and Blommestein et al. (2016).

[7] For empirical studies, see Reyes-Heroles & Tenorio (2019), Riedel et al. (2013), and Ma et al. (2018).

[8] When supply constraints hold, keeping a steady growth rate of production is physically impossible and should also be considered by economic modeling—see Meadows et al. (1972) and Daly (1987), who predict a decline in production capacity given physical resource constraints; see Greiner et al. (2012) and Nyambuu & Semmler (2014) for a model that considers the use of resources and the technical conditions for the extraction ratio. See also Solow (1974) for an extended Solow model with finite resources. For a literature review on the debate on the relationship between oil prices and growth, see Brown & Yücel (2002). Also, negative externalities arising from the use of nonrenewable resources and carbon emissions should affect the social welfare function, by decreasing capital accumulation and growth rates. It is also possible to introduce nonrenewable resource use to the utility function, as in Krautkraemer (1985). Nordhaus (2008) includes a damage function in the growth model, in which increasing temperatures reduce capital accumulation and output. Though, as we have discussed in chapter 4, we know that damages should impact not only production but also household utility as climate change and climate disasters might impact habits and health and living conditions, for example. Bonen et al. (2016) present a more comprehensive model that includes damages directly impacting the welfare function. Moreover, this model can be advanced with the introduction of technical change, to find nonpolluting renewable resources to replace the nonrenewable sources, as in Dasgupta & Heal (1974) and Acemoglu et al. (2012).

[9] For an empirical analysis, see Tapia (2016) and Vo (2009).

Balcilar & Ozdemir, 2013).[10] These volatilities bring unexpected price changes that negatively impact S&P 500 returns (Lee & Chiou, 2011), although regime-switching models show a different reaction to shocks depending on the regime and the direction of oil price shocks (Balcilar et al., 2015; Jammazi & Nguyen, 2015). This shock might also be particularly relevant for oil-producing countries and firms, as there is a strong positive relationship between oil prices and returns (Wang et al., 2013; Naifar & Al Dohaiman, 2013; Phan et al., 2014).

The link between business cycles and oil prices raises the question of whether green securities—like green bonds—are a better fiscal policy instrument to fund recovery plans. Debt instruments are especially important to fund green investments in the current business cycle regime, which is characterized by negative growth rates accompanied by low sovereign bond yields (Kemfert et al., 2019). The economic landscape after the COVID-19 pandemic was also characterized by a strong decrease in oil prices and related impacts on financial markets. The next sections compare green, conventional, and fossil fuel bond performance and test if green bonds are less vulnerable to business cycle regimes and oil price fluctuations and thus a better hedge for investors and a more stable funding source for fiscal policy under the current recessionary regime.

6.2 Green, Fossil Fuel, and Conventional Asset Return Volatility: Harmonic Estimations

Green security investors should expect benefits due to green assets' hedge role against oil price fluctuations during business cycles. Investors concerned with ESG practices are usually aware of climate transition risks and have been attracted to green securities,[11] but they are not necessarily aware of their benefits as a hedge. Early literature has shown that green securities in bond and stock markets can protect investors from oil price volatility, but this finding is not yet a consensus in the literature.[12] We apply harmonic estimations to oil price changes and to green and fossil fuel–related financial market indexes data from January 2011 to March 2020 and evaluate the influence of oil price variations on asset returns (see appendix D for a methodological discussion and additional empirical studies). We find that private investors can reduce their exposure to riskier fossil fuel securities with the purchase of green assets.[13]

Harmonic estimations show that green bond returns are less impacted by oil price volatility in financial markets. The harmonic estimations for oil price changes (based on the European Brent oil spot price) capture low-frequency movements before and after oil price shocks (figure 12). This movement is compared with the harmonic estimations for the total returns of a fossil fuel–related market index (S&P 500 Energy Corporate Bonds, a subindex of the S&P 500 Bond Index composed of mainly bonds from carbon-intensive firms in the

[10] The S&P 500 and the S&P Energy Select Sector are conventional stock market indexes. The latter is made up of the S&P 500 firms that mainly operate in the energy sector, including fossil fuel firms. When we refer to energy indexes, we can use interchangeably the terms "fossil fuel" and "conventional."

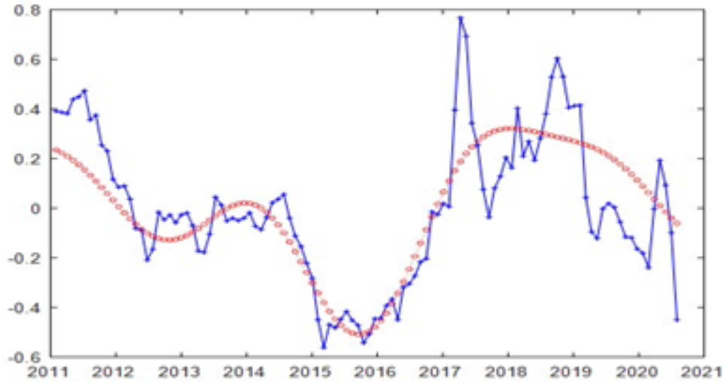
[11] Green bonds, for example, attract new investors (Climate Bonds Initiative, 2018) and allow known institutional investors to gain exposure to climate-friendly assets (Venugopal, 2015).

[12] See section 5.2.

[13] We use the term "conventional" to refer to conventional market indexes that are not labeled as green. Conventional energy market indexes mostly comprise carbon-intensive assets.

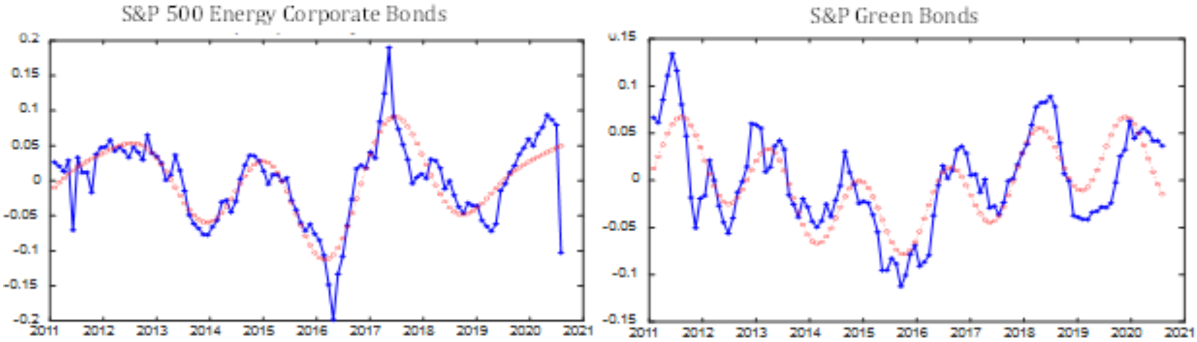
energy sector) and of a green bond market index (S&P Green Bonds) (figure 13). Figures 12 and 13 show that fossil fuel–related bond returns are correlated with oil price fluctuations. On the other hand, when we observe the fluctuations in the green bond index, the similarities are not very strong. Estimations for other indexes show similar results (see appendix D).[14] Although the green bond and clean energy indexes also follow cyclical movements, total returns are less associated with oil price changes in this time period.[15] This analysis shows that the swings in the volatility of oil prices mainly spill over to fossil fuel and conventional securities.

Figure 12. Oil Prices: Monthly Annual Changes and Harmonic Estimations, January 2011–March 2020 (in percentage points)



Source: Author calculations based on International Energy Agency data.

Figure 13. Bond Indexes: Monthly Total Returns and Harmonic Estimations, January 2011–March 2020 (in percentage points)



Source: Author calculations based on Standard & Poors data.
Note: Each graph's y-axis has a different scale, so the graphs should be carefully compared. We compare the return's volatility for each index with the oil price changes shown in figure 13. For more details on the relationship between each index's volatility and oil prices, see the regressions shown in appendix D.

Our regressions confirm a greater correlation between oil price movements and conventional and fossil fuel bond returns, showing that green assets can reduce investor risk. To complement the graphical analysis, we run new linear regressions using oil price changes as the independent variable and financial market indexes' total returns as dependent variables (appendix D). We find a greater correlation between oil price movements and conventional and fossil fuel securities. Green bonds and securities appear to be better instruments for hedging risk than oil price–driven assets. The purchase of green financial assets by private investors can reduce their

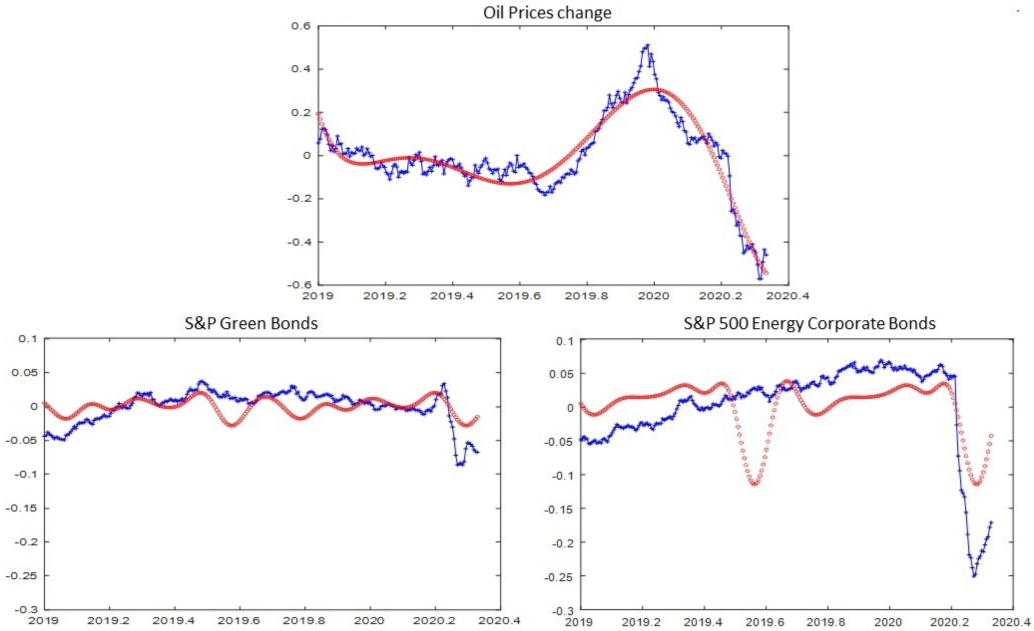
[14] In appendix D, we additionally use (a) conventional stock market indexes (S&P 500 Index and S&P Energy Select Sector; the latter includes only S&P 500 firms operating in the energy sector, mainly fossil fuel stocks); (b) a green equity index (S&P Global Clean Energy, which comprises 30 of the global largest firms in clean energy); (c) a conventional energy bond index (S&P 500 Energy Corporate Bond Index, a subindex of the S&P 500 Bond Index mainly composed of fossil fuel bonds); and (d) a green bond index (S&P Green Bonds Index, which comprises the universe of global bonds labeled as green by the Climate Bonds Initiative). The S&P 500 indexes cover large firms that access the U.S. equity or debt market. The S&P Global Clean Energy covers firms in advanced and developing countries. The S&P Green Bonds Index is a global index, but most of the green bonds are issued in the United States, Europe, and China. The results for the equity indexes are presented in appendix D.

[15] See in appendix D, the S&P Global Clean Energy versus oil prices and conventional equity indexes; see also the S&P Green Bond Index versus oil prices and the S&P 500 Energy Corporate Bond Index.

exposure to riskier carbon-intensive bonds because the volatility of green security returns is disconnected from fluctuations driven by oil prices.

Furthermore, the data suggest that oil price downturns accompanied by declining returns in the stock market trigger a run to safer assets like bonds (figure 14). This higher demand for bonds can increase bond prices and reduce yields. This effect might be stronger for green assets than for fossil fuel assets. To evaluate the effect, we run harmonic estimations for the daily returns of the green and fossil fuel bond indexes from January 2019 to April 2020 (figure 14) and run additional linear regressions (see appendix D). Our purpose is to analyze the impact of the 2020 oil price crash on the bond market.

Figure 14. Oil Prices and Bond Indexes: Total Returns and Harmonic Estimations for Daily Returns, January 2019–April 2020 (in percentage points)



Source: Author calculations based on Standard & Poors data.
Note: We compare the return's volatility for each index with the oil price changes. For more details on the relationship between each index's volatility and oil prices, see the regressions in appendix D.

There is evidence of excess demand for green bonds as their return falls after an oil price decrease (as bond price increases and yield decreases). The regression coefficients show that green bond daily returns are usually negatively associated with oil price changes (that is, the coefficient is -0.014), while fossil fuel bonds are positively correlated (that is, the coefficient is 0.14).[16] Moreover, the recent green bond yield performance observed is a consequence of the oil price crash and is not observed over the whole time series. Thus, there is strong evidence that investors look to green bonds as a safe asset during economic downturns.

An analysis of green bonds' index performance since the COVID-19 outbreak shows that investing in green assets was a profitable strategy. By September 2020, the yield to date (YTD) return for the S&P Green Bond Index was 5 percentage points greater than that of the S&P 500 Energy Corporate Bond Index (6.8 percent and 1.22 percent, respectively). The Bloomberg Barclays indexes show a similar performance, with the green bond's 8.2 percent YTD return in 2020 beating the global bond index by almost 2 percentage points (Bloomberg News, 2020). Investors that shifted their portfolio investing toward green bonds also achieved higher total returns.

[16] We report the regression coefficient results and their significance in appendix D, table D.2.

6.3 Constraining Portfolio Risks through Green Bonds

Here, we reinforce the previous section's results by examining the impact of the share of green bonds on a portfolio's overall risk, measured using portfolio variance.[17] According to modern portfolio theory, investors can lower their risk by investing in noncorrelated assets. In other words, portfolio risk can be reduced by introducing assets that will rise (or decrease less) when other investments fall; green bonds can act as such a de-risking strategy for investors, especially during economic downturns. We thus analyze the effect of increasing the share of green bonds relative to fossil fuel bonds on portfolio variance and find additional evidence for the de-risking effect of green bonds during periods of oil price declines. Note that we study here a regime-dependent reduction of portfolio risk.

We use the static portfolio theory and the CAPM to determine the correlation between green and fossil fuel bond yields when oil price changes are above and below zero. As shown in Semmler (2011), the CAPM can be used as a proper starting point for studying regime-dependent risk reduction. We illustrate the procedure by referring to two risky assets. Here, we evaluate the portfolio variance between green and fossil fuel bond yields based on oil price change fluctuations as the regime-defining variable. We do this by analyzing the impact of increasing percentages of green relative to fossil fuel bonds in the portfolio. The portfolio variance (${\sigma_{R_p}}^2$) for a two-asset portfolio is as follows:

$${\sigma_{R_p}}^2 = \gamma_1^2\sigma_{R_1}^2 + \gamma_2^2\sigma_{R_2}^2 + 2\gamma_1\gamma_2\sigma_{R_1}\sigma_{R_2}corr(R_1R_2) \quad \text{(Eq. 6.1)}$$

Where R_1 represents the green bonds yields (S&P Green Bond Index), R_2 represents the fossil fuel bond yields (S&P 500 Energy Corporate Bond Index), γ_1 is the percentage of green bonds in the portfolio, γ_2 is the percentage of fossil fuel bonds in the portfolio, and $\sigma_{R_1}^2$ and $\sigma_{R_2}^2$ are the variance of green and fossil fuel bond yields, respectively.

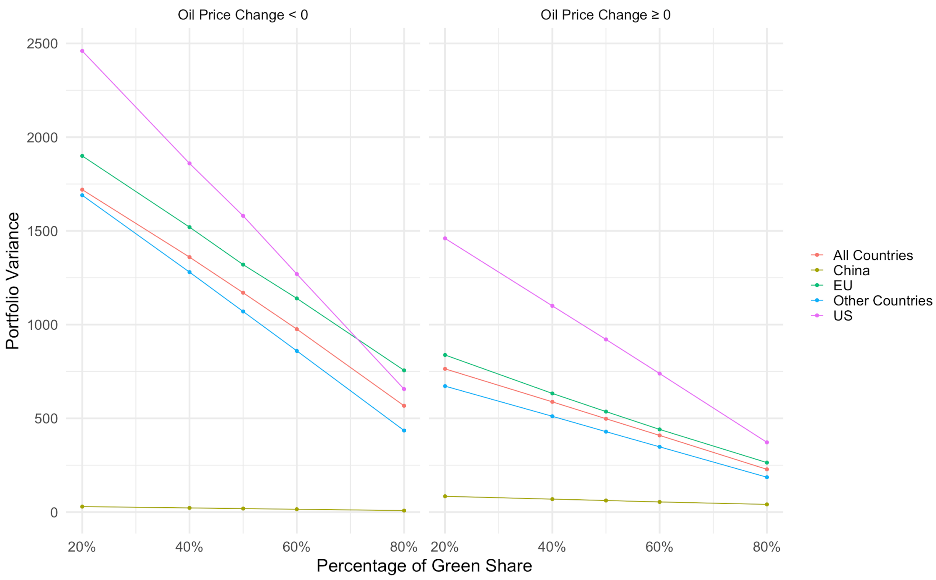
Our analysis highlights that a larger share of green bonds leads to a de-risking effect on portfolios, especially when oil prices fall (see figure 15 and appendix F for more details).[18] Indeed, as the percentage of green bonds in a portfolio comprising green and fossil fuel bonds increases, the portfolio variance decreases during recessions (that is, when oil price changes are negative).[19] That decrease in portfolio variance when the share of green bond increases is true for bonds issued in the United States, the European Union, China, and the other countries included in our sample (see appendix F). This finding complements the results detailed in section 6.2, which show that the yield of fossil fuel bonds is impacted more by the change in the oil price than the yield of green bonds.

Figure 15. Portfolio Variance of Different Shares of Green and Fossil Fuel Bonds

[17] Portfolio variance shows how the aggregate actual returns of a portfolio fluctuate over time.

[18] The data range for this calculation was from January 2019 to April 2020. Oil prices have recovered since the second half of 2020, so the relationship might have changed.

[19] For a more elaborate approach, one would also compute the changing optimal weights on the Markowitz efficient frontier (see Chiarella et al. [2016], chapter 3). But our suggested procedure here might suffice to illustrate what approximately would happen for the portfolio risk in a regime change model, whereby the regime is defined by the oil price changes.



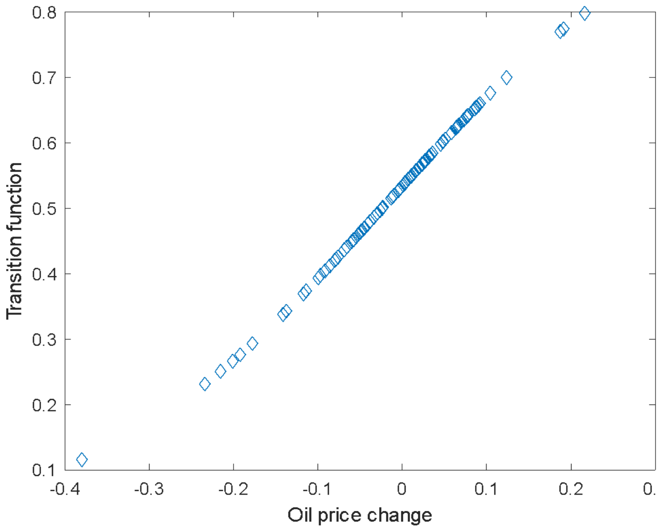
Source: Author calculations based on Standard & Poors data.

6.4 Oil Price Fluctuations and Green and Fossil Fuel Securities: A Nonlinear LVSTAR Model

Next, we evaluate the performance of green and fossil fuel securities, verifying the existence of different regimes when oil prices change. For this purpose, we apply a nonlinear LVSTAR as in Hubrich & Teräsvirta (2013) and Schleer & Semmler (2016). We use this model to study the response of green and fossil fuel bonds to changes in oil prices. We also test for the linearity of the model and the causality between these variables through a Granger causality test (see Schleer & Semmler [2015, 2016] and Teräsvirta & Yang [2014]).

We evaluate the performance based on two regimes, determined by oil price change as a transition variable (see appendix E for the methodology description): One regime has an increasing oil price; the other regime has a decreasing oil price. Oil prices are obtained through the European Brent oil spot price level, which allows us to determine the model threshold. The green bond data are the annual monthly total returns of the S&P Green Bonds Index (which contains renewable energy and other green assets), and the fossil fuel bond data are obtained through the monthly total returns of the S&P 500 Energy Corporate Bond Index (a more comprehensive index that also

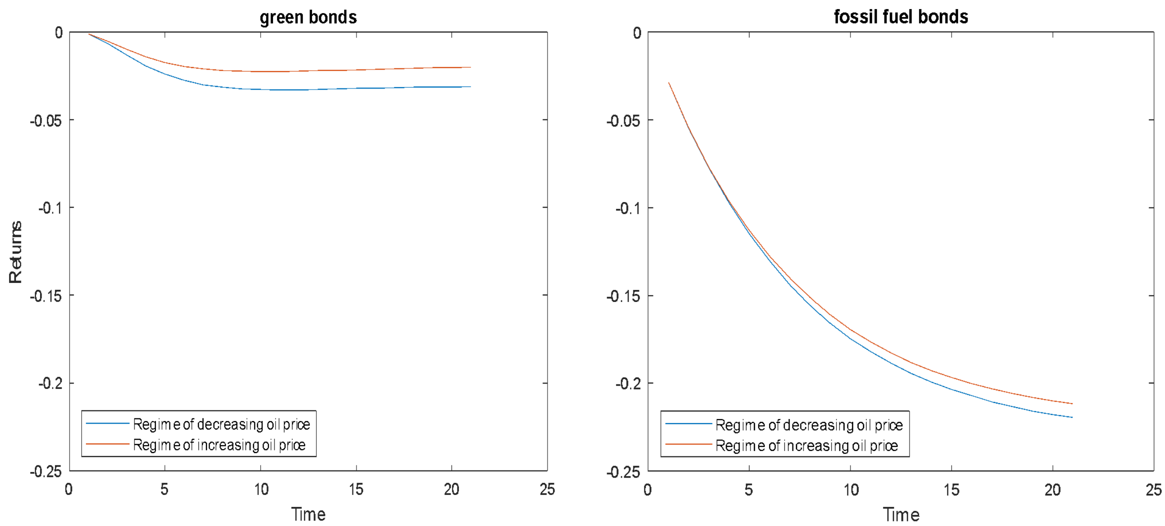
Figure 16. LVSTAR Model Estimated Transition Function for Different Oil Price Regimes



includes carbon-intensive energy assets).[20] Using this data, we estimate a transition function in which the oil price changes drive regime change (figure 16).

Modeling results show that oil price regime changes do not significantly impact green bond returns. We impose a 1 standard deviation shock to the fossil fuel bond yield and study the impact on both fossil fuel and green bond yields as dependent on the regime of the oil price, using impulse responses from the LVSTAR model. Overall, the performance of green bonds changes very little with respect to oil price changes, though in the regime of declining oil price the effect is a bit stronger than in a regime of increasing oil price (figure 17, left panel). As noted, the shock is imposed on fossil fuel bond yields and occurs in the regimes of decreasing and increasing oil prices. Yet, in size, the oil price change regime (either increasing or decreasing oil price changes) does not impact much green bond yield movements.

Figure 17. Green Bonds and Fossil Fuel Bonds: Impulse-Response Behavior Under Decreasing and Increasing Oil Price Regimes



Source: Author calculations based on Standard & Poors data.
Note: Returns are measured in basis points.

However, the oil price regime clearly impacts the yields of fossil fuel bonds. The right panel of figure 17 shows how the yield of fossil fuel bonds is impacted by a shock to fossil fuel bonds, using the same impulse responses from the LVSTAR model.[21] The responses show quite different yield movements for fossil fuel bonds in size of the effects of shocks; see the scaling. Fossil fuel bonds perform worse under both decreasing and increasing oil price regimes (though only a bit worse in the decreasing oil price regime). Note that we have assumed that the shock occurs first to fossil fuel bonds with the subsequent effects as depicted in figure 17 (right panel). In both cases, negative or positive oil price changes make fossil fuel bond yields much more volatile than green bond yields.[22] Green bond yields respond much less to shocks in the decreasing and increasing oil price regimes. This is further proof that green bond returns are less volatile to oil price fluctuations and are an asset preferable for

[20] The S&P Green Bonds Index is a global index comprising the universe of global bonds labeled as green by the Climate Bonds Initiative. Most of these bonds are issued in China, Europe, and the United States. The S&P 500 Energy Corporate Index is a subindex of the S&P 500 Bond Index. It covers large firms with higher ratings that can access the U.S. debt market. Note that we have imposed a negative shock.

[21] We have imposed a negative shock.

[22] As noted in the literature, both green and conventional bonds can be affected by oil price changes; see Nasreen et al. (2020), who state that "that energy intensive sectors are more heavily affected than other sectors due to the fluctuation in oil prices." Expansions in oil prices are expected to benefit renewable energy sectors relative to carbon-intensive sectors, while reductions are expected to harm, as both sectors can be viewed as substitutes. This result is similar to the study by Semmler & Issa (2019), who study in parallel the performance of banks with respect to oil price changes.

risk reduction. This means that low fat-tail correlations with other assets would thus imply that green bonds are a good hedge against oil price fluctuations.

We also observe some nonlinear behavior in the regime-switching LVSTAR model, which means that oil price changes actually imply different returns for fossil fuel bonds. To detect those nonlinearities, we have applied several linearity tests for our LVSTAR model to check if the model is linear or nonlinear (see appendix E for a discussion on linearity tests). Our null hypothesis is that the data are described by a linear system. If the tests reject the linearity, we cannot argue that the regime changes do not impact the fossil fuel bond returns. Table 9 shows the results for a Lagrange multiplier (LM) test, an F-test, a likelihood ratio (LR) test, a Wilks's statistic test, and a Rao's F-statistic test: All the tests reject the linearity hypothesis. Thus, we can argue that the model outcome reflects data being driven by nonlinear dynamics. Figure 17 supports this evidence, and we conclude that there is nonlinearity due to fossil fuel bond behavior under different oil price change regimes. However, we cannot determine yet if oil price changes are the actual driver of the differences in energy security performance under distinct regimes; this conclusion depends essentially on a Granger causality test, which is undertaken in other kinds of work (see Mittnik & Semmler [2018] and appendix E).

Table 9. Linearity Tests for the LVSTAR Model

Test	Value of test statistic	p-value
LR	64.7273***	0.0002
LM	52.5238**	0.0067
F	1.5856*	0.0347
Wilks's	56.4837**	0.0024
Rao's	2.188**	0.0031

Note: F = F-test; LM = Lagrange multiplier; LR = likelihood ratio.
* p<0.05 **p<0.01 ***p<0.001

7 Conclusion

Global warming, climate disasters, and climate transition risks can move the economies of advanced and developing countries into a lower growth regime and toward greater financial instability. The COVID-19 pandemic provides an example of a crisis with severe economic and social impacts—as in climate risk and climate disaster, though in the latter case evolving more locally. Our study shows how two types of fiscal policies—carbon taxation and green bonds—can be combined to tackle climate risks and help the economy smoothly transition to more stable growth and low-carbon emissions. A carbon tax creates the right incentives for actors across the economy to reduce CO_2 emissions in various ways. However, current carbon taxation initiatives alone are not likely to be scaled up to create enough additionality for climate protection. Furthermore, the effectiveness of carbon taxation depends on the ability of economies to switch to low-carbon alternatives—yet, in some cases, low-carbon substitutes may be lacking entirely and complementary public policies need to be implemented to provide the needed financing. Therefore, green bonds can support carbon taxation as a bridge instrument to smooth the low-carbon transition path and overcome policy makers' and investors' myopic behavior.

Our model results and discussion demonstrate how these two policies together, in addition to mobilizing revenues, providing environmental and welfare benefits, and speeding up climate protection, can also generate better intergenerational equity and reduce countries' vulnerability to potential future climate-related disasters and financial instability. We show that carbon taxation should complement financial market resources such as the issuance of green bonds whereby both can be used for climate protection policies. Furthermore, this policy combination can drive down carbon emissions while keeping debt sustainable in the long run. This view is also supported through insights from the discussion on the advancements in macroeconomic climate modeling. We also provide lessons for a fiscal countercyclical policy after recessions, such as is needed to get out of the current severe pandemic-driven recession. Our empirical evidence on green and conventional bonds also has ramifications for dynamic portfolio decisions in financial markets, in the sense of preventing the portfolio from being exposed to too much risk and giving better guidance for future financial investment decisions.

We provide empirical evidence as to what extent carbon taxation and climate bonds are already implemented globally or will be soon. A significant segment of the financial market is recognizing that effective climate protection requires the mobilization of financial market resources: Across countries, renewable energy-based asset holdings are rising. We acknowledge that investors are short-term oriented and loss averse and explain how green bonds can help promote a long-term and more sustainable approach to investment decision-making. This is shown with a survey of literature and assessments on empirical features and trends that indicate that the returns of green bonds—though exhibiting lower yields and thus lower capital cost in the long run—also exhibit lower volatility and have additional favorable features; for example, green bonds show less fat-tail correlations with other risky assets in a recessionary regime. Green bonds can provide a successful hedge against conventional and fossil fuel–based asset returns. Furthermore, their lower volatilities can guarantee a higher reward-to-risk ratio to green financial investors even with lower yields, since green bonds can generate higher overall portfolio Sharpe ratios. Green bonds can also be made more attractive: Fiscal and monetary policy can influence its performance, and in dynamic portfolios green bonds are likely to be more profitable in the long run since related positive externalities are to be expected. In some cases, we do find green bonds exhibiting higher yields than conventional bonds, but this might be due to a perception of risk related to less experience in good governance and insufficient "learning by doing" in certain areas and sectors.

The empirical and theoretical results relating to green bonds are important since the benefits arising from them might induce an increase in the share of green assets in portfolio holdings, in particular, due to the great climate-related future uncertainty faced by the financial market. That green assets can be viewed as a hedge against riskier assets is demonstrated by a supporting study on harmonic oscillations, which shows that the green bonds reveal less fluctuation in amplitude and frequency than fossil fuel and conventional bonds. This view is bolstered by two additional studies: (a) a portfolio CAPM analysis, highlighting that a larger share of green bonds leads to a de-risking effect on a portfolio, and (b) a study using a regime-switching model, looking at oil price shock impacts on green and fossil fuel bonds under both increasing and decreasing oil prices. The latter study also corroborates the previous results that green bonds are less sensitive to oil price regime changes than fossil fuel bonds. These results should be interesting not only for households, firms, and financial institutions deciding on their long-term portfolio holdings, but also for governments issuing debt to fund countercyclical policies.

Though the findings should be differentiated across countries, time, and business cycles, they also have implications for policy responses to the current and worldwide pandemic-driven recession. The findings in this report are relevant for monetary and fiscal stimulus packages that have been initiated in many countries. In the COVID-19 downturn regime, the bust of commodity prices (in particular of oil prices) and the spillovers to asset prices and returns suggest that policy makers should open up more space for greater use of climate-oriented fiscal policy embedded in economic recovery programs.

We explain that the use of fiscal instruments such as well-calibrated carbon taxation and green bonds should be not only an effective stimulus against the current downturn but also the means used to expedite climate protection. Carbon taxation and green bond instruments will likely play an important role in a green economic recovery plan both during and after the current recession. Though policy makers might tend to use a carbon tax only in a moderate way in the current deep recession, issuing green bonds is especially important to fund a green fiscal stimulus under the current regime of the business cycle, which is characterized by high negative growth rates associated with very low sovereign bond yields, which entail low capital costs for green investments.

First, there is a growing perception and empirical evidence that green expenditures can provide greater multiplier effects (Batini et al., 2021). Second, oil prices co-move with macroeconomic regimes and thus are drivers of sovereign risks and fluctuations in financial markets, strongly impacting fiscal policy conditions, in particular in developing economies. The correlation of macro regimes and oil prices suggests the use of green securities—such as green bonds—as favorable fiscal instruments to fund green recovery plans. There is thus a strong argument that a green recovery plan should be aligned with climate goals and financially funded by green bonds to tackle climate-related risks and the risk of moving onto a long-term low-growth path or poverty traps in certain regions, as discussed by Mittnik et al. (2020). Investors can also take advantage of this opportunity and include green bonds in their portfolio as a hedging instrument.

Such a policy of carbon taxation and green bond issuance might affect sovereign debt and sovereign borrowing conditions. In the context of macro models, we show under what conditions such debt issuance can be kept sustainable. This of course is an important issue because some countries have relatively more fiscal space than others. The World Bank has done a lot of work on the rise of private and public debt in the last decades,[1] but since the pandemic-driven global economic meltdown has brought new perspectives to the forefront, we contribute some additional remarks to this discussion.

Issuing green bonds is an important strategy to fund a green fiscal stimulus under the current business cycle regime (characterized by negative growth rates), but what are the long-run effects of pursuing such a strategy? There are two scenarios one can envision. The first scenario involves higher growth rates, the loosening of social distancing rules, and the successful implementation of fiscal stimulus packages. Countries ahead in this scenario are those that already have some fiscal space. If the growth rate becomes higher than the interest rate, the Blanchard (2019) prediction of sustainable debt is likely to hold: Countries can slowly grow out of their public and private debt and the sovereign debt to GDP ratio may come down (see Blanchard [2019] and Kemfert et al. [2019]). In the second scenario, growth rates for 2020 and 2021 will be negative and thus the option of growing out of debt will not materialize in the short term; therefore, a debt deflation process could pose a real threat.[2] Overall, however, the more optimistic scenario (the first one) might hold for advanced countries and developing countries with more fiscal space.

This might be different for developing countries that already have less fiscal space and that are implementing, possibly weak, rescue and recovery efforts late, either due to being hit last by the worldwide pandemic or due to additional constraints in their fight against the pandemic. Economic damages might also be worse because of a combination of a lack of fiscal and monetary capacity and the presence of natural disasters, economic losses, and financial panic—a scenario that is more likely to happen in developing economies rather than advanced ones.[3] Such countries were already affected more severely by declining revenues from a sudden drop in commodity prices and sales and must issue further debt for rescue and recovery policies. For low-income developing countries, early debt forgiveness and debt restructuring are presumably needed. Also, new financial instruments such as green convertible bonds or climate-to-debt swaps can be considered as alternatives to minimize the debt of low- and middle-income countries.

If countries do not, or cannot, undertake monetary and fiscal stimuli to address both pandemic containment measures and economic support for recovery, the economic fallout will likely be larger still, with larger fiscal debt impacts. Econometric studies done after the Great Recession of 2008–09 comparing conservative versus generous fiscal support for given levels of initial debt show that (given the regime dependence of fiscal spending effects) debt may rise even more with conservative fiscal spending and budget consolidation policies. An important point to note is that in recessionary periods, risk premia and credit constraints usually rise, and credit flows decline, with conservative spending actions. Though the behavior of risk premia is uncertain, during the financial crisis of 2008–09 downgrades and jumps in risk premia seemed to be driven more by "low growth," or negative growth, and high financial stress than by "high debt" problems (see Semmler & Proaño [2015]). These are important additional aspects of global debt and fiscal space that have become relevant during the COVID-19 pandemic recession. Surely, further fiscal policy questions will arise as the recession evolves and signs of recovery emerge, but this is a subject for future research.

[1] See Kose et al. (2020).

[2] The latter scenario might materialize if there is a delay in scaling up the vaccination of the population in countries or regions.

[3] See Mittnik et al. (2020).

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Appendixes

Appendix A: Theoretical and Empirical Background, Descriptive Statistics, and Bond Estimations

A.1. Theoretical Background: Merton's Generic Approach

The financial economics literature offers several approaches to explain the drivers of bond yields and risk premia. The structural bond pricing tradition is one of the most relevant fields and focuses on firm-specific drivers. The Merton (1974)[1] model inaugurates this tradition, providing a bond price theory for the case when default is probable. Merton (1974) was the first to model credit risk using a firm value model. With this perspective, modeling credit risk means modeling default probability. It expands the seminal Black & Scholes (1973) model toward a general theory for corporate debt and creates the well-known Black-Scholes-Merton model, widely used in financial markets.

Merton (1974), taking for granted the Modigliani-Miller theorem (1958),[2] assumes that the value of a firm is given by the sum of its debt and equity levels (and thus the equity and liabilities are a fraction of the firm's value). The risk of or default premium is caused by both the high leverage of the entity and the high volatility of asset value. A default could only occur at the maturity of the debt if the value of the firm (V) minus the outstanding debt is negative, which is likely to occur through a shock with greater probability if the debt is high as compared to the value of the asset. As shown in Semmler (2011, ch. 20), Merton treats corporate liability from the perspective of derivative pricing, whereby the value is given by a Brownian motion (Eq. A.1):

$$dV = \mu V dt + \sigma V dw \qquad (\text{Eq. A. 1})$$

in which V is the value of firm's prime assets, σ is the asset volatility, μ is the expected rate of return, and dW is a Wiener process. V (together with time t) determines the value of the asset.

This conceptual framework should be used to explain the corporate bonds' interest rate term risk structure, though accessing data for the Merton model application might not be an easy task.[3] Thus, Kealhofer (2003) developed the KMF model, an application of the Merton approach using the idea of "distance to default" (DD) using firms' balance sheets and security return data. The model states that two main elements determine the default probability: (a) the value of assets, that is the market value of the firm's assets and its volatility; and (b) the leverage, that is, the extent of the firm's contractual liabilities. Thus, the formula for default probability is the book value of liabilities relative to the market value of assets, divided by the volatility of the asset value.

[1] Later, other authors implemented advances to Merton's model (see Eom et al. [2004] for a historical perspective for this type of model).
[2] The theorem states that the market value of a company is independent of its capital structure.
[3] See Chou (2005) for a recent empirical application of the Merton approach.

We can combine both variables in the DD approach, as shown in equation A.2:[4]

$$[DD] = \frac{[Market\ Net\ Worth]}{[Size\ of\ one\ standard\ deviation\ of\ the\ Asset\ Value]} = \\ = \frac{[Market\ Value\ of\ Assets] - [Default\ Point]}{[Asset\ Volatility]} \qquad \text{(Eq. A. 2)}$$

Thus, yields (or the return to be paid by corporate debt) can be obtained based on the DD as shown by equation A.3.[5] The risk structure of the corporate bond yield (r_b) is mainly driven by the risk-free rate, the DD, the volatility of the asset, and the debt ratio of the firm (Eq. 3). The smaller the distance to default and the volatility, the larger the spread, risk premium, and borrowing costs:

$$r_b = rf + (rv_A - rf)N(1 - DD\ \sigma_e\ )b \qquad \text{(Eq. A.3)}$$

in which rf is the risk-free rate, rv_A is the expected rate of return on the asset value, σ_e is the volatility of the value of the firm, and b is the debt to asset ratio of the firm.

1. Corporate Bonds

As shown by Anderson & Sundaresan (2000), structural models have proved difficult to implement: They relate yields to fundamental determinants in a highly nonlinear way and have greater data requirements than other approaches.[6] Their goal is to find a stable relationship between corporate yields and aggregate measures of leverage and volatility. They use the risk-free rate and the volatility of monthly returns on the S&P 500 as proxies for leverage and volatility.[7] Thus, simple structural models have been used in practice without conditioning default on asset value and assuming that default can be defined exogenously.[8] Indeed, empirical evidence shows that ratings strongly explain yield differences between corporate and risk-free bonds (see Löffler [2007] and Gabbi & Sironi [2005]). Nevertheless, additional studies show that only part of the yield differentials can be explained by the risk of default. Christensen (2008) highlights the importance of two non-default factors besides the financial health of the firm: (a) taxes—Elton et al. (2001) also include bond federal taxes as a main determinant of corporate yields; and (b) liquidity—a time-varying variable, determined by the size of the bond issuance, the bid-ask spread, or other liquidity estimations (see Driessen [2005]).

In the literature, additional factors commonly used as corporate bond yield and risk premium drivers include ratings (sovereign and sector rating), time to maturity, coupon rate, liquidity, risk-free rate, cashflow rate, and business cycle conditions. Krylova (2016) shows that while rating effects were the main driver of corporate bond spreads before the 2007 global financial crisis, cross-country and cross-sector heterogeneity became the main drivers of corporate bond spreads after the crisis. Thus, industry attribution was not important before 2007 on bond pricing, but after 2007 corporate bonds from the financial sector started to yield more than bonds of the nonfinancial sector with similar characteristics. Moreover, Krylova, based on Merton's work, highlights high variance of corporate bond spread for high-rated bonds (AAA to AA), low-rated bonds (BBB segment), and sector effects (financial and nonfinancial sectors). Also, risk-free rate and standard deviation of monthly returns on

[4] See Semmler (2011), chapter 20.

[5] See Semmler (2011), chapter 20.

[6] It requires the company's asset value to be observable and continuous in time, cannot incorporate changes in credit ratings of corporate bonds, and assumes that default is predictable shortly in advance (Krylova, 2016).

[7] They also find greater corporate bond spreads on BBB-rated bonds.

[8] See, for example, Litterman & Iben (1991), Jarrow & Turnbull (1995), and Duffie & Singleton (1999).

S&P 500 over 12 months are found to be important drivers of corporate bond yields, as shown in Anderson & Sundaresan (2000).

One should note that the structural framework of Merton's corporate finance model was also used to analyze sovereign bond yields and sovereign default probabilities. Risk premia are measured at a corporate level, but investors also demand the assessment of security yield spreads at a macro level. Therefore, an analysis of bond yields can be also carried out in a country-level context by investigating the sovereign analogue to credit risks, which are sovereign default probabilities.

2. Sovereign Bonds

Studies that applied the Merton financial framework to sovereign countries were able to explain sovereign default probabilities. The combined balance sheet of the government and central bank lays the groundwork for further application of Merton's corporate finance model to explain market-assessed sovereign credit risks. A discussion by Gray et al. (2007), arguing that balance sheets of countries and corporations show similarities in structure and priorities, encourages authors to use data from government budget sheets in the structural model of Merton (see Table A.1). Empirical analyses of sovereign debt defaults have been carried out for emerging economies (Duyvesteyn & Martens, 2011) and European countries (Wang et al., 2012; Ruiz-Porras & Juárez, 2015). All the mentioned studies use information on sovereign credit risks from sovereign credit default swap (CDS) spreads, financial assets and liabilities of sovereign countries (like the ratio of financial assets to total liabilities) together with volatility measures in their regression models. The papers show that the application of Merton's structural model helps explain a proportion of market-assessed sovereign credit risk's dynamic.

Table A.1. Typical Balance Sheets

Corporate balance sheet		Balance sheet of government and central bank	
Assets	**Liabilities**	**Assets**	**Liabilities**
Cash	Corporate bonds	Foreign reserves	Guarantees
Accounts receivable	Accounts payable	Net fiscal assets	Foreign currency debt
Inventories	Equity	Credit to other sectors	Local currency debt
Non-current assets (property, etc.)	Provisions, deferred tax, etc.	Other public assets	Monetary base

Source: Duyvesteyn & Martens (2011).

Models that allow for multiple equilibria can also help develop policies to avoid default points and move toward the non-default equilibrium. Semmler & Proaño (2015) studied sovereign default risks of European countries and escape routes from sovereign default. Compared to previous macroeconomic models they allow for an endogenous determination of aggregate output. Given the low growth-regime after the financial crisis, their findings suggest that specific credit policies were needed to target specific risk factors and that an increase of central bank balance sheets through quantitative easing may not have been sufficient to trigger lending and economic activity. In a moving debt crisis, rising interest rates increase the path for debt and increase future default probabilities. A sufficiently aggressive fiscal policy rule and a shift toward longer debt maturities can move the economic state toward the "good" equilibrium and prevent the occurrence of sovereign default (Lorenzoni & Werning, 2019). In a recent article on extraordinary operations in response to COVID-19, Blanchard & Leigh (2020) also express support for severe interventions and the purchasing of sovereign bonds. If investors become worried, they will search for higher risk premia, which slowly increase debt services and potentially make debt unsustainable if their worries become self-fulfilling. Given the current crisis, central banks should use their tools to mutualize costs of the crisis, purchase sovereign bonds, and commit to buy if investors sell so to avoid a "bad" equilibrium.

The joint analysis of the corporate and sovereign bond literature helped us identify yield and default risk drivers for our empirical analysis. Next, we list all the relevant variables first selected to employ our empirical analysis for bond yield drivers.

A.2. Data Sets: Variables, Sources, and Properties

For bond yield analysis, one can rely on data sources such as Reuters, Bloomberg, Refinitiv, Thomson Reuters, and S&P Capital IQ. These platforms provide information on bond performance and issuer profile, including microdata at the asset level. However, data for green-labeled bonds are found on specific platforms such as Climate Bonds Initiative (which has bonds aligned with the Green Bond Principles or classified by their taxonomy as green), Environmental Finance (which has issuers' self-labeled green bonds aligned with a list of green bond's guidelines), and Bloomberg (which has issuers' self-labeled green bonds or those identified as a sustainability-oriented bond according to the Green Bond Principles).[9] These databases provide us with an additional variable, classifying an asset as green or not.

For the present study, we rely on data downloaded from the Bloomberg Terminal using the Fixed Income search. We downloaded the green bonds listed in the search "@Green," which filters green corporate bonds as well as green sovereign and supranational bonds. Municipal bonds, loans, mortgages, and certificates are not included in the sample.

An advantage of using the Bloomberg data is the easiness of integrating asset information. Based on this sample, we selected similar conventional bonds, not labeled as green in the whole universe of Bloomberg's Fixed Income search based on the criteria provided by the Merton model and other studies. We included criteria such as currency, rating, maturity, and sectors (if in the same sector). We also included performance measurements such as the following:

- Yield at issue (primary market performance variable)
- Current yield (secondary market performance variable)
- Yield to maturity (secondary market performance variable)
- Date of issuance
- Coupon rate
- Amount issued (in US dollars)
- Price (bid, mid, and ask price), to calculate liquidity (secondary market performance variable)
- Volatility (secondary market performance variable)
- Debt to assets ratio

Table A.2 presents the list of potential variables used to match green and conventional bonds and to measure the risk premia drivers for corporate and sovereign bonds. The list is inspired by Merton (1974). We used this list for our model variable selection process (in bold, we have variables that should be used only for corporate or only for sovereign bonds).

[9] See The Green Bond Principles (2017) for detailed information on these and other sources.

Table A.2. Yield Differentials and Risk Premium Drivers for Corporate and Sovereign Bonds: Variables and Main Sources

Corporate		Sovereign	
Driver	**Sources**	**Driver**	**Sources**
Asset volatility	S&P Green Bond Index, S&P 500 Index, S&P 500 Bond Index, Bloomberg (volatility for 30, 90, and 260 days)	Asset volatility	S&P Green Bond Index, S&P 500 Index, S&P 500 Bond Index
Debt leverage	**Debt/Total Assets (Bloomberg Fixed Income search)**	**Sovereign leverage**	**Debt/GDP for the country of issuance; Foreign Debt/GDP; Foreign Reserves/GDP at the time of issuance (International Financial Statistics, IMF)**
Rating	S&P and Moody's Rating (Bloomberg Fixed Income search)	Rating	S&P and Moody's Rating (Bloomberg Fixed Income search)
Risk-free rate	US Treasury Bonds; Germany Treasury Bonds	Risk-free rate	US Treasury Bonds; Germany Treasury Bonds
Liquidity	Bid-ask spread (Bloomberg Fixed Income search)	Liquidity	Bid-ask spread (Bloomberg Fixed Income search)
Country of risk and currency	Bloomberg Fixed Income search	Country of risk and currency	Bloomberg Fixed Income search
Sector of issuance	**BICS Levels 1 and 2 (Bloomberg Fixed Income search)**	**Government entity**	**BICS Levels 1 and 2 (Bloomberg Fixed Income search)**
Date of issuance	Bloomberg Fixed Income search	Date of issuance	Bloomberg Fixed Income search
Coupon	Bloomberg Fixed Income search	Coupon	Bloomberg Fixed Income search
		CDS risk premium	**Bloomberg Fixed Income search**
Time to maturity and maturity	Bloomberg Fixed Income search	Time to maturity and maturity	Bloomberg Fixed Income search
Business cycle indicator	GDP growth (World Bank Database)	Business cycle indicator	GDP growth (World Bank Database)

A.3. Bond Data Set Summary for Green and Conventional Bonds

Our analysis is based on green and conventional bond data downloaded from the Bloomberg Terminal. Bloomberg provides a "green instrument indicator," which was our criterion for green bonds. Conventional, or plain vanilla, bonds are simply non-green bonds—in other words, bonds for which the "green instrument indicator" does not hold.

The last complete version of bond data was downloaded from the Bloomberg Terminal on October 1, 2020. Because of the higher availability of conventional bond data and the restrictions on Bloomberg downloads, we limited our analysis to a set of sectors with the highest amount of green bonds and to the period when the most green bonds were issued.

As we were mostly interested in comparing the performance of green and conventional bonds and since green bonds became more popular in 2015 and their issuance kicked off in 2017, our period covers January 1, 2017, to September 22, 2020. Also, we selected conventional bonds only from the sectors that showed the highest amount of green bonds: (a) the financial sector with the banking and real estate subsector; (b) the utilities sector with the utilities and power generation subsector; (c) the government sector with the government development bank, supranational and sovereign subsectors; and (d) the energy sector with the renewable energy subsector. Table A.3 provides the green bond sectoral distribution using the Bloomberg BICS level 1 and 2 classifications.

Table A.3. Green Bonds Sample: Sectoral Distribution, BICS Level 1 and BICS Level 2

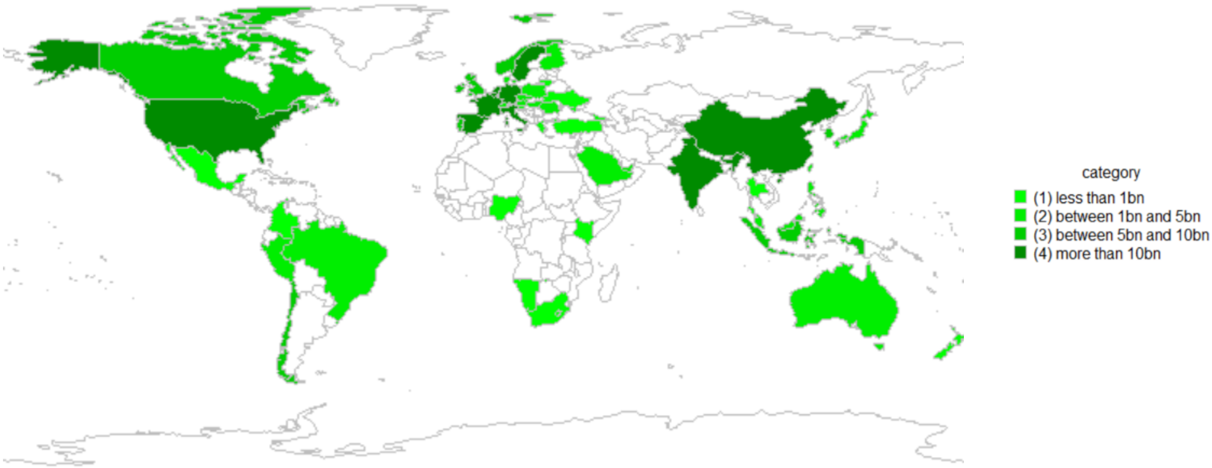
BICS 1	Observations	Share
Financials	739	48.3%
Utilities	419	27.4%
Government	271	17.7%
Energy	100	6.5%

BICS 2	Observations	Share
Banks	379	24.8%
Real estate	360	23.5%
Power generation	224	14.7%
Utilities	195	12.8%
Supranationals	161	10.5%
Renewable energy	89	5.8%
Gov development banks	80	5.2%
Sovereigns	30	2.0%
Refining & marketing	8	0.5%
Integrated oils	2	0.1%
Coal operations	1	0.1%

Source: Author calculations based on Bloomberg Terminal data.
Note: Sectoral distribution of the green bond sample download from Bloomberg. It includes all the bonds labeled as green by Bloomberg and issued since 2010.

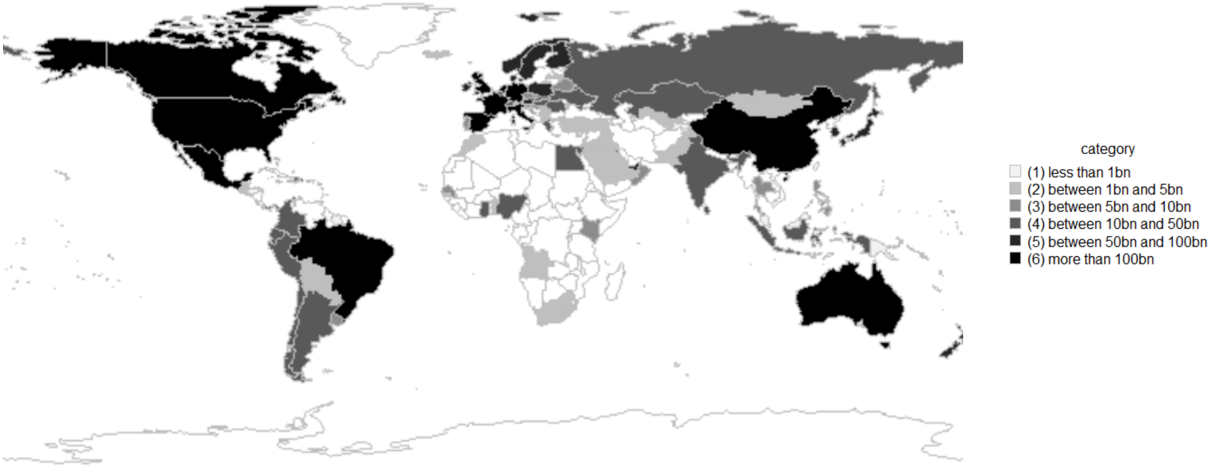
Figures A.1 and A.2 show the total amount of green and conventional bonds issued per country. While the major issuers of green bonds are China (19.0 percent), Germany (11.9 percent), France (11.3 percent), and the United States (8.7 percent), the major issuers of conventional bonds are the United States (16.3 percent), Canada (10.5 percent), Germany (8.4 percent), and Brazil (6.3 percent).

Figure A.1. Green Bond Issuance by Country (US$, billions), January 2017–September 2020



Source: Bloomberg Terminal data.
Note: Amount of bonds issued by corporations and government institutions from our Bloomberg data.

Figure A.2 Conventional Investment Grade Bond Issuance by Country (US$, billions), January 2017–September 2019



Source: Bloomberg Terminal data.
Note: Amount of bonds issued by corporations and government institutions from our Bloomberg data.

Table A.4 gives an overview of countries and economies in our data set regarding the World Bank income classification.

Table A.4. Countries and Economies Categorized by Income Level

World Bank classification	Countries and economies
Low income & lower middle income	Angola; Benin; Bolivia; Egypt, Arab Rep.; Ghana; Honduras; India; Kenya; Mongolia; Morocco; Nigeria; Papua New Guinea; Philippines; Pakistan; Senegal; El Salvador; Sri Lanka; Togo; Tajikistan; Ukraine; Uzbekistan
Upper middle income	Albania; Argentina; Brazil; Belarus; China; Colombia; Dominican Republic; Ecuador; Fiji; Georgia; Guatemala; Indonesia; Iraq; Jordan; Kazakhstan; Lebanon; Montenegro; North Macedonia; Mexico; Malaysia; Namibia; Peru; Paraguay; Serbia; Russian Federation
High income	Austria; Australia; Barbados; Belgium; Bahrain; Bermuda; Bahamas; Canada; Chile; Croatia; Czech Republic; Cyprus; Denmark; Finland; France; Germany; Greece; Hong Kong SAR, China; Hungary; Ireland; Israel; Iceland; Italy; Japan; Korea, Rep.; Kuwait; Lithuania; Luxembourg; Latvia; Mauritius; Netherlands; Norway; New Zealand; Oman; Panama; Poland; Portugal; Puerto Rico; Qatar; Romania; Saudi Arabia; Singapore; Slovenia; Slovak Republic; Spain, Sweden; Switzerland; Trinidad and Tobago; Taiwan, China; United Arab Emirates; United Kingdom; United States; Uruguay

A.4. Bond Statistics for Green and Conventional Bonds

Our data set contains 10,556 observations, with 1,529 green bonds and 9,027 conventional bonds. To stay within the data limits of Bloomberg, we reduced the number of conventional bonds by only downloading those that included an S&P rating (all "N/A" in the S&P rating column were excluded). Therefore, all 9,027 conventional bonds show an S&P rating (7,986 of which are investment grade, that is, with a credit rating above BBB-), while only 498 green bonds out of 1,529 have an S&P rating (455 of which are investment grade). Non-rated (NR) bonds or bonds where the rating is not available (N/A) are commonly regarded as sub-investment grade (Charles Schwab & Co., 2017). The maturity structure forms an additional categorical variable, with the binary states "short term" if the issue-to-maturity duration is less than 10 years and "long term" if the duration is more than 10 years.

Tables A.5 and A.6 show the descriptive statistics of the data.

Table A.5. Green and Conventional Bonds by Maturity: Descriptive Statistics, January 2017–September 2020

	conventional		green	
	long term (N=2966)	short term (N=5198)	long term (N=372)	short term (N=978)
Yield to Maturity				
Mean (SD)	2.35 (2.65)	2.76 (7.31)	2.02 (1.79)	2.03 (2.75)
Median [Min, Max]	1.79 [-1.54, 49.5]	0.701 [-8.96, 95.2]	1.43 [-0.995, 10.0]	0.996 [-4.72, 39.0]
Current Yield				
Mean (SD)	2.87 (2.31)	2.96 (4.50)	2.54 (1.86)	2.58 (2.36)
Median [Min, Max]	2.82 [0, 44.6]	1.90 [0, 87.3]	2.10 [0.00995, 9.14]	1.70 [0, 16.7]
Missing	62 (2.1%)	140 (2.7%)	11 (3.0%)	25 (2.6%)
Yield at Issue				
Mean (SD)	3.94 (1.76)	3.89 (4.13)	2.93 (1.98)	3.06 (2.55)
Median [Min, Max]	3.95 [-0.460, 13.8]	3.20 [-0.476, 100]	2.86 [0.0600, 7.60]	2.56 [0.0200, 12.9]
Missing	1473 (49.7%)	3336 (64.2%)	174 (46.8%)	708 (72.4%)
Volatility				
Mean (SD)	3.46 (3.93)	3.79 (4.02)	1.66 (0.920)	1.83 (1.27)
Median [Min, Max]	1.64 [0.00737, 17.9]	1.64 [0.00267, 17.9]	1.58 [0.448, 11.5]	1.36 [0.00339, 11.5]
Missing	3 (0.1%)	1 (0.0%)	0 (0%)	4 (0.4%)
Sharpe Ratio				
Mean (SD)	2.53 (40.4)	1.73 (55.2)	1.55 (1.66)	3.19 (27.8)
Median [Min, Max]	0.748 [-1.62, 1480]	0.320 [-2.57, 2810]	0.982 [-0.858, 8.44]	0.698 [-2.87, 461]
Missing	3 (0.1%)	1 (0.0%)	0 (0%)	4 (0.4%)
Liquidity				
Mean (SD)	-0.00766 (0.00586)	-0.00361 (0.00426)	-0.0216 (0.209)	-0.00580 (0.0238)
Median [Min, Max]	-0.00655 [-0.0610, 0]	-0.00248 [-0.0945, 0]	-0.00557 [-3.99, 0.000279]	-0.00275 [-0.357, 0]

Source: Author calculations based on Bloomberg Terminal data.
Note: (1) Descriptive statistic for green and conventional bonds for our whole sample of bonds by maturity. Long-term bonds are those with a duration greater than 10 years. The volatility is measured by the standard deviation of the yield to maturity of the bonds (based on a combination of maturity and conventional/green type of bonds), the liquidity by the bid-ask spread. The Sharpe ratio uses the SRp approach (as defined in section 5.2). (2) We generally observe that green bonds tend to have lower yields and volatility. The Sharpe ratio is higher for shorter-term bonds, but not so for long-term bonds.

Table A.6. Green and Conventional Bonds by Rating: Descriptive Statistics, January 2017-September 2020

	conventional		green	
	investment grade (N=7249)	**non-investment grade (N=915)**	**investment grade (N=441)**	**non-investment grade (N=909)**
Yield to Maturity				
Mean (SD)	1.70 (3.72)	9.84 (12.6)	1.06 (1.57)	2.49 (2.75)
Median [Min, Max]	0.877 [-8.96, 95.2]	6.18 [-3.38, 94.2]	0.689 [-0.657, 17.7]	1.60 [-4.72, 39.0]
Current Yield				
Mean (SD)	2.30 (2.43)	7.74 (7.64)	1.82 (1.43)	2.92 (2.45)
Median [Min, Max]	1.90 [0, 62.7]	6.35 [0.0499, 87.3]	1.49 [0, 12.0]	2.32 [0.00978, 16.7]
Missing	193 (2.7%)	9 (1.0%)	18 (4.1%)	18 (2.0%)
Yield at Issue				
Mean (SD)	3.37 (3.28)	6.36 (1.96)	2.82 (1.44)	3.10 (2.64)
Median [Min, Max]	3.27 [-0.476, 100]	6.25 [-0.460, 14.2]	2.81 [0.0900, 9.55]	2.55 [0.0200, 12.9]
Missing	4508 (62.2%)	301 (32.9%)	289 (65.5%)	593 (65.2%)
Volatility				
Mean (SD)	3.14 (3.33)	7.89 (5.86)	1.71 (0.879)	1.82 (1.31)
Median [Min, Max]	1.64 [0.00955, 17.9]	6.50 [0.00267, 17.9]	1.58 [0.00339, 3.79]	1.36 [0.0124, 11.5]
Missing	3 (0.0%)	1 (0.1%)	0 (0%)	4 (0.4%)
Sharpe Ratio				
Mean (SD)	0.886 (8.18)	11.0 (148)	2.64 (27.5)	2.79 (21.6)
Median [Min, Max]	0.372 [-2.57, 333]	1.15 [-1.30, 2810]	0.435 [-1.21, 410]	1.08 [-2.87, 461]
Missing	3 (0.0%)	1 (0.1%)	0 (0%)	4 (0.4%)
Liquidity				
Mean (SD)	-0.00490 (0.00517)	-0.00655 (0.00586)	-0.00480 (0.00459)	-0.0128 (0.136)
Median [Min, Max]	-0.00328 [-0.0945, 0]	-0.00515 [-0.0631, 0]	-0.00369 [-0.0481, 0]	-0.00302 [-3.99, 0.000279]

Source: Author calculations based on Bloomberg Terminal data.
Note: (1) Descriptive statistic for green and conventional bonds for our whole sample of bonds by rating. Non-investment grades are those with an existent S&P rating greater or equal than BBB-. The volatility is measured by the standard deviation of the yield to maturity of the bonds (based on a combination of maturity and conventional/green type of bonds) and the liquidity by the bid-ask spread. The Sharpe ratio uses the SR_p approach (as defined in section 5.2). (2) We generally observe that green bonds tend to have lower yields and volatility. Here, the Sharpe ratio is higher for investment-grade bonds.

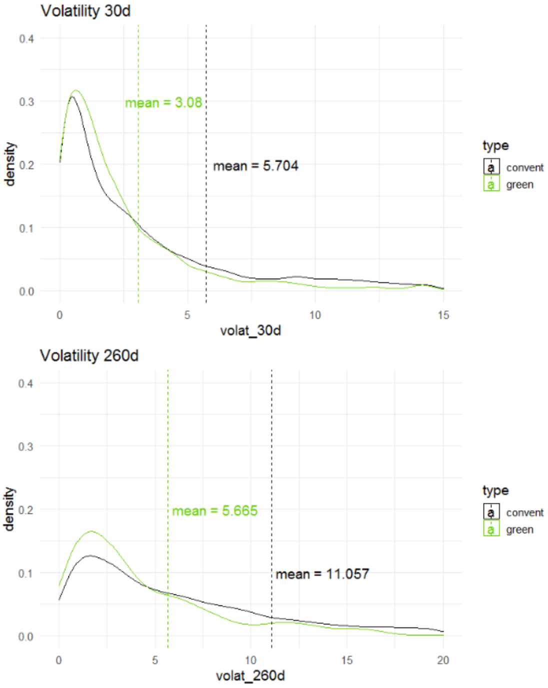
Next, this section contains information on volatility measures of individual assets (figure A.3) for a 30-, 90-, and 260-day period before the reference date (which is October 1, 2020). Based on these volatility measures and the yield to maturity rate, we calculate the bond-specific Sharpe ratio (SR_b) for green and conventional bonds (density plots depicted in figure A.4). In relation to the classic Sharpe ratio (what we call the portfolio Share ratio, SR_p), we define the SR_b as follows:

$$SR_b = \frac{R_b - R_f}{v_b} \qquad \text{(Eq. A. 4)}$$

where for each bond we have SR_b= bond-specific Sharpe ratio, R_b = individual asset return, R_f = risk-free rate, and v_b = individual asset volatility measure.[10] We also provide a table that summarizes portfolio-specific Sharpe ratios (SR_p) for the whole data set in the form of Sharpe ratio differences, where ΔSR_p represents a green SR_p minus a paired conventional SR_p (table A.7).

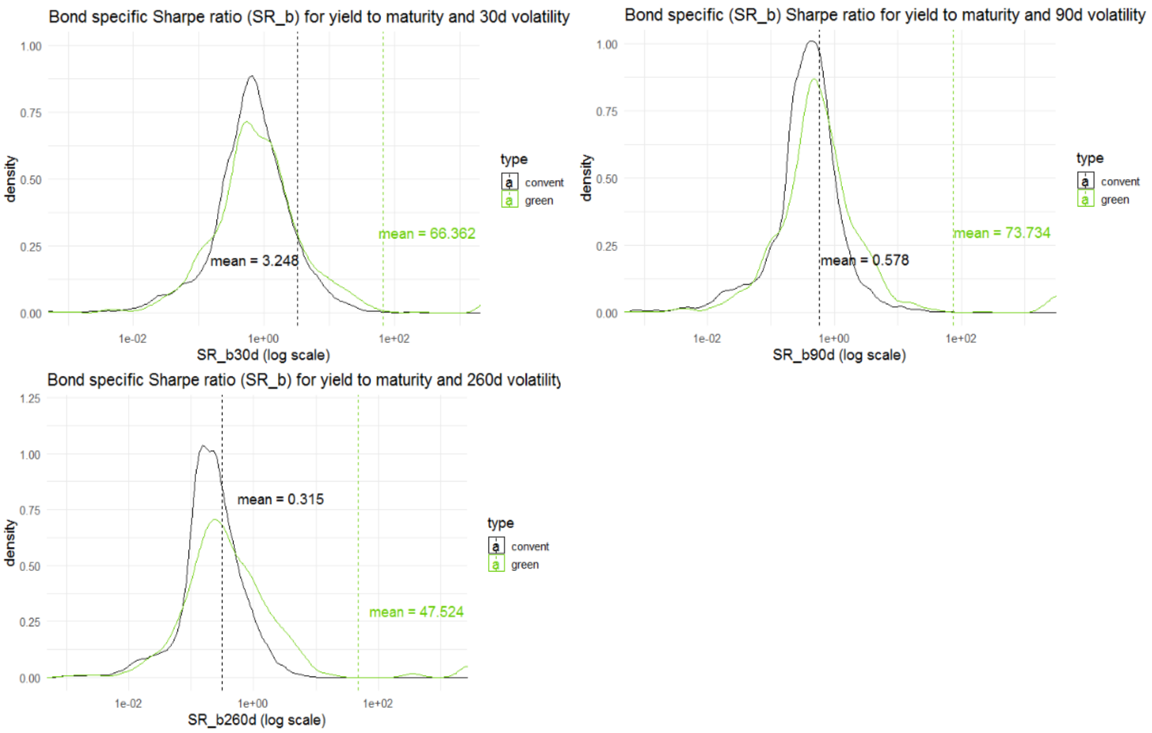
[10] We compared the bond-specific Sharpe ratio results with and without the risk-free rate for the two most frequent currencies (USD and EUR) and did not find a relevant change (differences in the size of the second or the third digit after the decimal). Hence, for simplicity, we do not consider the risk-free rate in our analysis when reporting results on the bond-specific Sharpe ratio (SR_b).

Figure A.3. Green and Conventional Bonds: Distribution for the 30-, 90-, and 260-Day Volatility Measurement, January 2017–September 2020



Source: Bloomberg Terminal data.
Note: (1) Volatility measurements for our whole sample, conventional or green bonds issued from January 2017 to September 2020. We used Bloomberg volatility measurements for each bond. This variable is calculated based on the standard deviation of day-to-day logarithmic historical price changes for each bond during the past 30, 90, or 260 days, with October 1, 2020, as the reference date. (2) We here also observe that green bonds have lower volatility.

Figure A.4. Green and Conventional Bonds: Bond-Specific Sharpe Ratio (SR_b) for 30-, 90-, and 260-Day Volatility, January 2017–September 2020



Source: Bloomberg Terminal data.
Note: (1) The bond-specific Sharpe ratio, SR_b as defined above, is calculated for our whole sample, conventional or green bonds issued from January 2017 to September 2020. We use as risk measurement, in the Sharpe ratio denominator, the Bloomberg volatility measurements for each bond during the past 30, 90, or 260 days, with October 1, 2020, as the reference date. (2) We observe here that green bonds can have higher Sharpe ratios.

Table A.7. Differences of Portfolio-Based Sharpe Ratio (SR_p) for Green and Conventional Bonds by Sector and Currency, January 2017–September 2020

Currency	BICS 1	BICS 2	obs (green/conv)	ΔSR_p^{ytm}	ΔSR_p^{yc}	ΔSR_p^{yai}
CNY						
CNY	Financials	Banks	80/111	0.173	-0.488	NaN
EUR						
EUR	Financials	Banks	133/1461	0.048	0.014	0.323
EUR	Financials	Real estate	46/150	0.66	0.233	-0.484
EUR	Government	Gov dvlpmt banks	18/333	-1.365	0.463	NA
EUR	Government	Sovereigns	12/120	-0.271	1.926	0.581
EUR	Government	Supranationals	28/120	-0.213	-0.004	NA
EUR	Utilities	Power generation	34/24	-0.371	-0.954	NA
EUR	Utilities	Utilities	73/98	0.018	-0.563	0.08
GBP						
GBP	Utilities	Utilities	17/64	-0.847	-0.858	9.053
JPY						
JPY	Financials	Real estate	52/30	-0.55	-0.162	-0.07
SEK						
SEK	Financials	Banks	12/129	0.565	4.481	NA
SEK	Financials	Real estate	142/31	-0.663	-0.563	NA
SEK	Government	Gov dvlpmt banks	17/30	0.211	-0.81	NA
SEK	Government	Supranationals	22/31	-0.018	0.197	1.795
USD						
USD	Energy	Energy	12/113	-0.284	1.161	-0.296
USD	Financials	Banks	59/1281	0.26	0.49	1.322
USD	Financials	Real estate	44/375	0.791	0.056	-1.061
USD	Government	Gov dvlpmt banks	20/219	0.635	-0.061	-0.809
USD	Government	Supranationals	39/200	0.116	0.155	0.294
USD	Utilities	Power generation	32/87	-0.833	0.116	0.434
USD	Utilities	Utilities	58/561	1.103	1.361	-0.397

Source: Author calculations based on Bloomberg Terminal data.
Note: (1) The Sharpe ratio uses the portfolio Sharpe ratio - SR_p approach as defined in section 5.2. It considers three return measurements in the numerators: yield to maturity (ytm), current yield (yc), and yield at issue (yai). In the denominator, we have the standard deviation of the bond returns for several groups of bonds according to their currency and sectors (BICS level 1 and BICS level 2). (2) The portfolio-based Sharpe ratio differences (ΔSR_p) for the different yield measures in the last three columns are calculated as the differences between the SR_p for green bonds minus the SR_p for conventional bonds. (3) SRp^{ytm} tends to be positive for USD-denominated bonds and bonds from the financial sector, but we do not actually see a clear sectoral or currency relationship. BCIS = Bloomberg Industry Classification Systems, CNY = Chinese yuan, EUR = euro, GBP = Great Britain pound, JPY = Japanese yen, SEK = Swedish krona, and USD = US dollar.

A.5. Volatility Analysis by a Classification and Regression Tree

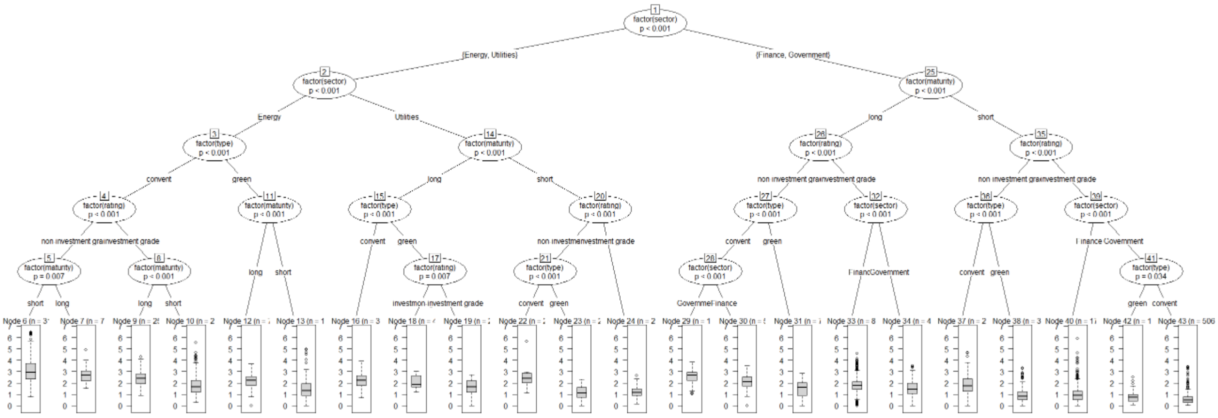
We use the classification and regression tree (CART) method to identify the most essential drivers in the volatility structure of bonds. A CART analysis uses a decision tree that results from a supervised learning predictive model. Based on a set of binary input variables (our categorical regressors), we are predicting the value of our target variable, which is a bond volatility measure. Some benefits of this type of analysis are that CART is nonparametric and therefore does not rely on data belonging to a particular type of distribution, CART is not significantly impacted by outliers in the input variables, and CART can use the same variables more than once in different parts of the tree and therefore uncover complex interdependencies between sets of variables (Nisbet et al., 2018).

By running a CART analysis, we find further validation that green bonds have lower volatilities than conventional bonds and also find that the sectoral attribute plays a very important role in predicting volatilities—for example, bonds in the energy sector have higher volatilities than bonds in other sectors. The widely used machine-learning CART technique is a helpful tool to identify complex interdependencies between different sets of variables and, because it is a nonparametric method, it also does not rely on data belonging to a particular type of distribution. We apply the CART method in R with the *rpart* command to predict bond volatilities based on four relevant categorical variables: (a) bond type (that is, green or conventional), (b) sectors, (c) maturities, and (d) ratings. Based on these variables we find that the top discriminating factor is sectoral division: The sectoral affiliation matters most when it comes to predicting high bond volatilities. Using this command in conjunction with our data set on conventional and green bonds (from 2017 to 2020) yields a huge tree (figure A.5). For better readability, figures A.6a and A.6b depict the left branch (energy and utilities sector) and the right branch (finance and government sector), respectively. These figures show that bonds in the energy and utilities sector have higher volatilities than those in the finance and government sector. The observation about higher volatilities in the energy sector is further analyzed in chapter 6, which analyzes bond performance with regard to oil price fluctuations. Additionally, the CART analysis validates our prior findings that green bonds are associated with lower volatilities than conventional bonds.

The CART results in figures A.5, A.6a, and A.6b show a decision tree that ranks the sectoral specification as the most important property regarding the volatility prediction. Bonds from the energy and utilities sectors open the top left branch, which means that bonds in these sectors will predict higher volatilities than bonds in other sectors (that is, the finance and government sector). A bond being in the energy (and utility) sector matters the most when it comes to predicting a volatility measure (graphically, energy is listed as the top classifier). Another good validation of our results is that bonds that are categorized as green are mostly shown “to the right” of conventional bond branches, which means that being a green bond predicts in most cases lower volatilities than being a conventional bond. The only case where we observe the opposite is for government bonds (see bottom right), but Kapraun and Scheins (2019) also found an opposite trend for green bonds when they looked at the government sector. For most of the decision nodes, we also see that non-investment grade bonds predict higher volatilities than investment grade bonds, which is analogous to the comparison of long-term bonds and short-term bonds.

This CART analysis was done across all currencies, but currency-specific CART analyses for the USD and EUR confirm the general findings: (a) The energy sector also appears as a high volatility classifier for both currencies (not necessarily as the top one but still appearing as a high-volatility predictor), and that (b) the bond type category shows lower volatilities for green bonds in the USD case but does not appear as a strong predictor for the EUR case (a currency anomaly that we already see in respect to the multivariate regressions).

Figure A.5. CART Analysis on the 90-Day Volatility for Bond Types, Sectors, Ratings, and Maturities



Note: This decision tree is retrieved by applying the *rpart* command from R to our data. We predict the 90-day volatility (volat_90d) with four categorical variables: (a) bond type (green vs. conventional bond), (b) sectors (energy, utility, finance, government), (c) ratings (investment grade vs. non-investment grade), and (d) maturities (short vs. long term). Because of the high amount of energy-related bond issuers in the "power generation" subsector (on BICS level 2), we categorized green as well as conventional bonds in this subcategory as bonds of the energy sector.

Figure A.6a. Left Branch (Starting with the Energy and Utilities Sector) of the CART Analysis on the 90-Day Volatility for Bond Types, Sectors, Ratings, and Maturities

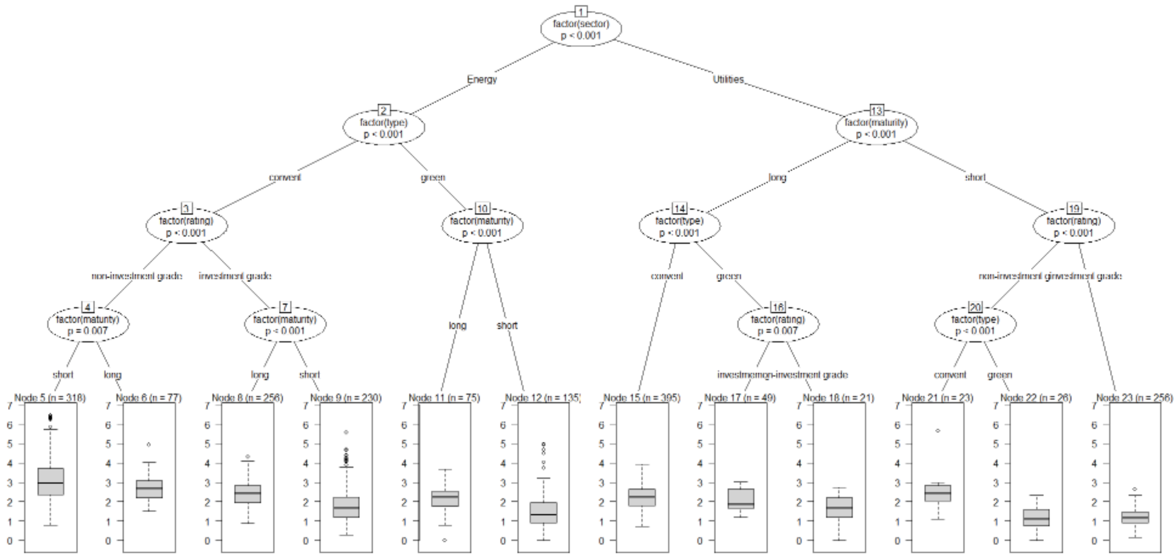
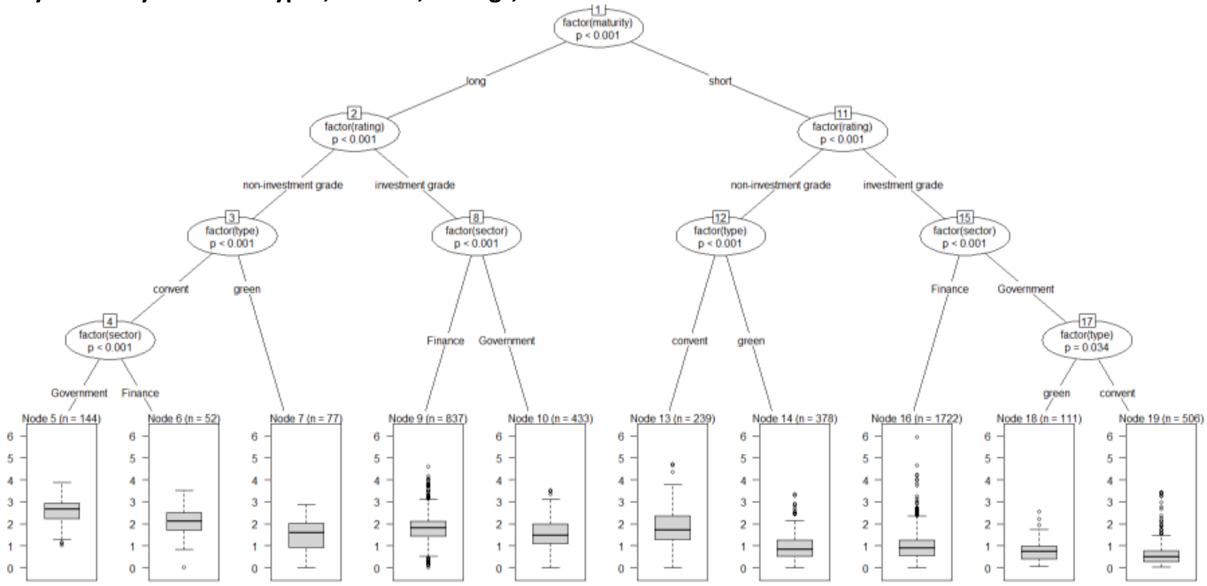


Figure A.6b. Right Branch (Starting with the Finance and Government Sector) of the CART Analysis on the 90-Day Volatility for Bond Types, Sectors, Ratings, and Maturities



A.6. Multivariate Regression Analysis

To evaluate the yield drivers in our data set, we use an ordinary least squares (OLS) regression. It helps us measure the degree to which more than one independent variable or predictor and one dependent variable or response are related.

A general multivariate-regression model can be written as follows:

$$\hat{y} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k \qquad \text{(Eq. A. 5)}$$

where $\hat{y}$ is the predicted or expected value of the dependent variable, x_1 through x_k are independent or predictor variables, β_0 is the value of $\hat{y}$ when all of the independent variables are equal to zero, and β_1 through β_k are the estimated regression coefficients. Each regression coefficient represents the change in $\hat{y}$ relative to a one-unit change in the respective independent variable. In the multiple regression situation, for example, β_1 is the change in $\hat{y}$ relative to a one-unit change in x_1, holding all other independent variables constant (that is, when the remaining independent variables are held at the same value or are fixed). The computation of the p-value through a statistical test enables us to determine the significance of the relationship between a dependent variable and an independent variable.

- **Model 1 – Base model**

As a first step, we determine the effect of a green bond on the expected return of bonds (using the yield to maturity rate) in a base regression (Eq. A.6) with the following covariates:

- X_1: A green dummy variable (when equal to one, the bond is green)
- X_2: The S&P rating (variable has the form of investment grade vs. non-investment grade dummy variable; when the variable is equal to one, the bond is non-investment grade)[11]
- X3: The maturity structure (variable has the form of short-term vs. long-term dummy variable; if the variable is equal to one, the bond is short-term)[12]
- X4: The coupon rate
- X5: The liquidity (computed as the bid minus the ask price)
- X6: The amount of bonds issued in US dollars divided by 10^9 (dividing by a billion gives us more similar numbers in comparison to the yield values)
- X7: The debt-to-assets ratio
- X8: The 90-day bond price volatility rate

Since all continuous variables show a pattern of negative exponentials in the upper tail, we use logarithmic transformations. Because of the appearance of negative and positive values (for example, for yield-to-maturity rates and bond-specific Sharpe ratios), we use the log modulus transformation, which we call $lm(x)$ and which is defined as $lm(x) = sign(x) \cdot log(|x| + 1)$. This transformation helps spread out the magnitude of the data while preserving the sign and is a common log transformation for positive and non-positive values (see John & Draper [1980]). The logarithmic regression is of the following form:

$$lm(Y_i) = \beta_0 + \beta_1 \cdot X_{1,i} + \sum_{k=2}^{3} \beta_k X_{k,i} + \sum_{k=4}^{8} \beta_k lm(X_{k,i}) + \epsilon_i \qquad \text{(Eq. A. 6)}$$

The multivariate linear regression shows the impact on yield for green versus conventional bonds and finds additional evidence that bonds labeled as green have lower yields (figure A.7). To capture the effect of a green bond concerning its behavior on the yield performance, we run a regression on the yield-to-maturity rate and use the bond type (green or conventional) as a dummy variable. The regression shows that for all models with different volatility measures (model 1 with 30d, model 2 with 90d, and model 3 with 260d), labeling a bond as green reduces the yield-to-maturity rate. This holds even when controlling for other key drivers of the yield determination, including the sector of issuance or currency (see figure A.9).

Figure A.7. Multivariate Linear Regression for the Yield to Maturity, January 2017–February 2020

A. Regression table

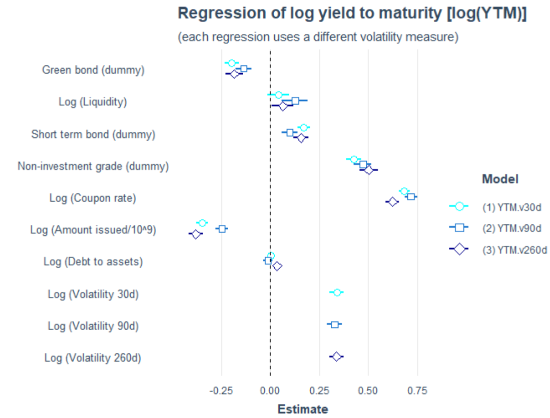
B. Regression plot

[11] Investment-grade bonds are defined by bonds with available S&P rating equal to or greater than BBB- (if not, they are classified as non-investment grade bonds), as in Charles Schwab & Co. (2017).

[12] Long-term bonds are those with a duration greater than 10 years, as in Thune (2019).

	(1) YTM.v30d	(2) YTM.v90d	(3) YTM.v260d
Green bond (dummy)	-0.20 ***	-0.14 ***	-0.18 ***
	(0.02)	(0.02)	(0.02)
Log (Liquidity)	0.04	0.13 ***	0.06 *
	(0.03)	(0.03)	(0.03)
Short term bond (dummy)	0.17 ***	0.10 ***	0.16 ***
	(0.02)	(0.02)	(0.02)
Non-investment grade (dummy)	0.43 ***	0.47 ***	0.50 ***
	(0.02)	(0.02)	(0.02)
Log (Coupon rate)	0.69 ***	0.72 ***	0.62 ***
	(0.01)	(0.02)	(0.02)
Log (Amount issued/10^9)	-0.35 ***	-0.25 ***	-0.38 ***
	(0.02)	(0.02)	(0.02)
Log (Debt to assets)	0.00	-0.01	0.04 ***
	(0.01)	(0.01)	(0.01)
Log (Volatility 30d)	0.34 ***		
	(0.02)		
Log (Volatility 90d)		0.33 ***	
		(0.02)	
Log (Volatility 260d)			0.34 ***
			(0.02)
N	7972	5524	6565
R2	0.66	0.72	0.68

Standard errors are heteroskedasticity robust. *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.



Source: Author calculations based on Bloomberg Terminal data.
Note: The regressions are run for our sample of all green and conventional bonds downloaded from the Bloomberg Terminal, using the yield to maturity as the dependent variable. We use a volatility measure of 30 days, 90 days, and 260 days, with October 1, 2020, as the reference date.

A regression on the bond-specific Sharpe ratios (figure A.8) allows for an alternative picture of the effect of the green label on a bond's attractiveness: Having a higher reward-to-risk depends much more on sector-specific drivers than on the green bond label, but the attractiveness of green bonds can be influenced by an appropriate monetary or fiscal policy.

$$lm(SRb_i) = \beta_0 + \beta_1 \cdot X_{1,i} + \sum_{k=2}^{3} \beta_k X_{k,i} + \sum_{k=4}^{7} \beta_k lm(X_{k,i}) + \epsilon_i \qquad (\text{Eq. A. 7})$$

Mind that in equation A.7 for the $lm(SRb_i)$, the second sum runs from k=4 to 7 only since we dropped the 90-day volatility rate (this information is now incorporated on the left-hand side).

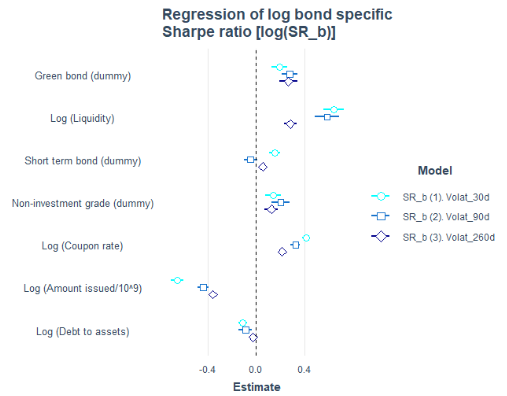
Figure A.8. Multivariate Linear Regression for the Sharpe Ratio, January 2017–February 2020

A. Regression table

	(1) SR_b30d	(2) SR_b90d	(3) SR_b260d
Green bond (dummy)	0.19 ***	0.28 ***	0.27 ***
	(0.03)	(0.03)	(0.04)
Log (Liquidity)	0.64 ***	0.59 ***	0.28 ***
	(0.04)	(0.05)	(0.03)
Short term bond (dummy)	0.15 ***	-0.05	0.05 ***
	(0.02)	(0.03)	(0.02)
Non-investment grade (dummy)	0.14 ***	0.20 ***	0.13 ***
	(0.03)	(0.04)	(0.03)
Log (Coupon rate)	0.42 ***	0.33 ***	0.22 ***
	(0.02)	(0.02)	(0.01)
Log (Amount issued/10^9)	-0.66 ***	-0.44 ***	-0.36 ***
	(0.03)	(0.02)	(0.02)
Log (Debt to assets)	-0.11 ***	-0.09 **	-0.03 *
	(0.02)	(0.03)	(0.01)
N	7929	5491	6540
R2	0.20	0.19	0.18

Standard errors are heteroskedasticity robust. *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

B. Regression plot



Source: Author calculations based on Bloomberg Terminal data.
Note: The regressions are run for our sample of all green and conventional bonds downloaded from the Bloomberg Terminal, using the bond-specific Sharpe ratio as dependent variable. We use a volatility measure of 30 days, 90 days, and 260 days, with October 1, 2020, as the reference date.

- **Model 2 – Adding sectoral control variables**

Next, we again look at the whole sample and evaluate with a multivariate regression model whether bonds labeled as green tend to have lower yields and higher Sharpe ratios, even when adding new control variables. We build a multivariate linear regression for the Sharpe ratio and the yield to maturity, considering the same independent variables as before, namely maturity (short or long term), rating (investment grade or not), coupon rate, dollar amount issued (divided by a billion), sector (BICS level 1),[13] liquidity (bid-ask price difference), volatility (90-day volatility), debt to assets ratio, and a dummy variable for a green-labeled bond. As a first control, we add categorical variables for the sectors that we are in:

- S_1 energy sector: The energy sector is expressed by Bloomberg Industry Classification Systems (BICS) level 1 "energy." Additionally, we also incorporate observations with the BICS level 2 "power generation" because of its consistent relation to energy bond issuers.
- S_2 finance sector: The finance sector is expressed by BICS level 1 "financials," which includes banks and real estate bonds.
- S_3 government sector: The government sector is expressed through BICS level 1 "government." It comprises "government development banks," "supranationals," and "sovereigns."
- S4 utilities sector: Utilities are expressed through BICS level 2 "utilities" and cover most public services and utility providers (for example, sewage).

$$lm(Y_i) = \beta_0 + \beta_1 \cdot X_{1,i} + \sum_{k=2}^{3} \beta_k X_{k,i} + \sum_{k=4}^{8} \beta_k lm(X_{k,i}) + \sum_{l=1}^{4} \gamma_l S_{l,i} + \epsilon_i \qquad (\text{Eq. A.8})$$

- **Model 3 & 4 – Adding currency control variables (model 3 for USD, model 4 for EUR)**

As a second control in our regression sequence, we further add currency as a grouping variable. Since the biggest part of our observations is expressed in EUR- and USD-denominated bonds, we only use these two currency controls:

- C = 1: USD
- C = 2: EUR

$$lm(Y_{i,c}) = \beta_0 + \beta_1 \cdot X_{1,i,c} + \sum_{k=2}^{3} \beta_{k,c} X_{k,i,c} + \sum_{k=4}^{8} \beta_{k,c} lm(X_{k,i,c}) + \sum_{l=1}^{4} \gamma_{l,c} S_{l,i,c} + \epsilon_{i,c} \qquad (\text{Eq. A.9})$$

After running a regression in the yield to maturity value, we run a regression on the bond-specific Sharpe ratios, computed with the yield to maturity rate and a volatility measure (our main reference is the 90d volatility):

$$lm(SRb_{i,c}) = \beta_0 + \beta_1 \cdot X_{1,i,c} + \sum_{k=2}^{3} \beta_{k,c} X_{k,i,c} + \sum_{k=4}^{7} \beta_{k,c} lm(X_{k,i,c}) + \sum_{l=1}^{4} \gamma_{l,c} S_{l,i,c} + \epsilon_{i,c} \qquad (\text{Eq. A.10})$$

In equation A.10 for the log ($SRb_{i,c}$), the second sum runs again from k=4 to 7 only since we dropped the 90-day volatility rate (this information is now incorporated on the left-hand side).

Our regressions show that at the aggregate level the green bond label seems to positively influence the Sharpe ratio (see regression output in figure A.8 for the base model 1 based on the regression equation A.7). Also for the augmented models 3 and 4 that control for sectors and currencies (namely USD- and EUR-denominated

[13] The sectoral picture is especially important as green bonds are concentrated in a few sectors (see appendix A.3, table A.3) and the use of proceeds might impact investor and issuer behavior.

bonds), we find that the effect of a green bond label on the SR_b is associated with a positive sign or not significant (see regression output in figure A.10). Our data analysis shows additional evidence that green bonds create benefits for issuers and investors in terms of lower volatility but also lower yields for issuers. However, the attractiveness of green bonds for investors in terms of the Sharpe ratio depends on other factors. Keep in mind also that the R^2 of our models is much lower compared to the prior regression on the yield to maturity rates. This effect might be due to other influencing factors (for example, issuer-specific effects).[14]

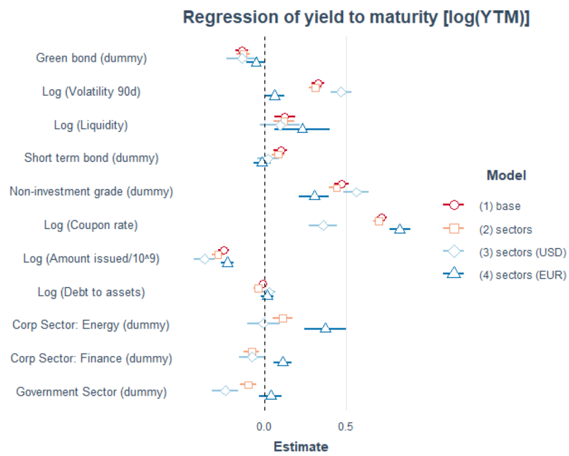
Figure A.9. Multivariate Linear Regression for the Yield to Maturity, January 2017–September 2020

A. Regression table

	(1) base	(2) sectors	(3) sectors (USD)	(4) sectors (EUR)
Green bond (dummy)	-0.14 ***	-0.13 ***	-0.13 **	-0.05
	(0.02)	(0.02)	(0.05)	(0.03)
Log (Volatility 90d)	0.33 ***	0.31 ***	0.47 ***	0.06 *
	(0.02)	(0.02)	(0.03)	(0.03)
Log (Liquidity)	0.13 ***	0.12 ***	0.10	0.23 **
	(0.03)	(0.03)	(0.06)	(0.09)
Short term bond (dummy)	0.10 ***	0.09 ***	0.02	-0.01
	(0.02)	(0.02)	(0.03)	(0.03)
Non-investment grade (dummy)	0.47 ***	0.44 ***	0.56 ***	0.31 ***
	(0.02)	(0.02)	(0.04)	(0.05)
Log (Coupon rate)	0.72 ***	0.70 ***	0.36 ***	0.83 ***
	(0.02)	(0.02)	(0.04)	(0.03)
Log (Amount issued/10^9)	-0.25 ***	-0.28 ***	-0.37 ***	-0.22 ***
	(0.02)	(0.02)	(0.03)	(0.02)
Log (Debt to assets)	-0.01	-0.04 **	0.03	0.02
	(0.01)	(0.01)	(0.02)	(0.02)
Corp Sector: Energy (dummy)		0.11 ***	-0.01	0.37 ***
		(0.03)	(0.05)	(0.06)
Corp Sector: Finance (dummy)		-0.08 **	-0.07	0.11 ***
		(0.02)	(0.04)	(0.03)
Government Sector (dummy)		-0.10 ***	-0.24 ***	0.04
		(0.02)	(0.04)	(0.04)
N	5524	5524	2784	2027
R2	0.72	0.73	0.72	0.58

Standard errors are heteroskedasticity robust. *** p < 0.001; ** p < 0.01; * p < 0.05.

B. Regression plot



Source: Author calculations based on Bloomberg Terminal data.
Note: The regressions are run for our sample of all green and conventional bonds downloaded from the Bloomberg Terminal, using the log-yield to maturity as the dependent variable. Model (1) is a base model with 8 regressors with 3 dummy variables (green bond, short-term bond, non-investment grade bond; baselines are conventional bond, long-term bond and investment grade bond) and 5 log-covariates (log volatility, log liquidity, log coupon rate, log amount issued/10^9, log debt to assets). Model (2) adds sectoral categorical variables (energy sector, finance sector, government sector, utilities sector; where utilities is the baseline). Model (3) computes the previous model for only USD-denominated bonds. Model (4) runs the same model for only EUR-denominated bonds.

Figure A.10. Multivariate Linear Regression for Sharpe Ratios, January 2017–September 2020

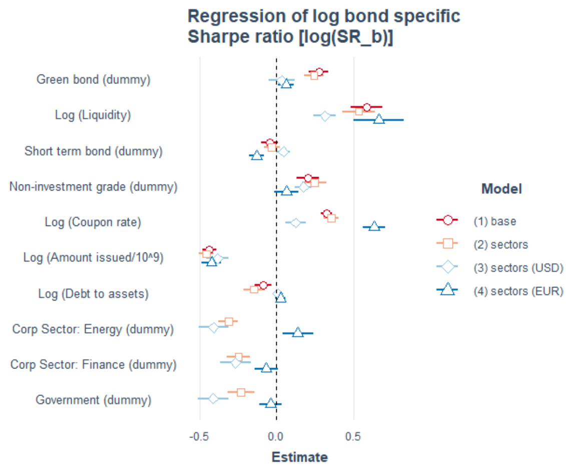
A. Regression table

B. Regression plot

[14] In a further analysis that compares non-green and green bonds from the energy sector (that is, “fossil fuel” bonds vs. renewable energy bonds), we obtain similar results: For green bonds, we find lower yield to maturity and volatility values and mostly higher bond-specific Sharpe ratios (SR_b). There is a positive and significant effect for the SR_b’s with a 30-day volatility measure and positive but not significant results for SR_b’s with the 90-day and 260-day volatility measures. Results are available upon request.

	(1) base	(2) sectors	(3) sectors (USD)	(4) sectors (EUR)
Green bond (dummy)	0.28 ***	0.24 ***	0.03	0.06 *
	(0.03)	(0.03)	(0.04)	(0.03)
Log (Liquidity)	0.59 ***	0.54 ***	0.31 ***	0.67 ***
	(0.05)	(0.05)	(0.04)	(0.08)
Short term bond (dummy)	-0.05	-0.03	0.04	-0.13 ***
	(0.03)	(0.03)	(0.02)	(0.02)
Non-investment grade (dummy)	0.20 ***	0.25 ***	0.17 ***	0.06
	(0.04)	(0.04)	(0.03)	(0.04)
Log (Coupon rate)	0.33 ***	0.35 ***	0.12 ***	0.64 ***
	(0.02)	(0.02)	(0.03)	(0.04)
Log (Amount issued/10^9)	-0.44 ***	-0.46 ***	-0.38 ***	-0.43 ***
	(0.02)	(0.02)	(0.04)	(0.03)
Log (Debt to assets)	-0.09 **	-0.15 ***	0.01	0.02
	(0.03)	(0.04)	(0.01)	(0.02)
Corp Sector: Energy (dummy)		-0.31 ***	-0.41 ***	0.14 **
		(0.03)	(0.05)	(0.05)
Corp Sector: Finance (dummy)		-0.25 ***	-0.27 ***	-0.07
		(0.04)	(0.05)	(0.04)
Government (dummy)		-0.23 ***	-0.41 ***	-0.04
		(0.04)	(0.05)	(0.04)
N	5491	5491	2767	2026
R2	0.19	0.20	0.19	0.31

Standard errors are heteroskedasticity robust. *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.



Source: Author calculations based on Bloomberg Terminal data.
Note: The regressions are run for our sample of all green and conventional bonds downloaded from the Bloomberg Terminal, using the log Sharpe ratio as dependent variable. Aside from dropping the volatility measure as covariate, the regressions here are identical to the models that used the yield to maturity rate (figure A.9).

A.7. Pairing Procedure for Green and Conventional Bonds

To control for issuer-specific effects, we compute a bond pairing algorithm that matches each green bond with a conventional bond.[15] First, we select pairs of similar green and conventional bonds and evaluate the yield differences (green bond returns minus conventional bond returns) on the primary market (yield at issue) and secondary markets (yield to maturity). The aggregate results of our paired subset of data confirm the findings of Kapraun & Scheins (2019), which is a negative green premium for yield at issue rates but a positive green premium for yield to maturity rates in comparison to conventional bonds. Additionally, we see higher bond-specific Sharpe ratios for green bonds than for their conventional bond pairings. Our bond pairing procedure selects green and conventional bonds with the same (a) issuer (and therefore the same sector), (b) currency, (c) maturity structure, and (d) S&P rating.[16] With this procedure, we create a subset of data that consists of 145 paired observations (145 green and 145 conventional bonds). Any green bond of this subset is required to match with a conventional bond in these five criteria. In many cases, these conditions do not exhaust possible conventional matching partners for a green bond. In these cases, the best match is further refined by checking for the same issue year and finally choosing the bond with the closest coupon value. This pairing procedure ensures that similar assets are compared. The paired bond subset confirms the existence of a "greenium" (lower yields when comparing green bonds to conventional bonds) for issued bonds on the primary market (see table A.8 and figure A.11). Yet the difference turns positive once the yield at issue is discounted by asset-specific volatility measures (see column "Yield at issue (yai)" for rows *(b-d)* in table A.8, as well as figure A.11). On the

[15] The data set comprises many more conventional bonds than green bonds, and on top of that it is unbalanced (that is, there is a very unequal number of observations for different bond types, sectors, currencies, maturities, and so on). Therefore, it is not possible to set up a panel data set or run a fixed-effects regression to account for latent factors. An alternative form to account for common, unobservable factors is to estimate a seemingly unrelated regression (SUR). A SUR computes error terms that are correlated across equations for a given individual but uncorrelated across individuals. In this case, the main attribute of an observation is being green or conventional, which is an exclusive attribute. Therefore, running a SUR is difficult not only because of the nature of the data set but also because it is not adequate for the estimation of the green bond effect, which we compute as a dummy variable.

[16] Since in many cases there are still many more conventional bonds than green bonds, we extend our matching procedure by filtering for the same issue year and choosing the paired bond based on the closest coupon rate (this should reflect similar issuing conditions).

secondary market, we find a positive yield premium and greater Sharpe ratios for green bonds. We see that by discounting the yields by the volatility (that is, comparing the yield to maturity differences with the SR_b^{ytm} differences) leads to stronger positive effects: See column "Yield to maturity (ytm)" in table A.8 where rows *(b-d)* show bigger values than row *(a)*, as well as figure A.12, where the average SR_b^{ytm} differences are bigger than the yield difference. The positive difference for paired green bonds increases when we add volatility to the indicator. This means that the conventional bond yields that are discounted by their bond-specific volatility measure show a weaker performance than their green partners. Thus, even if we look at a subset of data with similarly paired bonds, we find evidence that green bonds show lower volatility and can have lower yields, but they also are able to reward the investor with a better Sharpe ratio.

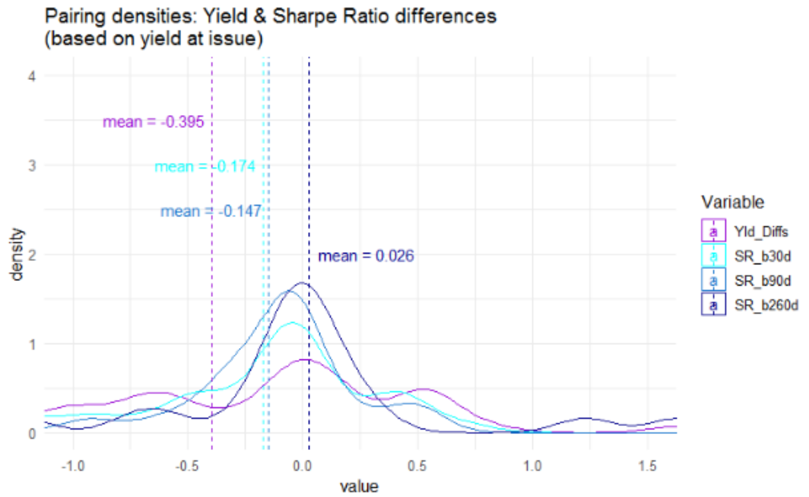
Table A.8. Mean Differences of Paired Bonds: Yield and Sharpe Ratio Differences

Measurement	Yield at issue (yai)	Yield to maturity (ytm)
(a) Mean yield difference: $avg(yield_{green} - yield_{convent})$	-0.424	0.300
(b) Mean SR_b difference for 30d volatility: $avg(SR_{bgreen}^{30d} - SR_{b\,convent}^{30d})$	1.05	2.12
(c) Mean SR_b difference for 90d volatility: $avg(SR_{bgreen}^{90d} - SR_{b\,convent}^{90d})$	0.997	2.96
(d) Mean SR_b difference for 260d volatility: $avg(SR_{bgreen}^{260d} - SR_{b\,convent}^{260d})$	1.19	3.50

Source: Author calculations based on Bloomberg Terminal data.
Note: Based on the paired bonds sample extracted from the Bloomberg bonds data set, this table shows the differences of paired means (that is, green bond value minus a conventional bond value) based on yield at issue or the yield to maturity values: (a) the mean of the simple yield difference of green minus conventional yields at issue or yield to maturity, (b) the mean of the difference of green and conventional bond specific SR for a volatility measure of 30 days, (c) 90 days, and (d) 260 days.

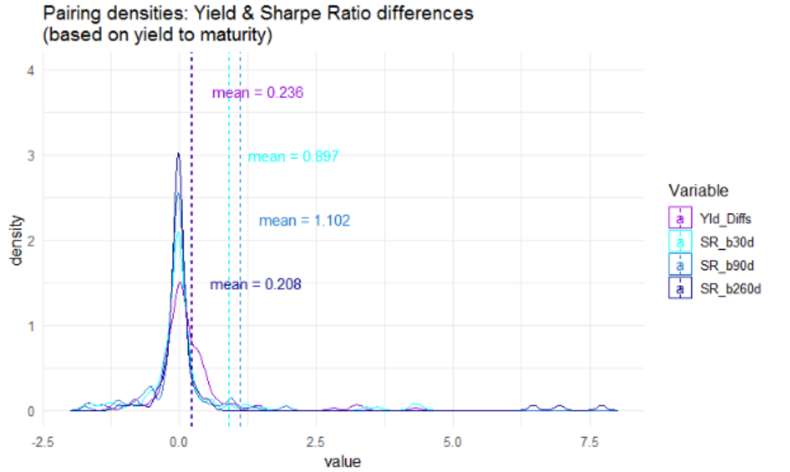
Figures A.11 and A.12 show density plots for green and conventional bond observations from the paired subset of data (Sharpe ratios represent bond-specific Sharpe ratios based on different volatility measures).

Figure A.11. Density Plot of Paired Bonds Based on Primary Market Performance (Using Yield at Issue)



Note: Based on the paired bonds sample, extracted from the Bloomberg bonds data set, this figure shows the mean for the yield at issue for the following density plots: (a) the simple yield difference between green and conventional yields at issue or yield to maturity, (b) the difference of green and bond-specific Sharpe ratio (SR_b) for a volatility measure of 30 days, 90 days, and 260 days, with October 1, 2020, as the reference date (bonds issued between January 2017–September 2020).

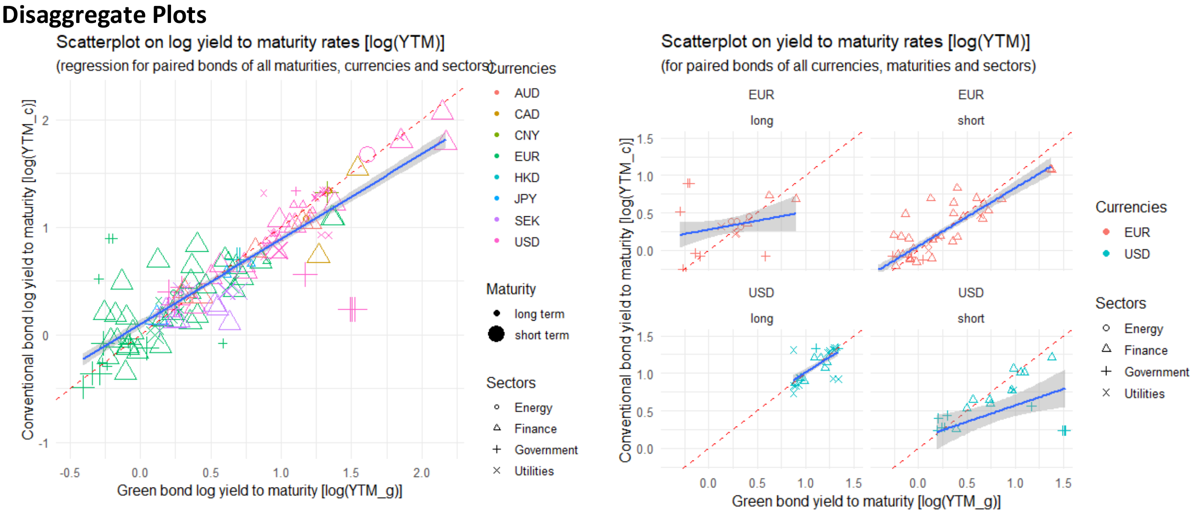
Figure A.12. Density Plot of Paired Bonds Based on Secondary Market Performance (Using Yield to Maturity)



Note: Based on the paired bonds sample, extracted from the Bloomberg bonds dataset, this figure shows the mean for the yield to maturity for the following density plots: (a) the simple yield difference between green and conventional yields at issue or yield to maturity, (b) the difference of green and bond-specific SR (SR_b) for a volatility measure of 30 days, 90 days, and 260 days, with October 1, 2020, as the reference date (bonds issued between January 2017–September 2020).

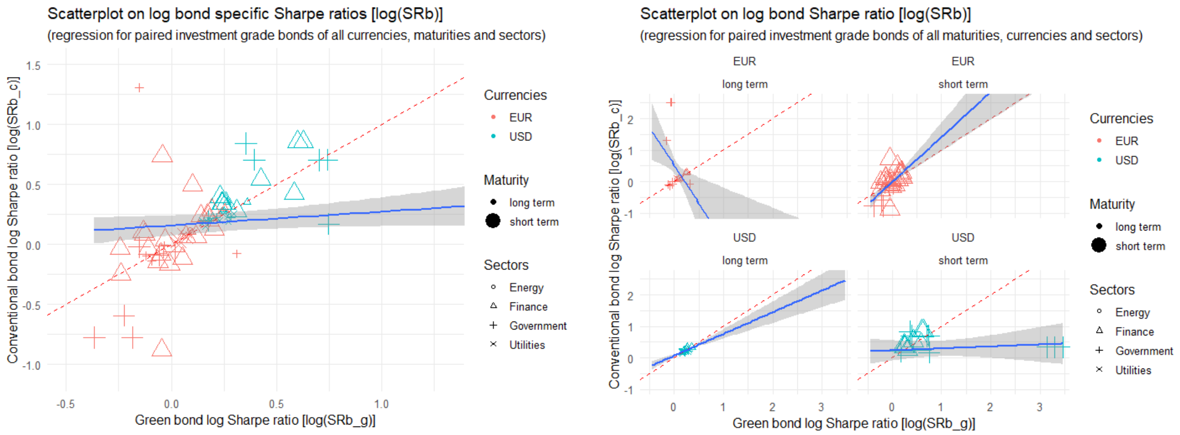
Comparing the bond pairings in a scatterplot shows, with some heterogeneity, that green bonds can achieve higher Sharpe ratios than conventional bonds. Bond-specific Sharpe ratios based on the yield to maturity rates are better for green bonds when looking at a higher yield to maturity values and at USD-denominated bonds. Figure A.14 shows that, for higher Sharpe ratio values, a green bond issued tends to have higher Sharpe ratio values than its conventional bond match. The sub-plots on the right panel of figure A.13 show some heterogeneity regarding currencies and maturities (for example, higher green yields when looking at USD-denominated and short-term bonds), which can be related to a small sample bias as our subset of data consists of less than 150 pairs of bonds. This heterogeneity is also visible in Figure A.13 for paired yield to maturity rates.

Figure A.13. Scatterplot of Paired Bond Data Based on Log Yield to Maturity Rates: (a) Aggregated and (b) Disaggregate Plots



Note: This figure shows scatterplots of the green and conventional bond paired data set (145 pairings). Left panel: observations from all pairings (across all ratings, maturities, currencies, and sectors for which a matching pair could be found); right panel: sub-graphs on only bond observations for investment-grade bonds, specific currencies (EUR and USD), maturities (long term vs. short term), and sectors (energy, finance, government, and utilities). The y-axis represents the log yield to maturity rate of conventional bonds and the x-axis represents the log yield to maturity rate of green bonds. The dashed red line is a 45° line. Each point on the 45° line reflects an equal yield to maturity of a green and a conventional bond. The blue line with grey shading reflects a regression line with a 75-percentile interval. A regression line and grey shading on the 45° line indicate no significant difference between the green and conventional bond yields.

Figure A.14. Scatterplot of Paired Bond Data Based on Log Sharpe Ratios: (a) Aggregated and (b) Disaggregate Plots



Note: This figure shows scatterplots for investment grade bonds that are based on the green and conventional bond paired data set (145 total pairings). Left panel: investment grade bond observations from all pairings (across all maturities, currencies, and sectors for which a matching pair could be found); right panel: sub-graphs on the bond observations for investment grade bonds, specific currencies (EUR and USD), maturities (long term vs. short term), and sectors (energy, finance, government, and utilities). The y-axis represents the log bond-specific Sharpe ratio of conventional bonds (SRb_c) and the x-axis represents the log bond-specific Sharpe ratio of green bonds (SRb_g). The dashed red line is a 45° line. Each point on the 45° line reflects an equal yield to maturity of a green and a conventional bond. The blue line with grey shading reflects a regression line with a 75-percentile interval. A regression line and grey shading on the 45° line indicate no significant difference between the green and conventional bond Sharpe ratios.

Our data show different patterns of Sharpe ratio performance for certain granularities. As shown in some cases, a lower Sharpe ratio does not, however, mean that green bonds cannot be attractive to investors. As for the denominator of the Sharpe ratio (the volatility of the return), green bonds generally show lower volatility. Regarding the return differences, there are benefits in investing in green assets even if we do not clearly observe asset return differences: There are negative externalities associated with carbon-intensive assets (that are frequently not priced in) and positive externalities associated with green investment (that are only visible in the long run). These externalities have increasingly been taken into account by financial market practitioners and the preferences of individual and institutional wealth holders. Also, in some countries, governments have acted to solve these externalities by implementing fiscal and monetary policy tools to influence investment in green and fossil fuel assets. Even if investors do not account for climate risks, governments can boost climate finance assets' relative returns with incentives such as tax incentives (or subsidies) for green bond issuance (or for low-carbon projects and sectors) and carbon taxes on carbon-intensive assets (or for brown projects and sectors). In section 2.2, we discuss the direct link between green bond issuance and green investment for policy makers.

Engle (2021) did a similar analysis for equity performance. A climate risk analysis on the equity performance of green and benchmark equities arrived at similar results as we did.[17] The V-Lab uses tools of modern finance and long-run risk management to measure and model environmental risks. Their analysis compares the performance of portfolios that offer a hedge against the risks of climate change. They compute mean returns, volatility, and the conventional Sharpe ratio over 1-, 3-, and 5-year periods and since inception. Their results also include risk loadings based on a Fama-French three-factor model (see equation A.11), where r is the portfolio rate of return, R_f is the risk-free rate of return, R_m is the return of the market portfolio, SMB (small minus big) is the excess return of small cap stocks over large-cap stocks, and HML (high minus low) is the excess return of high book-to-market stocks over low book-to-market stocks.

[17] The data are publicly available on their V-Lab website. See also https://vlab.stern.nyu.edu/welcome/climate.

$$r = R_f + \beta(R_m - R_f) + b_s \cdot SMB + b_v \cdot HML + \alpha \qquad \text{(Eq. A.11)}$$

Through risk diversification portfolios can be optimized by including green assets that are less sensitive to environmental shocks than fossil fuel–based assets. Among others, their data comprise equity returns, a volatility measure, and the portfolio Sharpe ratio for conventional benchmark equities as well as for sets of green equities. Table A.9 depicts the equity performance for a 5-year period of benchmark and sustainable sector equities. These results support our observations for green financial investment: The average Sharpe ratio (that is, the reward to risk measure) for the green sector is 0.77, which is above all benchmark Sharpe ratios. Especially noteworthy is the difference in the Sharpe ratio of stranded assets, which is only 0.33.

Table A.9. Equity Performance (5-Year Period) of Benchmark Equities vs. Sustainable Sector Equities

Security	Return	Return	SR_p
Sector: *Benchmark*			
iShares MSCI ACWI ETF	13.22%	18.25%	0.68
SPDR S&P 500 ETF Trust	14.69%	18.88%	0.74
SPY:US - XLE:US	15.51%	23.27%	0.67
Stranded Assets	5.53%	16.67%	0.33
Sector: *Sustainable Sector*			
First Trust NASDAQ Clean Edge Green Energy Index Fund	36.09%	30.28%	1.17
Invesco WilderHill Clean Energy ETF	37.80%	32.63%	1.13
Invesco Global Clean Energy ETF	25.95%	25.55%	0.99
VanEck Vectors Low Carbon Energy ETF	24.70%	25.55%	0.94
Invesco Cleantech ETF	21.17%	22.37%	0.91
First Trust Water ETF	19.91%	21.51%	0.89
Invesco Solar ETF	31.44%	34.67%	0.88
iShares Global Clean Energy ETF	23.47%	26.35%	0.86
First Trust NASDAQ Clean Edge Smart Grid Infrastructure Index Fund	21.83%	25.20%	0.84
New Alternatives Fund Inc/Fund	16.16%	18.49%	0.83
Firsthand Alternative Energy Fund	20.71%	24.99%	0.8
First Trust Global Wind Energy ETF	16.75%	20.69%	0.77
Eventide Healthcare & Life Sciences Fund	23.43%	29.53%	0.77
Calvert Global Energy Solutions Fund	16.10%	20.36%	0.75
Guinness Atkinson Funds - Alternative Energy Fund	16.84%	22.25%	0.72
VanEck Vectors Environmental Services ETF	16.11%	22.51%	0.68
Pax Global Environmental Markets Fund	13.22%	18.29%	0.68
Invesco Global Water ETF	13.03%	18.86%	0.65
Calvert Global Water Fund	11.79%	18.29%	0.6
Hartford Climate Opportunities Fund	10.02%	19.92%	0.46
Fidelity Select Environment & Alternative Energy Portfolio	10.53%	22.48%	0.43
VanEck Vectors Uranium+Nuclear Energy ETF	3.83%	17.43%	0.18

Source: V-Lab (see https://vlab.stern.nyu.edu/welcome/climate). Accessed March 7, 2021.

Appendix B: Climate Macroeconomic Model

B.1. Model for Kato et al. (2015)

The model is based on a representative agent that maximizes its utility by choosing an optimal consumption path according to a utility function that has a constant relative risk aversion preference structure:

$$U_t = \int_0^{\infty} e^{-\rho t} \frac{\left[H_t^{\beta} L_t^{\vartheta}\right]^{1-\sigma} - 1}{1-\sigma} dt \qquad \text{(Eq. B.1)}$$

The parameters *ρ, β, ϑ, σ* are strictly positive; consumption goods are either high carbon–intensive and are produced by the high-carbon-intensive sector (*H*), or they are low carbon–intensive and are produced by the low-carbon-intensive sector (*L*). The different carbon intensities in this growth model allow for structural change on a balanced growth path.[1] The different sectors have identical, Cobb-Douglas production functions with constant returns to scale. Two production factors (capital and labor) exist, and technical change is assumed to be labor augmenting. The per efficiency labor budget constraint can be derived under the conditions of perfect competition as:

$$B_K F(k_t, 1) = \dot{k_t} + (g_t + \delta)k_t + P_H h_t + P_L l_t \qquad \text{(Eq. B.2)}$$

The authors specify the estimation of output and employment growth effects for high- and low-carbon-intensive sectors (HCIS and LCIS, respectively) by a first-order, four-variable VAR model:

$$y_t = c + Ay_{t-1} + \epsilon_t.$$

where y_t is expressed as annual growth rates (that is, log differences):

$$y_t = \begin{bmatrix} out_{hi,t} \\ out_{lo,t} \\ emp_{hi,t} \\ emp_{lo,t} \end{bmatrix} = \begin{bmatrix} logOUT_{hi,t} - logOUT_{hi,t-1} \\ logOUT_{lo,t} - logOUT_{lo,t-1} \\ logEMP_{hi,t} - logEMP_{hi,t-1} \\ logEMP_{lo,t} - logEMP_{lo,t-1} \end{bmatrix} * 100 \qquad \text{(Eq. B.3)}$$

the disturbances ϵ_t are specified by:

$$E(\epsilon_t) = 0 \text{ and } Cov(\epsilon_t, \epsilon_s) = \begin{cases} \Sigma, t = s \\ 0, t \neq s \end{cases} \qquad \text{(Eq. B.4)}$$

and the variables *c* and *A* are a constant parameter vector and matrix.

The results for all countries were only available for the scenario with carbon taxation and subsidies for low-carbon products (table B.1).

[1] The carbon intensity of a third sector, the capital goods sector, is not further considered.

Table B.1. Modeling Results for Kato et al. (2015)

Country	HCIS employment	LCIS employment	Total employment	HCIS output	LCIS output	Total output
Australia	–1.41	–2.26	–1.63	–1.79	0.42	–0.98
France	0.00	0.32	0.15	–1.02	1.08	0.09
Germany	0.24	0.08	0.19	–0.36	0.90	0.36
Hungary	1.20	2.83	1.90	–0.11	4.52	2.31
Japan	–0.18	–0.56	–0.35	–1.04	0.20	–0.40
Korea, Rep.	–019	–0.44	–0.27	–0.73	0.69	–0.12
Sweden	–0.48	–013	–033	–0.34	0.99	0.35
United Kingdom	–0.12	–0.03	–0.08	–1.19	0.24	–0.45
United States	0.24	0.72	0.45	–0.93	1.97	0.55

Note: Changes in real employment (%) and output effects (%) relative to the business-as-usual 5 years after the introduction of a budget-neutral carbon tax with subsidies. HCIS = high-carbon-intensive sector, LCIS = low-carbon-intensive sector, total = aggregate effects.

B.2. Model for Semmler et al. (2019)

The model uses a five-dimensional system of differential equations to describe the dynamics of an integrated assessment model with green bonds. The timely derivatives of the five state variables $X = (K, R, M, b, g)$ are expressed in five equations (Eq. B.5–B.9) and describe changes in the private capital stock K, the stock of nonrenewable resources R, the atmospheric concentration of CO_2 M, the public debt level b, and the stock of public capital g. All variables are defined in per capita terms.

$$\dot{K} = Y \cdot (v_1 g)^{\beta}(1-\tau_k) - C - e_P - (\delta_K + n)K - u\Psi R^{-\zeta} \qquad \text{(Eq. B.5)}$$

$$\dot{R} = -u \qquad \text{(Eq. B.6)}$$

$$\dot{M} = \gamma u - \mu\big(M - \kappa\widetilde{M}\big) - \theta(v_3 \cdot g)^{\phi} \qquad \text{(Eq. B.7)}$$

$$\dot{b} = (r_t - n)b - \alpha_4 e_P - Y \cdot (v_1 g)^{\beta}\tau_k + \varsigma_k g \qquad \text{(Eq. B.8)}$$

$$\dot{g} = \alpha_1 e_P - \big(\delta_g + n\big)g + \varsigma_k g \qquad \text{(Eq. B.9)}$$

Private capital increases with output (Y) and a share of governmental expenditure attributed to productivity enhancement ($v_1 g$) and decreases with consumption (C), capital gains taxes (e_P), physical private capital and demographic depreciation together ($(\delta_k + n)K$), and opportunity cost of extracting the nonrenewable resource u (Ψ and ζ are the scale and shaping parameters that tie the marginal cost of u to the remaining stock of the resource as initially suggested by Hotelling [1931]). The nonrenewable resource stock R decreases by the amount of resources extracted (u). Emissions increase with increasing extraction rates (u) and decrease by natural reabsorption into the ecosystem ($\mu(M - \kappa\widetilde{M}$), where $\widetilde{M}$ is the preindustrial CO_2 concentration level) and with increasing mitigation efforts ($v_3 \cdot g$, where v_3 is the allocation of public capital g to mitigation projects). Debts rise with interest leveraged preexisting debt ($(r_t - n)b$) and with the issuance of green bonds ($\varsigma_k g$) and are paid with revenues from the capital gains tax ($\alpha_4 e_P$) and revenues from a regime-specific income tax for repaying the green bonds ($Y \cdot (v_1 g)^{\beta}\tau_k$). Public capital stock increases with revenues for public capital accumulation ($\alpha_1 e_P$) and with funds raised from green bond issuance ($\varsigma_k g$) and decreases with physical public capital and population growth ($(\delta_g + n)g$). Public budget shares are allocated to capital accumulation (α_1), social transfers (α_2), administrative costs (α_3), and the remainder to debt repayment ($\alpha_4 = 1-\alpha_1 - \alpha_2 - \alpha_3$). All parameters are non-negative.

Compared to Semmler et al. (2018), this model extends the government's fiscal stance by modifying the debt equation (Eq. B.8) and public capital equation (Eq. B.9) as well as the capital accumulation (Eq. B.5) by expressions that include regime-specific parameters τ_k and ς_k for the regimes $k = 1,2,3$, which are summarized in table B.2. For $k = 1$, no green bonds are issued ($\varsigma_k = 0$) that would increase public debt and that would add to the public capital funds for fighting climate change ($\varsigma_k g = 0$); due to $\tau_k = 0$ there is also no additional income tax for debt repayment ($Y \cdot (v_1 g)^\beta \tau_k = 0$). In the second phase of the model, green bonds are introduced as a financing option while special income taxes remain at zero ($\varsigma_k > 0$, $\tau_k = 0$). In the third and final phase, the government ceases to issue green bonds and starts repaying them by levying a special tax on income ($\varsigma_k = 0$, $\tau_k > 0$).

Table B.2. Overview of Regime-Specific Parameters and Equations in Semmler et al. (2019)

Regime	Green bonds	Special income tax	Capital accumulation	Debt	Public capital
$k=1$	$\varsigma_k = 0$	$\tau_k = 0$	$\dot{K} = Y \cdot (v_1 g)^\beta - C - e_P$ $-(\delta_K + n)K - u\Psi R^{-\zeta}$	$\dot{b} = (r_t - n)b - \alpha_4 e_P$	$\dot{g} = \alpha_1 e_P - (\delta_g + n)g$
$k=2$	$\varsigma_k > 0$	$\tau_k = 0$	$\dot{K} = Y \cdot (v_1 g)^\beta - C - e_P$ $-(\delta_K + n)K - u\Psi R^{-\zeta}$	$\dot{b} = (r_t - n)b - \alpha_4 e_P + \varsigma_k g$	$\dot{g} = \alpha_1 e_P - (\delta_g + n)g + \varsigma_k$
$k=3$	$\varsigma_k = 0$	$\tau_k > 0$	$\dot{K} = Y \cdot (v_1 g)^\beta (1 - \tau_k) - C - e_P$ $-(\delta_K + n)K - u\Psi R^{-\zeta}$	$\dot{b} = (r_t - n)b - \alpha_4 e_P$ $-Y \cdot (v_1 g)^\beta \tau_k$	$\dot{g} = \alpha_1 e_P - (\delta_g + n)g$

Output of the system is defined by a CES production function $Y(K,u)$ in equation B.10. A is a multifactor productivity index, and A_K and A_u are efficiency indices of the inputs K and u, respectively.

$$Y(K,u) \coloneqq A(A_K K + A_u u)^\alpha \qquad \text{(Eq. B.10)}$$

The objective function $W(T,X,U)$ indicates the economy's per capita social welfare. W is defined in equation B.11 and is maximized over a finite horizon [0,T]. T indicates the terminal time, X the five state variables, and U the control variables $U = (C, e_P, u, v_1, v_2, v_3)$. Consumption C is (a) augmented by tax revenues $\alpha_2 e_P$ that are used for welfare enhancement (for example, social transfers like health care); (b) decreased by the amount of emissions above the preindustrial level $\widetilde{M}$; and (c) increased by the share of public capital $v_2 g$ that is allocated to climate change adaptation measures. All exponents are non-negative, and the welfare function setup guarantees constant elasticity of substitution. Future welfare is discounted by the discount rate ρ and the demographic growth rate n.

$$W(T,X,U) \coloneqq \int_0^T e^{-(\rho-n)t} \frac{(C\cdot(\alpha_2 e_P)^{\eta}(M-\widetilde{M})^{-\epsilon}(v_2 g)^{\omega})^{1-\sigma}-1}{1-\sigma} dt \qquad \text{(Eq. B.11)}$$

In addition to consumption I, the capital gains tax rate (e_P), and the nonrenewables extraction rate (u), the policy maker also decides three other control variables: v_1 indicates the share of public capital to carbon-neutral private capital, v_2 the share of public capital for climate change adaptation, and v_3 the share of public capital that is allocated for climate change mitigation efforts. Importantly, $\sum_{i=1}^{3} v_i = 1$. Note, as the welfare function is formulated, several factors drive the welfare of households and not only consumption.

Appendix C: Sustainable Finance

C.1. Sustainable Finance and Green Bonds[1]

The model differentiates two asset types: one with risk-free returns and the other with fluctuating returns (that is, risky asset type). The instantaneous risk-free interest rate r^f is expressed in the change of the risk-free bond, which is $\frac{dB}{dt} = r^f \cdot B_t$. Similarly, the change in prices of the equity asset *i* in the economy is $\frac{dP_{i,t}}{dt} = r_{i,t}{}^e \cdot P_{i,t}$. Thereby, $P_{i,t}$ depends on the time-varying return of the equity asset *i* which is $r_{i,t,}{}^e$ and, since we want to mimic some cyclical fluctuations (see appendix D), is formulated by $r_i^e(t) = \alpha_1 sin(\alpha_2 \cdot t + \alpha_3)$, where α_1 modulates the amplitude, α_2 modulates the frequency, and α_3 modulates the phase shift.

In the simple baseline model, the agent invests a fraction of wealth to equity assets, $\pi_t = \frac{\Pi_t}{W_t}$. The decision on investment and consumption is a maximization problem with a budget constraint. The maximization of the value function is expressed by the Bellman principle of optimality:

$$V(W,x,t) \equiv max_{\{c_s,\pi_s\}} E\{\int_t^T e^{-\delta_0(s-t)} F(c_s W_s)ds\}$$

$$s.t. \dot{W}(t) = \pi_t r_t^e W_t + (1-\pi_t) r^f W_t - c_t W_t - X(\Pi_t, W_t) \qquad \text{(Eq. C.1)}$$

The budget constraint of equation C.1 is a sum of wealth gains from the different types of investment ($\pi_t r_t^e W_t +$ $(1 - \pi_t) r^f W_t$) minus consumption ($c_t W_t$) and minus additional costs that the investor incurs by holding the equity assets ($X(\Pi_t, W_t)$). The utility function $F(C_T) = \frac{C_t^{1-\gamma}}{1-\gamma}$ expresses a constant relative-risk aversion and is discounted by a general discount factor that we assume to be of the form $\phi_\alpha(\tau) = e^{(\alpha-1)\delta_0\tau - \alpha log(1+\delta_1\tau)}$, where α can be between 0 and 1. For α = 0, $\phi_0(\tau)$ becomes an exponential discount factor with discount rate δ_0 and for α = 1 we get a function $\phi_1(\tau)$ with a hyperbolic discount function with rate δ_1. The results in Semmler et al. (2020) for the hyperbolic case shows the agent shows time-inconsistent behavior, which means that she consumes at a higher rate in the short term and less over the long term.

The model is extended by including a fraction $u_t = \frac{U_t}{W_t}$ of investor wealth going into innovation efforts. Such efforts can be tailored to the development of clean technology, as in the spirit of directed technical change in Acemoglu et al. (2012). This change adds another decision variable to the maximization problem of the baseline model, which therefore yields the following:

$$V(W,x,t) \equiv max_{\{u_s,c_s,\pi_s\}E}\{\int_t^T e^{-\delta_0(s-t)} F(c_s, u_s)ds\}$$

$$\text{s.t.} \quad \dot{W}(t) = \pi_t(r_t^e - r^f)W_t + r^f W_t - (u_t + c_t)W_t - X(\Pi_t, W_t) \qquad \text{(Eq. C.2)}$$

The investment of a fraction of wealth into innovation efforts has a time-varying return $r^e(t)$ that can be positively or negatively affected by the investment decision. As defined by $r_i^e(t) = \alpha_1 sin(\alpha_2 \cdot t + \alpha_3)(1 \pm \mu(u_t W_t))$, an investment that does not create long-term negative externalities (such as renewable energy) will be positive

[1] For details of the subsequent model, see Semmler et al. (2020).

($+\mu(u_t W_t)$), whereas an asset that creates long-run adverse effects on the economy through the creation of negative externalities (such as CO_2 emissions, affecting temperature and creating damages in the long run) will be negative ($-\mu(u_t W_t)$).

Numerical solutions are obtained by applying nonlinear model predictive control (NMPC) as a solution procedure (see Gruene et al. [2015]).

C.2. Sustainable Finance with Convertible Green Bonds

Next, we suggest an extension and specification of the model expressed in equations C.1 and C.2 as a way to provide sustainable finance by using convertible bonds that might help support green start-up firms or climate infrastructure. Here, we apply the theory of positive and negative externalities, as mentioned above.

As noted, recent literature has pointed out that large-scale fossil fuel energy firms—large oligopolies in general—tend toward short-termism (see Davies et al. [2014]). As we have shown, portfolio decisions arising from short-termism in terms of higher discount rates or hyperbolic discounting may inhibit the accumulation of low carbon-based assets. We have also explored the role of the decision horizon as another manifestation of short-termism.[2]

Conversely, climate bonds may have long-term positive externality effects. In this context, it is useful to consider convertible bonds. Convertible bonds are bonds that can be converted into equity. The condition of convertibility to equity might be tied to an equity price per share through a strike price, as the Merton model for debt suggests and Black-Scholes for derivatives in general entails (see section 5.2, box 2). A similar idea can be applied to green bonds that are convertible to equity if the asset value (and with that, the equity value of a publicly listed firm, for example, a green start-up firm) goes up. This is likely to be accelerated if the distance to default decreases (given the firm's debt issuance), but the equity value of the firm increases.

On the other hand, since climate research showed fossil fuel bonds and fossil fuel equity are linked to negative externalities through CO_2 emission (for example, temperature rise, weather extremes, and climate disasters), a carbon tax is required to internalize the externality cost. Fossil fuel assets might also be quite volatile in value (see chapter 6), in particular during economic contractions and recessionary periods, triggering financial instability. In response, some countries have introduced mandatory disclosure on traded assets. An introduced carbon tax as well as the threat of financial instability and the disclosure requirements will lead to either lower net cash flows of fossil firms and/or their assets will face a devaluation in the market, triggered by higher discount rates capturing the long-run environmental risk involved (see Davies et al. [2014] and the discussion on stranded assets in section 5.1).

The above effect on firm value can be illustrated by the following simulations for the dynamic system equations C.1 and C.2. The dynamic saving and asset allocation choices are modeled in continuous time. In the objective function, in addition to spending a fraction c_t of wealth on consumption, a policy maker's decision to also spend a fraction u_t of the wealth on innovation efforts—efforts aimed, for instance, for developing clean technology. As noted, this is in line with the previous work of Acemoglu et al. (2012) on directed technical change. We can then explore the effects of time-varying returns and decision horizon, on the consumption-wealth ratio and the

[2] Risk aversion and discount rates have also been explored regarding their relevance for portfolio dynamics in Chiarella et al. (2016), chapters 4–5.

fate of wealth. This will allow us to observe whether wealth is increasing or decreasing over time for our two types of assets.

The two assets under analysis are a risk-free bond and equity, whereby the equity asset displays time-varying returns. The equity may also comprise long-term bonds, generating returns from some coupon payments. Hereby the bond prices for long-term bonds can be made dependent on the expected return of the short-term bonds.[3] We also could assume instead that we have equity convertible into long-term bonds (for example, green bonds) at the beginning as the second asset, which are turned into equity as the prospects of the rising asset value of the company (for example, a green start-up firm) is expected.

As before, we assume that the spending on u_t, as a fraction of wealth, can have an impact on the returns on the equity asset $r_t^e W_t$. We also assume that the mean of the returns for the short-term interest rate r^f is not affected, but the equity return is positively impacted by spending on innovation—or negatively impacted by the external effects if the firm is engaged in fossil fuel production. Thus, again the r^e is time dependent and can be formulated as follows:

$$r^e(t) = (\alpha_1 sin(\alpha_2 t) + \alpha_3)(1 \pm \mu(u_t W_t)) \qquad \text{(Eq. C.3)}$$

The time-varying return is formulated in a similar way as in the previous section. There is an additional return effect for the return on the asset, $r_{it}^e(x_t)$, represented by the term $(1 \pm \mu(u_t W_t))$. If we have the "+" sign, there is an asset such as renewable energy impacted by an innovation, not creating long-run negative externalities but rather growth for the economy. On the other hand, if we have the "-" sign, one can think of a fraction of the population operating as fossil fuel engineers who are creating long-run adverse effects on the economy through the creation of negative externalities through CO_2 emissions, affecting temperature and creating damages in the long run.[4] Finally, we attach weights (w_1) and ($1 - w_1$) to the two components of the objective functions (Eq. C.1), which could be varied exogenously.

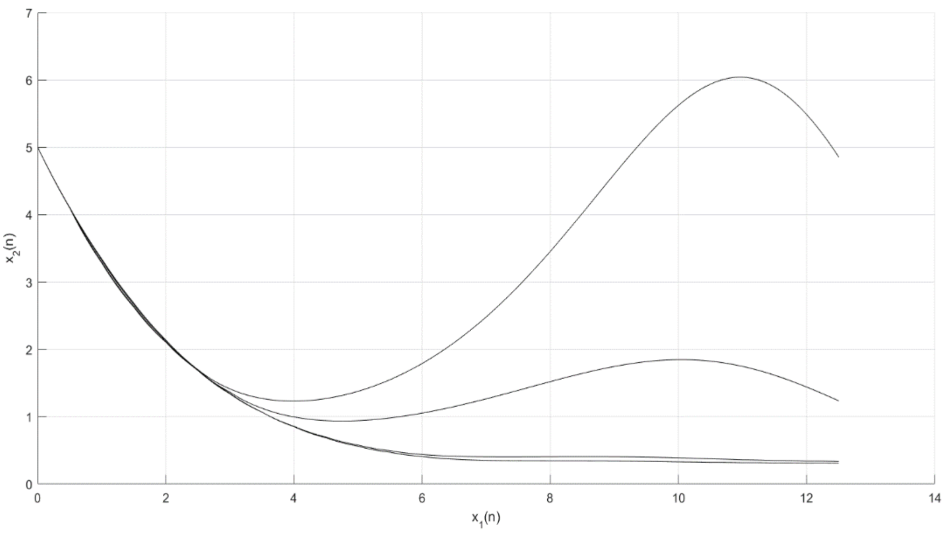
In the previous section, we numerically solved our baseline model for different values of the discount rates and different types of the discount factor while considering the decision horizon *N* to be fixed for a given iteration period *T*. Here, we solve the model using NMPC for $N = 6$ fixed and 25 time periods. We solve the model where the term $(1 \pm \mu(u_t W_t))$ holds for "+," which implies that $\mu(\cdot) > 0$—for example, for the new innovations in renewable energy firms. There might also be some temporary risk premium harvested by fossil fuel assets so we have $\mu(\cdot) > 0$. On the other hand, we might have $(1 \pm \mu(u_t W_t)) < 1$, with the "-" sign holding when $\mu(\cdot) < 0$.

In figure C.1, the lower trajectories represent the latter effect, with mostly fossil fuels bonds held in the portfolio facing the prospect of a carbon tax, stranded assets and downgrading through requirements of CO_2 disclosure, and higher liquidity and default risks. For this case, we use a computational parameterization of $\mu(\cdot) = -0.2$. As can be observed, the negative externalities are likely to lead to fewer assets built up, but more specifically to dissipating asset value in the long run. The small difference in the two lower trajectories arises from small changes in the initial conditions.

Figure C.1. Solutions Path of Wealth for Different Types of Externalities

[3] For details see Cochrane (2000), chapter 19, where then the bond price is then solved with an appropriate discount rate forward. In the portfolio context, see Semmler (2011), chapter 17.

[4] We could also think of the "-" sign as indicating that the fossil fuel subsidies are reduced and thus the return on conventional assets would fall.



Note: Two upper paths with graphs $\mu(\cdot) > 0$; two lower path graphs with $\mu(\cdot)<0$; $N = 6$, $T = 25$.

The middle graph, also with $N = 6$, is still computed with an additional term $(1 \pm \mu(u_t W_t))$, and the use of effort in the objective function $\mu(u_t W_t)$ as effort toward building up human capital in fossil fuel industries. So, the return on assets may still be higher than in the lower trajectories, but this represents some temporary effect where risk premia are captured in returns that might, however, lead to a loss in returns in the long run. The upper trajectory in equation C.2, also with $N = 6$, with the term $(1 + \mu(u_t W_t))$, represents firms with superior asset formation: where the effort is spent on human capital, as indicated in the objective function, exerting a positive externality effect on returns. This represents the case where the asset value could first represent equity or long-term green bonds but is then converted into equity as the asset value of the new firm (for example, a renewable energy start-up firm) is rising.

Overall, we might observe a case where in fact a carbon tax would be very complementary to a green bond strategy since a higher carbon tax (together with disclosure requirements and risky returns turned sour) can visibly reduce fossil fuel returns and can make green bonds more profitable even with negative bond premia, as reported in Kapraun & Scheins (2019). Thus, green bonds can be profitable in dynamic portfolios and successfully help the transition to a low-carbon economy. Therefore, we not only have a time-varying discount rate and decision horizon; we also have introduced a positive drift in the equity returns arising from energy innovation and negative drift from externalities respectively, and the use of convertible green bonds that can aid the transition to a low-carbon economy. Note that convertible bonds can also help keep sovereign debt sustainable—for example, when sovereign bonds can be turned into equity of renewable energy-related firms or climate-related infrastructure.

We finally would like to note that in Semmler et al. (2020), by using the NMPC program, the returns for risky assets are made time dependent, but they can also be defined as impacted by stochastic shocks along their paths. Empirically estimated low-frequency movements in returns can be built into a dynamic portfolio model—see chapter 4 in Chiarella et al. (2016)—an issue that is studied further in appendix D.

Appendix D: Harmonic Estimations of Bond and Stock Returns and Oil Price Changes

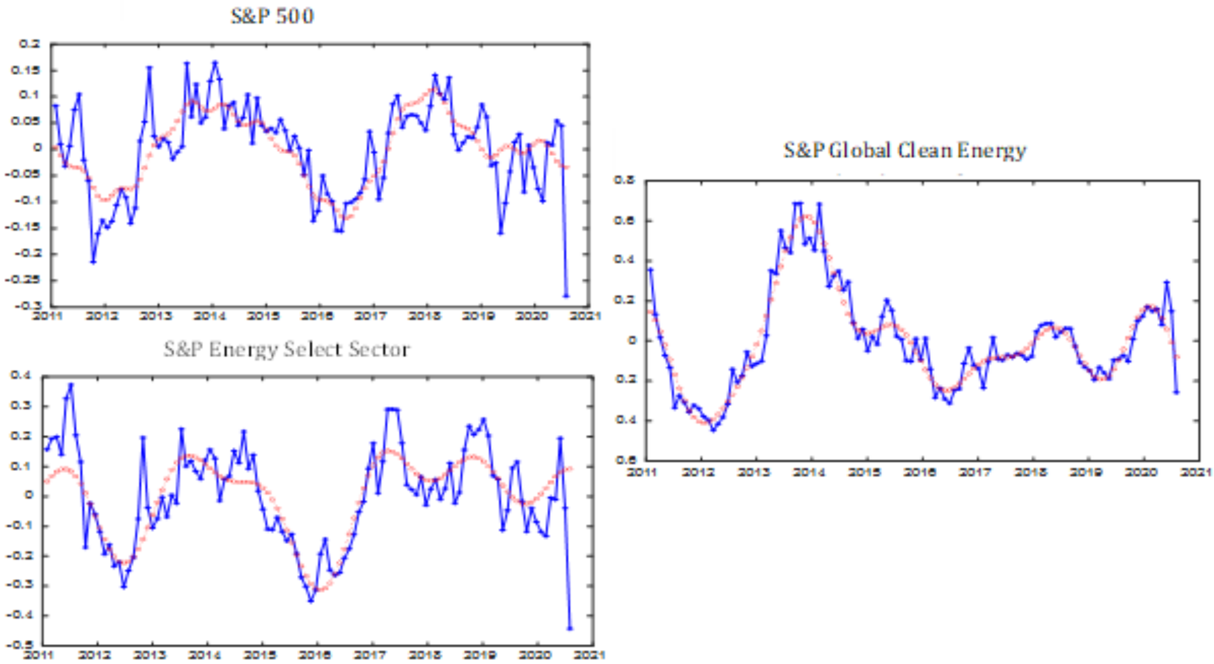
To assess the volatility of green securities due to energy price fluctuations, we compare market indexes for different types of assets with oil price variations, over the period January 2011 to March 2020. The oil price changes are given by the European Brent oil spot price annual variation for every month. For asset returns, we use the annual monthly total returns of five indexes: (a) S&P 500 Index; (b) S&P Energy Select Sector, which includes only the S&P 500 firms that operate in the energy sector; (c) S&P Global Clean Energy, which includes companies that produce clean energy or equipment; (d) S&P 500 Energy Corporate Bond Index, which includes private bonds issued by all types of energy firms, including carbon-intensive ones; and (e) S&P Green Bonds Index, which contains renewable energy and other green assets.

Given that asset allocation decisions are based on low-frequency movements in asset returns, we use the securities data to estimate low-frequency movements in asset returns by using harmonic estimations (see Chiarella et al. [2016]). We apply the fast Fourier transformation method on the de-trended real bond returns and oil price variation. We get empirical estimations based on linear regressions constructed with trigonometric functions: We fit each time series using a linear combination of sine and co-sine functions:

$$y(t) = \sum_{i=1}^{k} \left(a_i sin\left(\frac{2\pi}{\tau_i}(t - t_o)\right) + b_i cos\left(\frac{2\pi}{\tau_i}(t - t_o)\right)\right) \quad \text{(Eq. D.1)}$$

We estimate the harmonic regression model for different values of *k*, from 1 to 6, which represents different frequencies—from low- to high-frequency data. For our analysis, we selected the estimation with the lower squared error term (see estimations shown in figure D.1, and figures 13 and 14 in section 6.2). Although we observe similarities between the distinct cyclical movements, the downturns and upturns of green indexes' returns are clearly less associated with oil price changes over time. Thus, green securities appear to be better hedging instruments than conventional and fossil fuel–related assets.

Figure D.1. Equity Indexes: Monthly Total Returns and Harmonic Estimations, January 2011–March 2020 (in percentage points)



Source: Author calculations based on Standard & Poors data.
Note: Each y-axis has a different scale, so the graphs should be carefully compared. We compare the return's volatility for each index with the oil price changes shown in figure 13 (in section 6.2). This relationship between each index volatility and oil prices is clear in the regressions shown in appendix C.

To verify this relationship, we run linear regressions using the harmonic estimation values for the total returns of each selected financial market index. These regressions evaluate the influence of oil price cycles on investor returns:[1]

$$Index_i = \alpha_0 + \alpha_1 \Delta OilPrices + Trend \qquad \text{(Eq. D.2)}$$

The estimated coefficients for equation D.2 show that the fluctuations of oil prices have a greater impact on conventional and fossil fuel indexes, as shown in table D.1. If we take the equity indexes, we find that the coefficients α_1 for the S&P 500 and the S&P Energy Select Index are 0.12 and 0.37, respectively, while the coefficient for the green equity index (S&P Global Clean Energy) is not significant (that is, the green stocks seem to have decoupled from oil prices). If we take the bond indexes,[2] the estimated coefficient α_1 for green bonds is 0.06, while the one for energy corporate bonds is 0.1.

[1] We also add a simple trend equation to the regression, having a time index t as a dependent variable, affected also by random noise. It generates a predictor for the dependent variable for the next periods if a clear trend is observed.

[2] Although green bonds were implemented beginning in 2010, we start the regressions for bonds in 2012 since it took a while for market agents to adjust to the introduction of a new product.

Table D.1. Green and Conventional Security Indexes: Estimated Coefficients for the Regressions

Dependent variables	Coefficients	Estimate (standard error)
Equity indexes		
S&P 500	α_0	0.00 (0.01)
	α_1	**0.12*** (0.02)**
	Trend	0.00 (0.00)
S&P Energy Select Sector	α_0	0.0 (0.01)
	α_1	**0.37*** (0.03)**
	Trend	0.00 (0.00)
S&P Global Clean Energy	α_0	0.00 (0.00)
	α_1	0.00 (0.1)
	Trend	0.00 (0.00)

*p<0.05 **p<0.01 ***p<0.001

Dependent variables	Coefficients	Estimate (standard error)
Bond indexes		
S&P Energy Corporate	α_0	0.01 (0.01)
	α_1	**0.1*** (0.02)**
	Trend	0.00 (0.00)
S&P Green Bonds	α_0	**0.02* (0.01)**
	α_1	**0.06*** (0.01)**
	Trend	**0.00* (0.00)**

*p<0.05 **p<0.01 ***p<0.001

Additionally, we perform harmonic estimations for the daily returns for oil price changes, green bonds, and fossil fuel bonds and run new linear regressions following equation D.2. The new harmonic estimations are shown in figure 15 (section 6.2) and the estimated coefficients for the new regressions are shown in table D.2. We observe, during the 2020 oil price downturn, a run on green bonds as safer assets. This increase in demand increases green bond prices and reduces yields, as seen in figure 15. This behavior is not observed during the whole period as the coefficient α_1 for green bonds is −0.014, while the one for energy corporate bonds is 0.14.

Table D.2. Green and Conventional Security Indexes: Estimated Coefficients for the Regressions (Daily Returns)

Dependent variables	Coefficients	Estimate (standard error)
Bond indexes		
S&P Energy Corporate	α_0	0.00 (0.00)
	α_1	0.14*** (0.01)
	Trend	0.00 (0.00)
S&P Green Bonds	α_0	0.00 (0.00)
	α_1	-0.014* (0.00)
	Trend	0.00 (0.00)

*p<0.05 **p<0.01 ***p<0.001

Appendix E: Logistic Vector Smooth Transition Autoregressive Model

For the analysis of the behavior of green and fossil fuel securities for high and low oil price regimes, we apply a nonlinear logistic vector smooth transition autoregressive (LVSTAR) model. The LVSTAR model allows us to study nonlinear dynamics and regime changes for a transition variable. We use this model approach to study the performance of green and fossil fuel bonds based on two regimes, determined by oil price change as a transition variable. Thus, we can analyze bond performances when oil prices are in an increasing or decreasing regime.

We apply a vector smooth transition regression model, similar to the one proposed by Hubrich & Teräsvirta (2013). A related model was applied by Schleer & Semmler (2016) for a regime of high and low leveraging of banks and by Schleer & Semmler (2015) for a regime of high and low financial stress. The LVSTAR model looks as follows:

$$y_t = \phi' z_t + \psi' G_t(.) z_t + \epsilon_t \qquad \text{(Eq. E.1)}$$

where y_t = {*Green*;*Energy*} is a 2 × 1 column vector, in which Green is the annual monthly total returns of the S&P Green Bonds Index (which contains renewable energy and others green assets) and Energy is the monthly total returns of the S&P 500 Energy Corporate Bond Index (a more comprehensive index that mainly includes fossil fuel energy assets); $z_t = \left(1, y'_{t-1}, \ldots y'_{t-p}\right)$ is a vector of lagged endogenous variables and a constant; ϕ'^{0} and ψ^0 are coefficient matrices of dimension (p_k+1)k, where k = 2; and the error term ϵ_t is assumed to be white noise with a variance-covariance matrix Ω.

Our model considers the special case where we also add a logistic type of transition function governing the LVSTAR system:

$$G_t(.) = g(\gamma, c) I_k \qquad \text{(Eq. E.2)}$$

in which:

$$g(s_t|\gamma, c) = \left[1 + e^{-\gamma(s_t - c)}\right]^{-1},\ \gamma > 0 \qquad \text{(Eq. E.3)}$$

Equation E.3 is monotonically increasing in the transition variable (s_t), given by the lagged first difference of oil prices, and depends on the transition speed (γ)[1] and on the threshold for the oil price regimes (c). The oil prices are obtained through the European Brent oil spot price level. We should note that $g(s_t|\ \gamma, c)$ is bounded between zero and 1. The model outcomes are shown in section 6.4.

The main purpose of our analysis is to verify whether green and fossil fuel bonds perform differently when we have a regime change due to oil price variation. We expect that green securities are less volatile to regime changes. To test this hypothesis, we apply the LVSTAR model and do a linearity test. If the model is found to be nonlinear, we can say that oil price change matters for the security; if the model is linear, there is no regime-dependent influence.

First, we apply several linearity tests as proposed in Teräsvirta & Yang (2014): an LM (Lagrange multiplier) test, an F-test, an LR (likelihood ratio) test, a Wilks's statistic test, and a Rao's F-statistic test. However, the authors argue that Wilks's statistic and Rao's F-statistic that have satisfying size properties are recommended more for empirical use in an LVSTAR model. For the joint linearity test using the Rao's F-statistic test (Rao, 1965), the lag

[1] If $\gamma \rightarrow \infty$, the model converges to a threshold VAR model, and if it approaches zero it collapses to a linear VAR model.

length of s_t is selected using Schwarz information criterion (Schwarz, 1978) and the maximum lag length is set to maximize *lag* = (12(*t*/100)), as suggested by Schwert (1989). We set the maximum lag for the transition variable to 4. For Wilks's statistic model (Mardia et al., 1979), we follow Bartlett's approximation for a large *t* (Bartlett, 1954). We test the null hypothesis that the model exhibits linear behavior. Thus, if the p-value is lower than 0.05, we can reject the assumption of linearity and have evidence that there is nonlinear behavior that depends on the different oil price regimes. The same interpretation logic applies for the other tests we use in the analysis.

Second, one can apply a Granger causality test to verify the relationship between the different variables used in the model and the adequacy of using an LVSTAR model (see Hubrich & Teräsvirta [2013]). We use a standard F-test and F-statistics to perform this test, as in Awokuse & Christopoulos (2009). On the basis on that result, we can test if there is a statistically significant causality between oil price variation and security indexes performance.

Appendix F: Two-Asset Portfolio Analysis

To measure the portfolio variance between fossil fuel and green bond yields when oil price changes are above and below zero, we apply different shares of green and fossil fuel bonds to the portfolio. Tables F.1–F.5 summarize the results.[1]

Table F.1. 20% Green Bonds and 80% Fossil Fuel Bonds

	Portfolio variance ($\sigma^2_{R_p}$) (when $\gamma_{Green} = 0.2, \gamma_{Fossil\ Fuel} = 0.8$)	
	Oil price change ≥ 0	**Oil price change < 0**
All countries	$7.64 \cdot 10^2$	$1.72 \cdot 10^3$
United States	$1.46 \cdot 10^3$	$2.46 \cdot 10^3$
European Union	$8.38 \cdot 10^2$	$1.90 \cdot 10^3$
China	$8.42 \cdot 10^1$	$2.92 \cdot 10^1$
Other countries	$6.72 \cdot 10^2$	$1.69 \cdot 10^3$

Table F.2. 40% Green Bonds and 60% Fossil Fuel Bonds

	Portfolio variance ($\sigma^2_{R_p}$) (when $\gamma_{Green} = 0.4, \gamma_{Fossil\ Fuel} = 0.6$)	
	Oil price change ≥ 0	**Oil price change < 0**
All countries	$5.88 \cdot 10^2$	$1.36 \cdot 10^3$
United States	$1.10 \cdot 10^3$	$1.86 \cdot 10^3$
European Union	$6.33 \cdot 10^2$	$1.52 \cdot 10^3$
China	$6.91 \cdot 10^1$	$2.22 \cdot 10^1$
Other countries	$5.11 \cdot 10^2$	$1.28 \cdot 10^3$

Table F.3. 50% Green Bonds and 50% Fossil Fuel Bonds

	Portfolio variance ($\sigma^2_{R_p}$) (when $\gamma_{Green} = 0.5, \gamma_{Fossil\ Fuel} = 0.5$)	
	Oil price change ≥ 0	**Oil price change < 0**
All countries	$4.98 \cdot 10^2$	$1.17 \cdot 10^3$
United States	$9.21 \cdot 10^2$	$1.58 \cdot 10^3$
European Union	$5.36 \cdot 10^2$	$1.32 \cdot 10^3$
China	$6.18 \cdot 10^1$	$1.87 \cdot 10^1$
Other countries	$4.29 \cdot 10^2$	$1.07 \cdot 10^3$

Table F.4. 60% Green Bonds and 40% Fossil Fuel Bonds

	Portfolio variance ($\sigma^2_{R_p}$) (when $\gamma_{Green} = 0.6, \gamma_{Fossil\ Fuel} = 0.4$)	
	Oil price change ≥ 0	**Oil price change < 0**
All countries	$4.09 \cdot 10^2$	$9.76 \cdot 10^2$
United States	$1.27 \cdot 10^3$	$1.28 \cdot 10^3$
European Union	$4.41 \cdot 10^2$	$1.14 \cdot 10^3$
China	$5.47 \cdot 10^1$	$1.51 \cdot 10^1$
Other countries	$3.48 \cdot 10^2$	$8.60 \cdot 10^2$

Table F.5. 80% Green Bonds and 20% Fossil Fuel Bonds

[1] As indicated in chapter 6, these results can be considered as approximate correct results since we do not compute optimal weights as one would for a Markowitz efficient frontier.

	Portfolio variance ($\sigma^2_{R_p}$) (when $\boldsymbol{\gamma_{Green} = 0.8}, \boldsymbol{\gamma_{Fossil\,Fuel} = 0.2}$)	
	Oil price change ≥ 0	**Oil price change < 0**
All countries	$2.28 \cdot 10^2$	$5.67 \cdot 10^2$
United States	$3.72 \cdot 10^2$	$6.56 \cdot 10^2$
European Union	$2.64 \cdot 10^2$	$7.56 \cdot 10^2$
China	$4.11 \cdot 10^1$	$7.97 \cdot 10^0$
Other countries	$1.86 \cdot 10^2$	$4.35 \cdot 10^2$

Green Bonds for the Transition to a Low Carbon Economy

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August 14, 2021

Abstract

Climate change imposes big challenges and demands an active fiscal and financial policy response. Climate disasters and global warming can move economies onto a lower-growth path with a rise of 'stranded assets' and financial instability. The effectiveness of the financial market for this transition to a low carbon economy depends on attracting investors and removing financial market roadblocks. Many recent studies have focused on yield differential between green and conventional bonds. We focus on both yields and volatility and thus on the risk-return performance of the two types of bonds. Using cross-sectional methods, harmonic estimations, bond pairing estimations as well as regression tree methodology, we find that though the returns might be mixed as compared to conventional bonds, but the lower volatility of green bonds deliver superior Sharpe Ratios (risk adjusted returns), protect investors and portfolios from oil price and business cycle fluctuations, and stabilize portfolio returns and volatility. In an asset pricing model we demonstrate that, in the long-run, the positive externalities of green bonds benefit the economy through positive social returns even if these assets have currently lower yields– which enhances green investments due to lower capital cost. In contrast, conventional bonds and fossil fuel based assets exhibit lower risk adjusted returns because of higher volatility and the slow perception that they entail long-run negative externalities. We use a dynamic portfolio approach to obtain model-driven results and evaluate those through our empirical evidence using harmonic estimations that can facilitate online dynamic portfolio decisions. Beside the deterministic model, we also explore a stochastic version of the model.

JEL classification: C610, G120, 0380, Q580
Keywords: green bonds, innovation, climate finance, dynamic portfolio decisions.

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1 Introduction

Sustainable economic growth entails changes in production, consumption and therefore also in the form of financing "green investment". Since financial markets can appear as a roadblock[1] but can also be used as a bridge for the transition to a low carbon economy it is important to understand investment decisions and the financial performance regarding green assets as compared to conventional assets. We want to study the portfolio decisions with respect to green and non-green (brown, i.e. fossil fuel based, or conventional, i.e. plain vanilla) bonds in the context of a dynamic portfolio model. Focusing on its bridge finance role, we explore whether the gradual replacement of fossil fuel investments with green investments can reduce negative externalities, create positive externalities, and improve wealth accumulation. The theoretical part of this paper provides a generic model of asset pricing and dynamic portfolio decisions concerning the shift from brown to green investments by including positive and negative economic externalities. In the empirical part, we focus on the performance of bond financed green investments to analyze the differential bond performance of green and non-green bonds.

Though market decisions and market mechanisms are known to have positive or negative external effects since long, as demonstrated in microeconomics, macroeconomic versions of this became more popular with the endogenous growth theory. Economic investments can have positive feedback effects impacting output through some scale effects, for example through some increasing returns to scale or Romer type of inventive investments, see Greiner et al. (2005). Negative externality effects have also been studied in macroeconomic growth theory.[2].

As to our knowledge, what has been however not studied sufficiently are the positive and negative feedback effects, arising on the real side of the economy, impacting asset pricing, financial returns and portfolio decisions of investors. There is now some recent work on how negative externalities arising from GHG emission, and subsequent damage and disaster risks, impact asset value and returns. Engle et al. (2020) study the impact of climate disaster news on asset risks and portfolio decisions concerning equity portfolios of green and fossil fuel based equity, in an extended Markowitz portfolio model. There are also studies on the green and conventional (and fossil fuel based) bonds and how those asset returns and volatility are impacted by disaster or fuel price shocks.[3]

In the current paper we first present a dynamic asset price model studying a generic link between the real economy with externalities, asset pricing and dynamic portfolio decisions, resembling the Merton (1973) work on dynamic portfolio decision.[4] We then more specifically introduce green and fossil fuel based bonds into the dynamic portfolio framework, using some stylized movements of returns obtained from Fast fourier transform (FFT) and harmonic estimations of actual data from the US economy.[5] Hereby the positive and negative externalities are introduced and their asset price and portfolio allocation effects are studied and the fate of the evolution of wealth explored. An outlook for a stochastic version of this model is also presented in the Appendix B to account for financial market risks in the portfolio decision model.

In the empirical section of the paper, we study in more detail, using econometric methods, the drivers for green and conventional bonds performance. We, in particular, use multi variate regressions, regression tree models, and pairing algorithm for studying the differential performance of green and conventional bonds. We also explore subsets of the energy sector such as green renewable energy and fossil fuel bonds. We analyze primary and secondary market returns (using yield at issue and yield to maturity respectively), various volatility measures (over ranges of 30 days, 90 days and 260 days) and risk-adjusted returns (using the Sharpe ratio measure).

The remainder of the paper is structured as follows. Section 2 lists our theoretical hypothesis and discusses the empirical literature. In section 3, the background of our model is described and the dynamic portfolio model is presented. In section 4, we report the results from our numerical analysis, using the NMPC algorithm.[6] Section 5 presents our empirical methodology, data background and our empirical results. Section 6 concludes the paper.

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[1] For example short-termism in the financial market has been shown to be a roadblock, see Davies et al. (2014), Semmler et al. (2000).

[2] See Barro and Sala-I- Martin (2004)

[3] For a survey, see Semmler et al. (2021).

[4] See also Chiarella et al. (2016).

[5] As Chiarella et al. (2016) and Semmler & Hsiao (2011).

[6] For details of the solution algorithm used, see Gruene et al. (2015).

2 Theoretical hypotheses and empirical literature

2.1 Theoretical hypotheses

By integrating positive and negative externalities, that one knows from growth theory, into dynamic asset price and portfolio theory, one would expect higher returns on green bonds, since some positive long run externalities are to be expected. In contrast, one would expect lower returns in the long run for conventional (or fossil fuel based) bonds, since, following the Pigouvian argument that the negative externalities have to be paid in some way, we would expect a lower return.

In terms of financial accumulation, a model that is sensitive to negative externalities would predict a better long term wealth accumulation for green compared to non-green assets. Negative environmental externalities feed into uncertainties in the financial market and can have deteriorating impacts on investment. Therefore, negative environmental impacts can be seen as disruptive elements with volatility inducing impacts. For a continuous and steady accumulation of wealth, green assets are hypothesized to deliver better long term investment opportunities.

On an empirical level, we are going to study the wealth accumulation by using the Sharpe ratio (as well as yield and volatility measures) and expect green bonds to be a more stable form of investment, i.e. to have higher Sharpe ratios than non-green bonds. The Sharpe ratio is a risk-return measure, it discounts the portfolio return by its risk structure which is described by a volatility measure. Assets with a higher degree of fluctuation will report lower Sharpe ratios than assets with stable conditions. Though results will be different across sectors, we expect especially higher Sharpe ratios in the energy sector, given the immediate connection to environmental externalities, fossil fuel based emissions, and oil price fluctuations.

Given those model driven predictions, the major question we want to pursue in our empirical study is whether the predictions from theory hold in a visible way in the empirics. We argue that the theoretical predictions may be clarified better by studying not only the returns, but the return-risk ratio, the Sharpe ratio. As to the returns, there are puzzling results that are presumably arising from the fact that the positive and negative externality effects are currently rarely considered in the actual trading and financial decisions in the financial markets.

We also add some consideration on convertible green bonds, an innovative financial instrument that seems to help to achieve sustainable debt. Convertible bonds have recently been issued with green labels as an alternative to conventional fixed income bonds, given the surge of convertible instruments after the COVID-19 crisis (Gregory, 2020).

2.2 Review of empirical literature

As to the return differentials, a number of recent studies on the performance of green bonds have been published, with mixed results and analysis techniques. Most studies find a negative green premium based on bond indices (Ehlers & Packer, 2017) and primary market yields (Kapraun & Scheins, 2019; Immel et al., 2020; Löffler et al., 2021). For secondary market yields, studies find mixed results for green and conventional bond yield differentials (Kapraun & Scheins, 2019; Bachelet et al., 2019), which means that a premium is found only for specific cases (e.g.: institutional and certified green issuers). It is argued that lower yields for green bonds compared to conventional bonds are due pro-environmental attitude of investors (Löffler et al., 2021) and higher ESG credibility of certain issuers, which impacts the demand preferences (Kapraun & Scheins, 2019). As laid out in this paper, the risk structure of financial assets is also impacted by environmental factors: fossil fuel bonds evoke negative environmental externalities while green bonds are environmentally friendly, i.e. should show positive externalities.

In addition to using multivariate regression for primary and secondary market yields of green and conventional bonds, and like many other papers (Ehlers & Packer, 2017; Kapraun & Scheins, 2019; Löffler et al., 2021; Bachelet et al., 2019), we analyze bond performance also with regard to risk-adjusted returns (Sharpe ratio) and several bond volatility measures (30d, 90d, 260d). We also deploy a bond pairing algorithm to create a sample of matched green and conventional bonds.

Kapraun & Scheins (2019) analyze the yield performance (primary and secondary market yields) of green and conventional bonds in various regression designs. For the primary market, they evaluate the "yield at issue" in: (a) a fixed effects regression where they use the whole data sample and control for issuer specific effects, year-month fixed effects, currency fixed effects, seniority, maturity, issue size, issue country, yield curve and different interest rate environments; and (b) a fixed effects regression setup for subset of data (e.g.: looking for currency specific effects). For the secondary market, they analyze the "yield to maturity" in: (a) a similar fixed effects regression setup as in the case of the primary market yields, without the rating fixed effect, but adding a control for bond liquidity (using the bid-ask spread), and (b) a regression analysis of matched bonds where one green bond is paired with up to 10 comparable conventional bonds. In the paired bond analysis they control for coupon rate, maturity, issue size, green bonds traded at a green exchange and ESG rating.

Kapraun & Scheins (2019) find that the green yield premia is: in the primary market, on average, 18 bps lower than a conventional bond premia; and, in the secondary market, negative only for green bonds supplied by issuers with a better sustainability reputation, such as multilateral organizations, governments, or other bonds traded at green exchange markets as well as in countries with established environmental policies. They also report a high variation of premia across currencies and issuer types. Kapraun & Scheins (2019) do control for public vs corporate investors, however they do not control for different corporate bond issuing sectors (e.g. energy, finance, utilities) and their analysis does not deal with bond price volatility.

Löffler et al. (2021) analyze the conventional and green bond performance and find that the primary as well as the secondary market yield for green bonds is, on average, 15–20 bps lower than for conventional bonds and that the ask yield volatility of matched green bonds is higher than that of matched conventional bonds. The latter finding motivates their claim that the negative green premium results in a preference for buying green labeled assets. Their study uses two different bond pairing approaches, propensity score matching (PSM) and coarsened exact matching (CEM) methodology, to determine a sample of conventional bonds that is most similar to the sample of green bonds. However, compared to our analysis they do not control for bond rating and amount issued and their conclusions on bond volatility relies on a single volatility measure, whereas our analysis includes three different volatility measures.

Bachelet et al. (2019) analyze a set of 89 paired green and conventional bonds from 2013 until 2017. Their matching criteria are based on issuer, currency, rating, amount issued, coupon rate, maturity date, and coupon type. They analyze green versus conventional bonds with regard to differences in the bond premium (only for secondary markets), the liquidity, and the bond price volatility (also based on secondary bond market prices). Similar to Kapraun & Scheins (2019), they differentiate between private and institutional bond issuers and find that the yield differential of green minus conventional bonds is positive and about 2-3 bps for private issuers and negative, between -1.9 bps and -9.6 bps, for institutional issuers. For private issuers without a green label, the green premium is even bigger, in the range of 3.2 bps and 11.2 bps. This difference also holds for the volatility analysis: green bonds are significantly and slightly less volatile than conventional bonds in the case of established issuers, i.e. institutional and green certified private issuers. Bachelet et al. (2019) does not bring a sector-specific analysis and provides a single measure only for the volatility analysis (ex-post standard deviation of bond yields which considers a spanning period of 20 days). In contrast, our empirical analysis looks into different sectors and uses three different volatility measures with spanning periods of 30, 90, and 260 days.

Additionally, none of those papers that use a bond pairing algorithm investigate extensively the financial performance of green and brown bonds based on a risk-reward performance measure, like the Sharpe ratio (SR). In fact, Ehlers & Packer (2017) uses the Sharpe ratio to investigate the green bond performance, however they only use a cross-sectional sample of 21 green bonds issued between 2014 and 2017. Our sample includes 1529 green bonds that were issued between 2017 and 2020 and, in contrast to their bond analysis, our algorithm also controls for rating. Their study finds that the risk-adjusted performance (i.e., the Sharpe ratio) was, in some cases, slightly higher for green bond indices than for global bond indices, though that difference was not statistically significant to evaluate the bond performance of green bonds. The paper, with a CoVaR model[7], finds that green bonds improve the SR of a stock-bond portfolio in different market environments and can provide downside risk protection during the COVID-19 pandemic.

The novelty of our paper is to combine an established bond pairing procedure with new bond performance measures (the Sharpe ratio and several volatility measures in addition to primary and

[7]The CoVaR model looks at the impact of financial distress in one market (using the value at risk, VaR, indicator) on the VaR of another market.

secondary market yield measures) to analyze a recent set of green and conventional bonds (from 2017 until 2020). We also apply a categorization and regression tree analysis which has not been applied so far in the analysis of bond performance. Our dataset is obtained through the Bloomberg terminal and considers the sectors in which most green bonds were issued globally: finance, utilities, energy, and government (i.e. we consider the following Bloomberg Industry Classification Sectors (BICS 2): banks, real estate, power generation, utilities, sovereigns, renewable energy, and development banks).

Though, overall the econometric results on the differential performance of green and conventional, or fossil fuel bonds respectively, appear to be mixed (see Section 5). Next, we want to explore the long-term implications of holding green assets, by employing recent macroeconomic and dynamic portfolio theory.

3 Background and description of the model

In terms of a macro model – as model background for the portfolio framework – we can consider some endogenous growth type macro model with externalities[8], and a Romer type of growth model with expenditure for innovations impacting economic growth rates.[9]

In terms of modeling[10] one can consider the possibility of having a fraction of accumulated wealth wealth going into consumption, and addition a fraction going into the spending of resources for new technologies. As in Romer (1986) we can assume this latter fraction being spent for human capital creating innovations. Yet, we want to let it spent for innovations either for green or fossil fuel based innovations. So this spending is again subdivided into two purposes which will be taken for reason of simplicity as fixed.

The investment of the fraction of wealth into innovation generates a time-varying return $r^e(t)$ which can generate positive or negative effects on growth in the long run. The value of an investment which does not create long-term negative externalities (such as renewable energy) can thus have positive effects on growth but also increase portfolio returns; whereas the value of investment which creates long run adverse effects to the economy through negative externalities (such as CO2 emission) will negatively affect the portfolio return and growth.

Building on dynamic portfolio models of the Merton type (Merton, 1973), the allocation paths can be assumed to evolve driven by a finite decision horizon. Further we can assume that portfolio decisions that promote green innovations are likely to yield higher asset returns than investment decisions that fund non-renewable technology. The latter induces negative environmental externalities which is usually not reflected in the asset return but maybe in the longer run having destructive effects and embody greater risk – climate risks– usually not immediately taking into account while investing. Thus, neglecting to invest in green technologies can lower returns for the portfolio in the long run due to negative externality effects and realized risks resulting from CO_2 emissions (for example, disrupted production processes due to environmental damages). Negative externalities not internalized in asset price formation will prevent green investments from easily taking off and accumulation of wealth will be lower. This is often the case as argued by Davies et al. (2016) due to short-termism by cash flow oriented investors.

Though assets from climate projects often do not promise such high returns as from fossil fuel assets (since they are still in the stage of learning and with high risk of failure), they are usually less vulnerable to exogenous shocks and should be of interest for private long term investors. This has been shown in empirical studies comparing bonds of the same issuer and similar maturity, see Kapraun and Scheins (2019) and Section 5. A comparison of the financial performance of fossil fuel bonds and green bonds often show lower yields of the latter. Yet, the puzzle is why it can be beneficial for long run asset accumulation? Is it the case that low yield real investors (for example, in the renewable energy sector) can issue bonds purchased by financial investors that pursue the social and environment good, and thus those would be expected to add in the long run social returns? Is there a long run service that a green bond provides for the environment not accounted for in the market yield?

[8]See Greiner et al (2005, ch. 4)
[9]See Greiner et al (2005, ch. 4)
[10]See Semmler et al. (2020)

If this is so then we have to take account the immediate private yields and the additional social returns which would then provide a higher return for green energy than for fossil fuel energy. Yet, this evaluation effect is undertaken presumable very imperfectly in the market and thus the evidence on performance green investments might be mixed. And of course the better overall performance of green investments would come out more distinctively if, at the same time, fossil fuel energy is facing a carbon tax or is forced to disclose CO2 emission – which is presumably also imperfectly done. Thus, in theory we would expect clear results though the empirics could look mixed, see Section 5

Yet pursuing the theory nexus here first, in a model portfolio model of wealth build up we consider a fixed decision horizon and compare the possibility of the different externality impacts associated with portfolio decisions on wealth accumulation (either a positive impact due to environmental investments, or a negative impact due to fossil fuel investments and negative externalities). Though the model will first be written in terms of regular fixed-income fossil fuel and green bonds, we will later introduce convertible green bonds, that might also be a good transitional instrument to avoid excess debt accumulation and ensure varying returns linked to green innovation success.

The model distinguishes two risky assets with fluctuating returns: a green and a fossil fuel asset. For the long-term oriented investor, these returns can be represented by low frequency movements, as in harmonic estimations.[11] By definition, savings and portfolio decisions represent low-frequency movements (Chiarella et al., 2016). This is also true for green investments, that require overcoming short-termism in financial markets (Semmler et al., 2020). We use a Fast Fourier Transform (FFT) - as in Chiarella et al. (2016, ch. 2), and Semmler & Hsiao (2011) - to empirically estimate the harmonic oscillations of the monthly annual total returns for green and fossil fuel bonds, based on two market indices provided by Bloomberg Barclays MSCI[12] and available from December/2015 to December/2020. The FFT is smoothing asset returns to obtain low-frequency movements, filtering out short-term shocks that dot not impact long-term investors' preferences (See Appendix A).

In our model, the change in prices of the bond i in the economy is $\frac{dP_{i,t}}{dt} = r^e_{i,t} \cdot P_{i,t}$. Thereby, $P_{i,t}$ depends on the time-varying return of the asset i which is $r^e_{i,t,}$ for the green or the fossil fuel asset. This is given by sine-cosine functions obtained by harmonic estimations (see eqs. 1 and 2) from US data.[13] Using such harmonic estimations we presume that financial market practitioners dynamically re-balance portfolios by looking at low frequency movements in the financial data. We get the following results for the returns of green and fossil fuel bonds:

$$\begin{aligned} r^e_{green}(t) = 0.029\ sin(\frac{2\pi}{60}(t)) + 0.0273\ cos(\frac{2\pi}{60}(t)) - 0.0119\ sin(\frac{2\pi}{20}(t)) - 0.007\ cos(\frac{2\pi}{20}(t)) \\ + 0.004\ sin(\frac{2\pi}{30}(t)) + 0.0217\ cos(\frac{2\pi}{30}(t)) - 0.0037\ sin(\frac{2\pi}{15}(t)) - 0.0004\ cos(\frac{2\pi}{15}(t)) \end{aligned} \quad (1)$$

$$r^e_{fossilfuel}(t) = -0.0361\ sin(\frac{2\pi}{30}(t)) + 0.0113\ cos(\frac{2\pi}{30}(t)). \quad (2)$$

Next, we presume that in a stylized baseline portfolio model an investor invests a fraction of his/her wealth to each risky asset, defining the share of green assets given by the decision variable π_t, which may also allow divestment in fossil fuels as well. Thus we can have π_t>1. The decision on the share of investment for innovations and consumption is a maximization problem with a budget constraint. The maximization of the value function is expressed using the usual dynamic discounting cash flow model:

$$V(W, x, t) \equiv max_{\{c_s, \pi_s\}} \mathbb{E}\{\int_t^T e^{-\delta_0(s-t)} F(c_s W_s, u_s W_s) ds\} \quad (3)$$

[11]In economics, harmonic estimations can capture the business cycles in prices, industrial production, employment, and asset returns. For the potential application of harmonic estimations, see Artis et al. (2007).

[12]Respectively, the Bloomberg Barclays MSCI US Global Green Bond in USD (GBUSTRUU) and the Bloomberg Barclays US Corporate Energy in USD (I00388US).

[13]The harmonic estimations are obtained using a FFT. As described in Appendix A, we first de-trend the time series for the real asset returns and we are able to apply the FFT in order to filter short-term movements by estimating the coefficients for a linear combination of a sine-cosine function, based on the original data. The harmonic regression model is estimated for six different frequencies. We select the estimation with the lowest sum of squared errors.

$$s.t.\dot{W}(t) = \pi_t r^e_{t_{green}} W_t + (1-\pi_t) r^e_{t_{fossilfuel}} W_t - c_t W_t - X(\Pi_t, W_t) \tag{4}$$

The budget constraint of equation 4 is a sum of wealth gains from the different types of investment ($\pi_t r^e_{t_{green}} W_t + (1-\pi_t) r^e_{t_{fossilfuel}} W_t$) minus a fraction of the assets going to consumption ($c_t W_t$) and minus additional adjustment costs that the investor incurs by obtaining the equity assets ($X(\Pi_t, W_t)$). The preferences in eq. (3) are defined by a log-utility function over both objectives.

This baseline model is extended by including a fraction $u_t = \frac{U_t}{W_t}$ of the investor's wealth going into innovation efforts. Such efforts can be tailored to the development of clean technology, as in the spirit of directed technical change in Acemoglu et al. (2012). Additionally to consumption, efforts to develop clean technology is added to the log-utility function, each of the spending types weighted with w_1 and $(1-w_1)$. This change adds another decision variable to the maximization problem of the baseline model which therefore yields. Now we have 3 decision variables, the share of investment for innovations, consumption and the allocation decisions on asset holdings:

$$V(W, x, t) \equiv max_{\{u_s, c_s, \pi_s\}} \mathbb{E}\{\int_t^T e^{-\delta_0(s-t)} F(c_s W_s, u_s W_s) ds\} \tag{5}$$

$$s.t.\dot{W}(t) = \pi_t r^{e^{\backprime}}_{t_{green}} W_t + (1-\pi_t) r^{e^{\backprime}}_{t_{fossilfuel}} W_t - (u_t + c_t) W_t - X(\Pi_t, W_t) \tag{6}$$

The investment of a fraction of wealth into innovation efforts, which could be investment into renewable and/or fossil fuel energy innovations, generates a time-varying return $r^{e^{\backprime}}(t)$ which can be positively or negatively affected by the investment decision (depending if there are climate positive or negative externalities). The renewable energy oriented innovation investments additionally take into account the long-term return benefits of green investment (lower volatility of returns and higher social returns). We thus can define the two types of returns

$$r^{e^{\backprime}}_{green}(t) = (1 + \mu(\nu u_t))(\alpha + \gamma * r^e_{green}(t)). \tag{7}$$

$$r^{e^{\backprime}}_{fossilfuel}(t) = (1 - \mu((1-\nu) u_t)) r^e_{fossilfuel}(t). \tag{8}$$

Hereby the fractions of wealth used for renewable energy innovations, ν, and the remaining part used for fossil fuel innovations, $\nu - 1$, will be taken as fixed with equal shares.[14]

As defined by $r^{e^{\backprime}}_i(t)$ in eq. (7) an investment which does not create long-term negative externalities (such as renewable energy) and has positive externality effects will be positive ($+\mu(\nu u_t)$) and additional will have lower volatility of returns, and possibly higher returns in the long-run (α is a mean-adjustment term that represents the positive impact of externalities which will be varied in our simulations). In eq (8) an asset return is represented which creates long-run adverse effects on the economy caused by the creation of negative externalities (such as CO_2 emission, affecting temperature and creating damages in the long run) which will be negatively affecting returns, thus ($-\mu((1-\nu)u_t)$).

Thus the two above return equations (7) and (8) indicate if we have the sign "+" there is an asset such as renewable energy impacted by an innovation, not creating long-run negative externalities but rather having a beneficial effect for the economy. On the other hand, if we have the sign " $-$ " one can think of a fraction of wealth invested in fossil fuel innovations (or as fraction of population operating as fossil fuel engineers) that are creating long-run adverse effects on the economy through the creation of negative externalities, such as CO_2 emission, affecting temperature and creating damages in the long run.[15]

As mentioned, the term $\mu(\nu u_t)$ and $\mu((1-\nu)u_t)$,could depend for example (as in the Romer model) on the engineers' innovation effort and the therefrom resulting returns. But in order to

[14]Note that in order to avoid additional state variables defining stocks of innovation capacity we undertaken a short cut and let the respective innovations being driven by the respective fraction of wealth. Simulations could be undertaken with various fractions of ν_t.

[15]We could also think of the sign " $-$ " as indicating that the fossil fuel subsidies are reduced and thus the return on fossil fuel asset would fall.

smooth out the transition we use in the simulation a logistic function for u_t so that we have for example for renewable energy innovations:

$$\mu(\nu u_t) = \mu\nu L(\beta u_t) \tag{9}$$

in which μ is the externality scale factor (for example set as 0.2); βu_t is the fraction of wealth now in the logistic function, allocated to green or fossil fuel innovations. The logistic function L is here introduced to capture the possibly increasing social returns of innovation effort (Hall et al., 2010; Leibowicz, 2018 and Jones & Summers, 2020). The logistic function is given by

$$L(\beta u_t) = 130/(1 + e^{-30u_t}). \tag{10}$$

The upper bound in the logistic function is based on estimations by Jones & Summers (2020). They estimate that the social returns of an innovation expense in the health sector is from 79% to 159%.

Furthermore, the adjusted-returns for green and fossil fuel assets for the cases of α in eqs. (7) and (8) equals to 0.034, 0.024 and 0.014 which are shown by Figure 1.

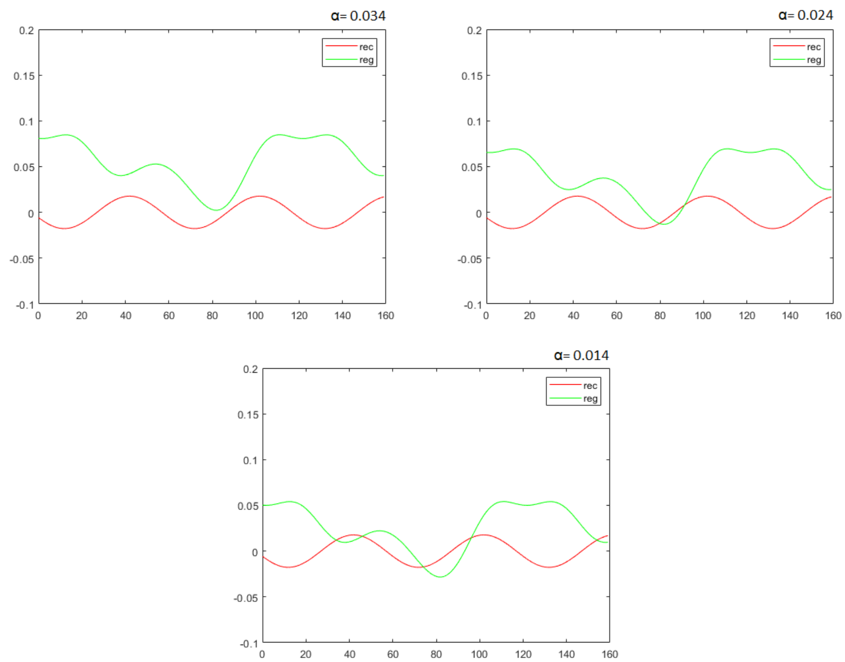

Figure 1: Returns for green (reg) and fossil fuel bonds (rec): adjusted harmonic estimations as in eqs. 7 and 8.

Using our harmonic estimations of eqs (1) and (2) the Figure 1 shows the paths of two returns of green energy bonds, *reg*, and carbon energy bonds, *rec*, for the different scaling factors. Since the actual empirical effects are not known with some certainty we explore the paths of the harmonic estimates for different size of the α.

Though assets from climate projects often do not promise such high returns as from fossil fuel assets, they are less vulnerable to exogenous shocks and should be of interest for investors. This has been shown in empirical studies comparing bonds of the same issuer and similar maturity, see Kapraun and Scheins (2019) and Semmler et al. (2021). We explore a stochastic version of this model in Appendix B to account for these shocks in order to analyze the model behavior when investors face additional financial risk. An additive shock is added to the model, and the realizations of the different shock sequences create slightly different solution paths.

Overall, we might observe the case that in fact a carbon tax could be very complementary to a green bond strategy since a higher carbon tax (or a disclosure requirements) can make the risky return turn sour. This can visibly reduce the fossil fuel returns, and can make green bonds even with negative bond premia, as reported in Kapraun and Scheins (2019), profitable in dynamic portfolios and successfully help the transition to a low carbon economy. Moreover, to indicate this possible positive externality effect, the "+" we have introduced a positive drift in the returns arising from energy innovation, the α. The negative externality effect is represented by the negative sign, the "-".[16]

The possibility to have (negative) premia for green bonds – possibly reflecting the individual preferences of green bond holders (as compared to fossil fuel bonds) – is also indicated, since the short and medium run effects could just be driven by the preferences of the asset buyers. Thus, there can be (direct) negative premia for green bonds, see Kapraun and Scheins (2019). Yet, in fact, through green investments (green energy, conservation of energy etc.) there is through the externality for the society some "extra productivity" or "service" achieved (through scale effects with freely available energy and avoidance of destruction through CO_2) which should show up in extra long-run returns in portfolio holdings, indicated by the the size of the α.

Next, numerical solutions are obtained by applying to our model the method Nonlinear Model Predictive Control (NMPC) as a solution procedure, see Gruene et al. (2015).

4 Modelling results

As noted, much recent literature has pointed out that large scale fossil fuel energy firms tend to short-termism, see Davies et al. (2014). In Semmler et al (2020), it is shown that portfolio decisions arising from short-termism in terms of higher discount rates or hyperbolic discounting may inhibit the accumulation of low carbon based assets. It has been also explored the role of the decision horizon as another manifestation of short-termism.[17]

On the other hand, as climate research showed, fossil fuel bonds and fossil fuel equity are linked to negative externalities through CO_2 emission, temperature rise, weather extremes and climate disasters, requiring a carbon tax to internalize the externality cost. Fossil fuel assets might also be quite volatile in value, in particular in contractions and recessionary periods, triggering financial instability. Some countries have introduced a mandatory disclosure on traded assets. An introduced carbon tax as well the threat of financial instability and the disclosure requirements will lead to either lower net cash flows of fossil fuel firms and/or their assets will face a devaluation in the market, triggered by higher discount rates capturing the long run environmental risk involved.[18]

The above mentioned two opposite effects on the return and firm value can be illustrated by the following simulations for the dynamic system eqs. 5 - 8. The dynamic saving and asset allocation choices are modeled in continuous time. In the objective function we have included, in addition to spending a fraction c_t of wealth on consumption, a policy maker's decision to spend also a fraction u_t of the wealth on innovation efforts; efforts aimed for instance for developing new energy technologies, each of the spending types weighted with w_1 and $(1 - w_1)$ in the utility function. As noted, this is in line with the previous work of Acemoglu et al. (2012) on directed technical change. We have have further split up the innovation effort u in different fractions, one fraction for clean energy and possible one fraction for fossil fuel energy. We can then explore those modeling procedure on the time consumption wealth ratio, the time varying returns and the fate of wealth. This will allow us to observe whether wealth is increasing or decreasing over time for our two types of assets.

We want to note in the model above so far we referred to those two generic risky assets. But we can allow the two risky assets, to be a green and a fossil fuel bond that display time varying returns impacting wealth accumulation. These bonds could be long-term bonds, generating returns from some coupon payments. These bonds can also be long-term bonds, generating returns from some coupon payments. Hereby the bond prices for long term bonds can be made dependent on the expected return of the short term bonds.[19]

[16]We also want to note that the weights ω_1 and $(1 - \omega_1)$ of the two parts of the objective functions (3) and (5) can be varied and some Pareto frontier can be computed to explore which weights are the realistic ones, see Kaya & Maurer (2014).

[17]Risk aversion and discount rates have been explored in its relevance for portfolio dynamics dynamics in (5)-(6).

[18]See Davies et al (2014) and there the discussion on stranded assets.

[19]For details see Cochrane (2001, ch.19) where then the bond price is solved for solving then the appropriate discount rate forward. In the portfolio context, see Semmler (2011, ch. 17.5).

In this section we solve the model using NMPC for a decision horizon $N = 6$ fixed and 160 iteration time periods T for the different returns showed in Figure 1. We solve the model where the term $(1 \pm \mu(u_t W_t))$ using the logistic function, L, and where it holds for "+" , which implies that $\mu(\cdot) > 0$,for example for the new innovations in renewable energy firms. Note that there might also be some temporary risk premium harvested by fossil fuel assets so that we have $\mu(\cdot) > 0$. On the other hand, for the fossil fuel asset we might have $(1 \pm \mu(u_t W_t)) < 1$), with the minus sign " $-$ ", holding when $\mu(\cdot) < 0$.

In Figure 2 we have depicted only the case of positive externalities. For this purpose we use for example a computational parameterization of $\mu(\cdot) = 0.2$, running this with different parameterization of α. It is obvious that a $\mu(\cdot) < 0$ will always generate lower returns with mostly fossil fuel bonds held in the portfolio facing the prospects of a carbon tax, stranded assets and downgrading through requirements of CO_2 disclosure, and higher liquidity and default risks and lower accumulation of wealth we do not need to solve for this.

Our depicted cases present only results for $\mu(\cdot) > 0$.. We use for this case, for example a computational parameterization of $\mu(\cdot) = 0.2$. In Figure 2, the lowest graph represents the effect with a parameter $\alpha = 0.014$, .the middle graph is for $\alpha = 0.024$ and the upper graph for $\alpha = 0.034$. As can be observed the greater the positive externality effects, the more wealth is accumulated over time. And even without simulations we can conclude that having negative externalities these are are likely to lead to less asset built up, but more specifically to dissipating asset value in the long run.

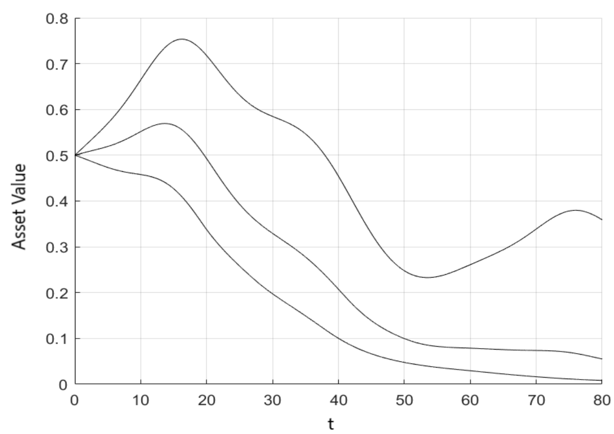

Figure 2: Solutions path of wealth for different asset returns, the upper graph with $\alpha = 0.034$, middle graphs with $\alpha = 0.024$ and lowest graph $\alpha = 0.014$ ($N = 6$, $T = 160$)

We observe that the referred effects on wealth and investor's asset value are as well associated with their portfolio composition choice. If investors hold a larger share of green bonds, with long-term positive externality effects, the negative effects of climate transition tend to be mitigated. Figure 3 shows the share of green bonds hold by investors for the three cases simulated in Figure 2. We observe that, in the case with $\alpha = 0.034$, upper panel of Figure 3, which is associated with the upper solution path of wealth, investors invest only in green assets and divest fossil fuel assets, since the asset share held in green assets is $\pi = 1.2$,meaning that there is short selling for the fossil fuel asset. On the other hand, in the other two cases, investors tend to diversify and still chose (partially or totally) carbon-intensive securities in some periods.

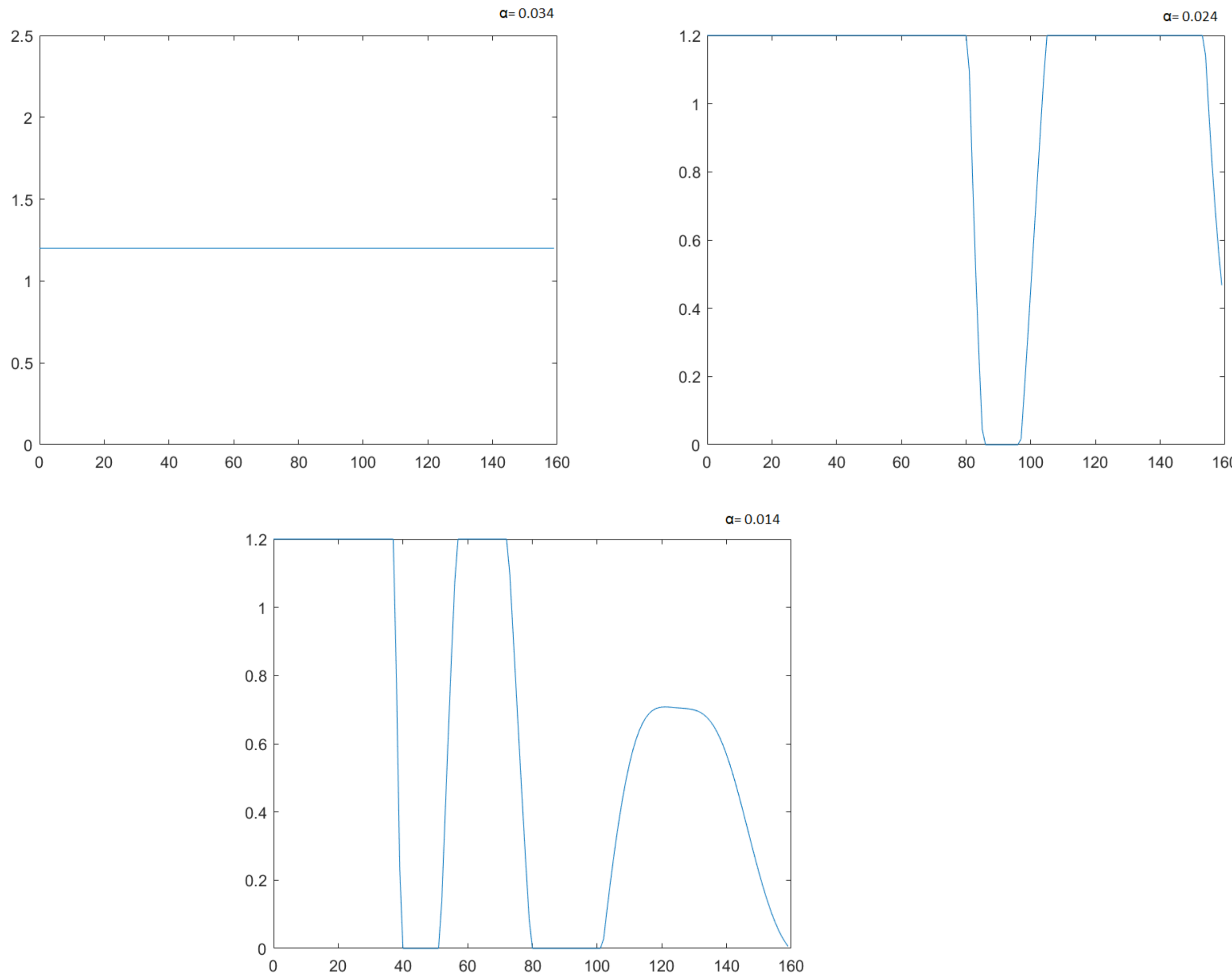

Figure 3: Portfolio decision - share of green assets for the cases with $\alpha = 0.034$, $\alpha = 0.024$, and $\alpha = 0.014$.

As mentioned in the model above when referring to green and fossil fuel assets as the two risky assets, we could also assume that we have green convertible bonds, instead of fixed-income securities. These are bonds that can be converted into equity. The condition of convertibility to equity might be tight to some equity price per share through some strike price as the Merton model for debt suggests and Black-Scholes for derivatives in general entails. A green bond is convertible to equity if the asset value goes up, which might be the case of a successful green start-up firm. This is likely to be accelerated if the distance to default also decreases, given the firm's debt issuance, and the equity value of the firm increases.[20] Moreover if these are sovereign bonds, the conversion of sovereign bonds into firms' equity could allow the sovereign to reduce debt that it had increased first by selling bonds and increasing debt. This way debt sustainability could be achieved.

Convertible bonds have recently been issued with green labels as an alternative to conventional fixed income bonds, but still represents a small share of the market (Gregory, 2020). A convertible green bond is an innovative instrument that can address climate challenges and benefit long-term issuers and investors, with higher future returns linked to the success of green innovations. A surge in the convertible bond market was observed in 2020 following the COVID-19 crisis, with creates opportunities also for convertible green bonds (Semmler et al., 2021). In the United States, new convertible bonds totaled \$ 77 billion as of September 2020, an increase of 45 percent over 2019 and 200 percent over 2015. The convertible bond market index (ICE BofA US Convertible Index—

[20]It might help to support green start up firms, ensuring a minimum return if the business does not succeed but high returns if it succeeds. If we think in terms of green treasury bonds, it can help to reduce sovereign debt due to debt to equity swaps.

VXA0) outperformed the S&P 500 and S&P 500 bond index. In order to account for the effect of external shocks and financial market risks, we also explore a stochastic version of the model in Appendix B. The results do not differ significantly from the deterministic version presented here. An additive shock is added to the model and the realizations of the different shock sequences create slightly different solution paths.

5 Data, empirical analysis, and results

Next, we want to explore to what extent our model-driven hypotheses can be supported by the data. Our analysis is based on green and conventional bond data downloaded from the Bloomberg terminal. Bloomberg provides a "green instrument indicator" which was our criterion for green bonds. Conventional, or plain vanilla, bonds are simply non-green bonds; in other words, bonds for which the "green instrument indicator" does not hold. The last complete version of bond data was downloaded from the Bloomberg Terminal on October 1, 2020. Due to the higher availability of conventional bond data and the restrictions on Bloomberg download limits, we restricted our analysis to a set of sectors with the highest amount of green bonds and to the period of time in which the most green bonds were issued. As we are mostly interested in comparing the performance of green and conventional bonds and since green bonds became more popular in 2015 and their issuance kicked off in 2017, our period of selection includes data from January 1, 2017, to October, 1 2020. Also, we select conventional bonds only from the sectors that showed the highest amount of green bonds: (i) the financial sector with the banking and real estate sub-sector, (ii) the utilities sector with the utilities and power generation sub sector, (iii) the government sector with the government development bank, supranational and sovereign sub-sectors, and (iv) the energy sector with the renewable energy sub-sector.

In our analysis, we measure bond performance by looking at (i) the expected return of bonds (yield at issue for the primary bond market yields and the yield to maturity for the secondary bond market), (ii) the volatility measure of bonds, which is represented by the Bloomberg volatility measure (the day to day logarithmic historical price changes, for the 30, 90 and 260 most recent trading days closing prices[21], and (iii) the bond specific Sharpe ratio (SR_b).

The bond specific Sharpe ratio is similar to the original Sharpe ratio (which we call "portfolio Sharpe ratio" SR_p) which is an information criterion of the risk-to-return measure of a portfolio, whereby the portfolio standard deviation describes the risk of a portfolio (see Sharpe, 1994). The combination of both the yield level and the variation in yields (portfolio volatility and risk) is integrated in the portfolio Sharpe ratio, which is defined as $SR_p = \frac{\bar{R}_p - R_f}{\sigma_p}$,where $\bar{R}_p$ is the average portfolio return, R_f the risk free rate, and $\sigma_p$the portfolio standard deviation. The bond specific Sharpe ratio SR_b(or SRb) is inspired by the original SR_p(or SRp), carries individual excess bond returns in the numerator and a measurement for a bond return volatility over time in the denominator and is defined as $SR_b = \frac{R_b - R_f}{v_b}$,where R_b is the individual asset return, R_f is the risk free rate, and v_b is the individual asset volatility measure. The advantage of using the bond specific over the portfolio Sharpe ratio is that we can obtain a reward risk measurement for each separate bond which can then be used in a regression analysis. For computing the SRb we use the yield to maturity rate in the numerator and different volatility measures (the 30d, 90d or 260d) in the denominator.[22]

We use four different types of empirical analysis: a base regression (analysis 1), that only uses key explanatory variables; a first extension, that adds sector controls (analysis 2); an extension to the second model, by controlling for USD as a currency (analysis 3); and an extension to the second model that controls for EUR as a currency (analysis 4). In this section, each analysis is presented in a separate subsection.

[21]We abbreviate volatility measures for these 30, 90, and 260 day ranges by writing 30d, 90d, and 260d

[22]In our empirical analysis, we compared the bond specific Sharpe ratio results with and without the risk-free rate for the two most frequent currencies (USD and EUR) and did not find a relevant change (differences in the size of the second or the third digit after the decimal). Hence, for simplicity, we do not consider the risk-free rate in our analysis when reporting results on the bond specific Sharpe ratio SRb.

5.1 Multivariate regression

As a first step we determine the bond performance of green and conventional bonds by running multivariate regressions on three different dependent variables: yield at issue (YAI), yield to maturity (YTM), bond specific Sharpe ratio (SRb)[23]. Four different model specifications are deployed which also slightly differ with regard to the dependent variable, but are defined in their most extended form as follows:[24] Model 1 is defined in equation 11 where X_1 is a green dummy variable (when equal to one, the bond is green), X_2 is the 90-day bond price volatility rate[25], X_3 is the liquidity (computed as the ask minus the bid price)[26], X_4 is the maturity structure (this is a dummy variable which is one for long-term bonds and zero for short-term bonds)[27], X_5 is the S&P rating (integer variable which where AAA is 1, AA+ 2 and so on), X_6 is the coupon rate[28], X_7 is the amount of bonds issued in US$ divided by 10^9 (dividing by a billion gives us more similar numbers in comparison to the yield values)[29], X_8 is the debt-to-assets ratio, and X_9 is the date issued based on year-quarterly information (dummy variables for available year-quarter combinations are used). We use OLS regressions and assume normally distributed error terms ϵ_i.

$$Y_i = \beta_0 + \sum_{k=1}^{9} \beta_k X_{k,i} + \epsilon_i \tag{11}$$

The extensions of model 1 are defined by equation 12 for model 2 which controls for different sectors, and by equation 13 for model 3 and model 4 where further a currency control is included through $c = \{USD, EUR\}$.

$$Y_i = \beta_0 + \sum_{k=1}^{9} \beta_k X_{k,i} + \sum_{l=1}^{3} \gamma_l X_{l,i} + \epsilon_i \tag{12}$$

$$Y_{i,c} = \beta_{0,c} + \sum_{k=1}^{9} \beta_{k,c} X_{k,i,c} + \sum_{l=1}^{3} \gamma_{l,c} X_{l,i,c} + \epsilon_{i,c} \tag{13}$$

The multivariate regression of the primary market yields shows negative yields for green bonds (see Table 1). This holds for the simple model (model 1) as well as for the case that controls for sectors (model 2) including a control for USD (model 3). Only in the EUR specific model we don't find a significant effect for green bonds.

[23]YAI values showed few outliers and only observations above the 99th percentile were truncated. In terms of YTM observations values below the 2.5th percentile and above the 97.5th percentile were truncated. The SRb was calculated based on the filtered YTM and volatility values and outliers below the 2.5th percentile and above the 97.5th percentile were truncated.

[24]e.g. the bond price volatility variable only appears in YTM regressions since YAI is the recorded bond yield at the time of bond issuance and its value is arguably not dependent on bond price changes of the more recent past, and SRb already includes information on bond volatility in its denominator.

[25]We carried out all analyses with all three different volatility measures but for the matter of simplicity (and unless specified, as in the case of analysis 4 on the energy sector) we only report regressions with the 90 day volatility measure. Results for the different volatility measures are similar and are available upon request. In order to reduce the impact of outliers the 90d volatility observations above the 95th percentile were truncated.

[26]In order to reduce the impact of outliers bid-ask spread observations below the 1st and above the 99th percentile were truncated.

[27]We define long-term bonds similar to Kapraun & Scheins (2019) who categorize them as bonds with a maturity structure of more than ten years (or see Kenny, 2021: https://www.thebalance.com/choosing-bond-fund-term-416948). Our non-long-term bonds include bonds with a maturity structure of 10 years or less and subsume short term and intermediate-term bonds. In order to reduce the influence of outliers we excluded observations with a maturity structure of more than 100 years.

[28]In order to reduce the impact of outliers coupon rate observations below the 1st and above the 99th percentile were truncated.

[29]In order to reduce the impact of outliers amount issued observations above the 97.5th percentile were truncated

Table 1: Analysis 1a - Multivariate regression yield at issue

	Dependent variable: Yield at issue			
	(1) Base model	(2) Sector model	(3) USD model	(4) EUR model
Intercept	0.283^{***}	0.262^{***}	0.572^{***}	-0.102
	(0.047)	(0.045)	(0.088)	(0.072)
Green bond (dummy)	-0.119^{***}	-0.106^{***}	-0.133^{***}	0.024
	(0.024)	(0.026)	(0.034)	(0.066)
Corp sector: energy (dummy)		0.031	0.003	0.154
		(0.020)	(0.021)	(0.134)
Corp sector: utilities (dummy)		-0.106^{***}	-0.220^{***}	-0.096
		(0.021)	(0.035)	(0.067)
Government sector (dummy)		0.308^{***}	0.304^{**}	0.160
		(0.078)	(0.094)	(0.112)
R^2	0.882	0.884	0.900	0.943
Adj. R^2	0.882	0.884	0.900	0.939
Num. obs.	2969	2969	1794	144

Standard errors are heteroskedasticity robust. $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$

Note: The table shows regression results for Yield at issue rate for Green and conventional bonds. The Green dummy is 1 if a bond is Green and 0 otherwise. The baseline sector for models (2), (3), and (4) is Corp sector: finance. Non-depicted regressors include Maturity (long term dummy), S&P Rating, Coupon rate, Amount issued in bnUSD, Debt to assets ratio.

The results for the secondary yield regressions are similar: there is no evidence for positive yield premia of green bonds (see Table 2). There is a strong significance of negative yields in the EUR model case and weak evidence in the case of the second model that controls for different sectors but not for currencies.

Table 2: Analysis 1b - Multivariate regression for yield to maturity

	Dependent variable: Yield to maturity			
	(1) Base model	(2) Sector model	(3) USD model	(4) EUR model
Intercept	-1.236^{***}	-1.342^{***}	-1.496^{***}	-0.829^{***}
	(0.086)	(0.087)	(0.128)	(0.091)
Green bond (dummy)	-0.119^{*}	-0.160^{**}	-0.133	-0.168^{**}
	(0.054)	(0.052)	(0.097)	(0.052)
Volatility 90d	0.126^{***}	0.121^{***}	0.153^{***}	0.016^{*}
	(0.010)	(0.010)	(0.013)	(0.008)
Corp sector: energy (dummy)		0.250^{***}	0.204^{*}	0.415^{*}
		(0.068)	(0.085)	(0.168)
Corp sector: utilities (dummy)		-0.470^{***}	-0.472^{***}	-0.443^{***}
		(0.041)	(0.058)	(0.049)
Government sector (dummy)		0.692^{***}	1.111^{***}	0.184^{*}
		(0.075)	(0.122)	(0.075)
R^2	0.755	0.772	0.771	0.690
Adj. R^2	0.753	0.771	0.769	0.685
Num. obs.	4454	4454	2433	1739

Standard errors are heteroskedasticity robust. $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$

Note: The table shows regression results for Yield to maturity rate for Green and conventional bonds. The Green dummy is 1 if a bond is Green and 0 otherwise. The baseline sector for models (2), (3), and (4) is Corp sector: finance. Non-depicted regressors include again Maturity (long term dummy), S&P Rating, Coupon rate, Amount issued in bnUSD, Debt to assets ratio, as well as the Bid-ask spread, and Quarterly dummies from 2017Q2 until 2020Q2.

And the regression results for the SRb regression in table 3 show a positive impact green bonds the bond specific Sharpe ratios.

Table 3: Analysis 1c - Multivariate regression for bond specific Sharpe ratio (SRb)

	Dependent variable: Bond specific Sharpe ratio (SRb)			
	(1) Base model	(2) Sector model	(3) USD model	(4) EUR model
Intercept	0.727^{***}	0.594^{***}	0.851^{***}	0.135
	(0.063)	(0.055)	(0.078)	(0.070)
Green bond (dummy)	0.603^{**}	0.535^{**}	1.189^{*}	0.004
	(0.215)	(0.204)	(0.537)	(0.029)
Corp sector: energy (dummy)		-0.132^{***}	-0.165^{***}	0.160^{*}
		(0.026)	(0.035)	(0.067)
Corp sector: utilities (dummy)		-0.100^{***}	-0.202^{***}	-0.116^{***}
		(0.022)	(0.031)	(0.029)
Government sector (dummy)		0.512^{***}	0.949^{***}	0.198^{***}
		(0.089)	(0.213)	(0.059)
R^2	0.115	0.133	0.163	0.255
Adj. R^2	0.111	0.129	0.155	0.245
Num. obs.	4028	4028	2357	1532

Standard errors are heteroskedasticity robust. $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$

Note: The table shows regression results for the Bond specific Sharpe ratio for Green and conventional bonds. The Green dummy is 1 if a bond is Green and 0 otherwise. The baseline sector for models (2), (3), and (4) is Corp sector: finance. Non-depicted regressors include again Maturity (long term dummy), S&P Rating, Coupon rate, Amount issued in bnUSD, Debt to assets ratio, as well as the Bid-ask spread, and Quarterly dummies from 2017Q2 until 2019Q4.

5.2 Pairing analysis

To control for issuer-specific effects, we compute a bond pairing algorithm that matches each green bond with a conventional bond. First, we select pairs of similar green and conventional bonds and evaluate the yield differences (green bond returns minus conventional bond returns) on the primary market (yield at issue) and secondary markets (yield to maturity). The aggregate results of our paired sub-set of data confirm the findings of Kapraun & Scheins (2019) which is a negative green premium for yield at issue rates but a positive green premium for yield to maturity rates in comparison to conventional bonds. Additionally, we see higher bond-specific Sharpe ratios for green bonds than for their conventional bond pairings.

Our bond pairing procedure selected green and conventional bonds with the same issuer (and therefore the same sector), currency, maturity, and S&P rating. With this procedure, we create a subset of data that consists of 1,022 paired observations (511 green and 511 conventional bonds). Any green bond of this subset is required to match with a conventional bond based on these five criteria. In many cases, these conditions resulted in more than one conventional matching partners for a green bond. In these cases, we allowed for maximum of 10 conventional bonds for each green bond. The closest matching candidates are identified based on a kNN algorithm that looks for similar coupon rate values. This pairing procedure ensured that similar assets were compared.

Similar to equation 11 we regress our key dependent variables (yield and SRb) onto the main explanatory variables. In order to estimate the differential effect of the green-conventional bond pairs we work with the "green minus conventional" (GMC) differences of the respective variables. Equation 14 shows the general regression setup for this section. The left-hand side contains the GMC value of the dependent variable. The right-hand side sums up the GMC value of the constant ($GMC.\alpha$) which represents the green premium, a set of variables like amount issued or bid-ask spread where values for green and conventional bonds differ ($GMC.X_k$), and a set of variables where green and conventional bonds variables are the same, e.g. their S&P rating or sector ($GMC.X_l$)

$$GMC.Y_i = GMC.\alpha_i + \sum_k \beta_k GMC.X_{k,i} + \sum_l \beta_l X_{l,i} + \epsilon_i \tag{14}$$

We take the green minus conventional (GMC) bond yields and find a positive difference (or "greenium") for issued bonds on the secondary market (higher yield to maturity when comparing green bonds to conventional bonds; see Table 5). In line with the literature we also find that institutional bond issuers reflect a negative green yield effect as the dummy variable for the government sector is significantly negative for all cases (see models 2-4 in Table 5). For the yield at issue regression, we mostly find no significant effect of the green dummy, except for for the base regression case where a weakly positive yield difference is reported (see Table 4). However, due to the lack of observations, it was not possible to control for all sectors or add a model for EUR bonds, which means that the outcome of the regression should not be over interpreted.

Similar to the non-paired regression we also find a positive impact of green bonds on the bond specific Sharpe ratio, i.e. the yield to maturity rates discounted by asset-specific volatility measures. As Table 6 shows the differences of green minus conventional bond SRb are positive and significant in the case of models (1)-(3) and range from 1.79 to 1.54; only in the case of EUR bonds we do not find a significant positive effect.

Comparing the results from the YTM regression (Table 5) and the SRb regression (Table 6) we see that the positive difference for paired green bonds increases when we add volatility to the indicator. This means that the conventional bond yields that are discounted by their bond-specific volatility measure show a weaker performance than their green pairs. Thus, even if we look at a subset of data with similarly paired bonds, we find evidence that green bonds show lower volatility and are also able to reward the investor with a better Sharpe ratio.

Different volatilities for the bonds depend highly on sector and currency specific effects. Table 7 and Figure 4 show that the bond specific volatilities of green bonds in the energy and the government sector (especially for the USD case) are significantly smaller than their conventional matches. These patterns are also currency sensitive: while trends are clear for bonds in USD the observations are less clearly structured for EUR denominated bonds. USD bonds in the energy and government sector also show a clear trend for different volatility periods: an increasing volatility period (i.e. moving from 30day to the 90 day volatility) also significantly increases the difference of green and conventional volatilities. Thus, taking finance bonds as the baseline, we find sector specific volatility effects that make USD denominated green bonds less volatile when associated with energy, and government and especially less volatile when looking over a longer period of bond price changes.

Table 4: Analysis 2a - Paired bond regression results for yield at issue

	Dependent variable: Yield at issue		
	(1) Base model	(2) Sector model	(3) USD model
Constant [green premium]	0.565*	0.157	0.396
	(0.232)	(0.885)	(0.840)
Government Sector (dummy)		0.089	0.172
		(0.423)	(0.402)
R^2	0.200	0.282	0.346
Adj. R^2	0.178	0.218	0.284
Num. obs.	115	50	47

Standard errors are heteroskedasticity robust. $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$

Note: The table shows regression results for Yield at issue rates for paired Green and conventional bonds. The Green dummy is 1 if a bond is Green and 0 otherwise. The baseline sector for models (2) and (3) is Corp sector: finance. Non-depicted regressors include GMC Amount issued, GMC Time to maturity, and S&P Rating.

Table 5: Analysis 2b - Paired bond regression results for yield to maturity

	Dependent variable: Yield to maturity			
	(1) Base model	(2) Sector model	(3) USD model	(4) EUR model
Constant [green premium]	0.080	0.428^{***}	0.792^{***}	0.080
	(0.080)	(0.084)	(0.199)	(0.081)
GMC Volatility 90d	-0.028	-0.010	0.115	-0.092^{*}
	(0.050)	(0.048)	(0.111)	(0.043)
Corp Sector: Energy (dummy)		0.187	-0.663^{**}	0.255^{***}
		(0.163)	(0.212)	(0.060)
Corp Sector: Utilities (dummy)		0.344^{***}	0.520^{*}	0.164^{**}
		(0.081)	(0.256)	(0.058)
Government Sector (dummy)		-0.396^{***}	-0.593^{**}	-0.449^{***}
		(0.071)	(0.196)	(0.087)
R^2	0.518	0.575	0.736	0.521
Adj. R^2	0.508	0.562	0.714	0.495
Num. obs.	304	304	116	176

Standard errors are heteroskedasticity robust. $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$

Note: The table shows regression results for Yield to maturity rates for paired Green and conventional bonds. The Green dummy is 1 if a bond is Green and 0 otherwise. The baseline sector for models (2) and (3) is Corp sector: finance. Non-depicted regressors include GMC Amount issued, GMC Time to maturity, S&P Rating, GMC Coupon rate, as well as GMC Bid-ask spread.

Table 6: Analysis 2c - Paired bond regression results for bond specific Sharpe ratio (SRb)

	Dependent variable: Bond specific Sharpe ratio (SRb)			
	(1) Base model	(2) Sector model	(3) USD model	(4) EUR model
Constant (green premium)	2.383^{***}	1.787^{**}	2.454^{*}	-0.153
	(0.620)	(0.644)	(1.154)	(0.115)
Corp Sector: Energy (dummy)		2.046^{**}	-0.248	0.093^{**}
		(0.786)	(0.755)	(0.034)
Corp Sector: Utilities (dummy)		1.434^{**}	1.800	0.052
		(0.479)	(1.000)	(0.029)
Government Sector (dummy)		0.755	-0.112	0.209^{***}
		(0.568)	(0.974)	(0.057)
R^2	0.536	0.549	0.664	0.246
Adj. R^2	0.525	0.531	0.638	0.165
Num. obs.	209	209	113	84

Standard errors are heteroskedasticity robust. $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$

Note: The table shows regression results for the Bond specific Sharpe ratio for paired Green and conventional bonds. The Green dummy is 1 if a bond is Green and 0 otherwise. The baseline sector for models (2) and (3) is Corp sector: finance. Non-depicted regressors include GMC Amount issued, GMC Time to maturity, S&P Rating, GMC Coupon rate, as well as GMC Bid-ask spread.

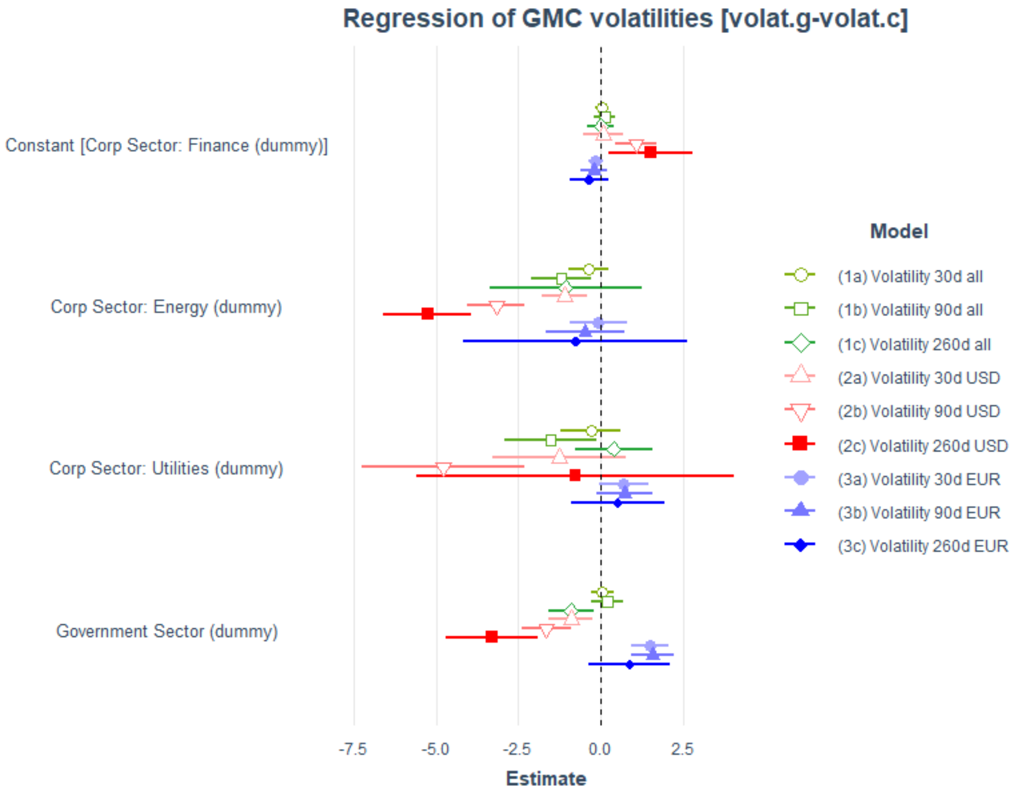

Figure 4: Analysis 2d - Paired bond regression results for bond specific volatilities (volat)

Table 7: Analysis 2d - Paired bond regression results for bond specific volatilities (volat)

	Dependent variable: Volatilities (30d, 90d, 260d)								
	(1a)	(1b)	(1c)	(2a)	(2b)	(2c)	(3a)	(3b)	(3c)
	30d	90d	260d	USD.30d	USD.90d	USD.260d	EUR.90d	EUR.90d	EUR.260d
Constant [Corp Sector: Finance]	0.039	0.124	0.015	0.092	1.076^{***}	1.536^{*}	-0.144	-0.193	-0.349
	(0.091)	(0.164)	(0.203)	(0.304)	(0.316)	(0.639)	(0.119)	(0.203)	(0.294)
Corp Sector: Energy (dummy)	-0.373	-1.192^{*}	-1.059	-1.093^{**}	-3.170^{***}	-5.259^{***}	-0.060	-0.464	-0.758
	(0.308)	(0.467)	(1.179)	(0.354)	(0.436)	(0.675)	(0.444)	(0.598)	(1.718)
Corp Sector: Utilities (dummy)	-0.288	-1.517^{*}	0.402	-1.257	-4.788^{***}	-0.774	0.697	0.733	0.533
	(0.463)	(0.703)	(0.600)	(1.028)	(1.252)	(2.416)	(0.380)	(0.435)	(0.713)
Gov Sector (dummy)	0.049	0.205	-0.902^{*}	-0.903^{**}	-1.645^{***}	-3.316^{***}	1.504^{***}	1.591^{***}	0.878
	(0.175)	(0.250)	(0.353)	(0.337)	(0.381)	(0.699)	(0.280)	(0.334)	(0.624)
R^2	0.005	0.057	0.033	0.057	0.305	0.345	0.177	0.126	0.024
Adj. R^2	-0.002	0.048	0.022	0.034	0.287	0.318	0.164	0.111	0.001
Num. obs.	413	312	265	125	117	77	190	183	132

Standard errors are heteroskedasticity robust. $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$

5.3 Volatility analysis

We use the classification and regression tree (CART) method to identify the most essential drivers in the volatility structure of bonds. A CART analysis uses a decision tree that results from a supervised learning predictive model. Based on a set of binary input variables (our categorical regressors) we are predicting the value of our target variable, which is a bond volatility measure. Some benefits of this type of analysis is that CART is non-parametric and therefore does not rely on data belonging to a particular type of distribution, CART is not significantly impacted by outliers in the input variables, and CART can use the same variables more than once in different parts of the tree and therefore uncover complex inter-dependencies between sets of variables (Nisbet et al., 2018).

By running a CART analysis we find further validation that green bonds have lower volatilities than conventional bonds and also find that the sectorial attribute plays a very important role in predicting volatilities, e.g. bonds in the energy sector have higher volatilities than bonds in other sectors. The widely-used machine learning CART technique is a helpful tool to identify complex inter-dependencies between different sets of variables and, due to being a non-parametric method, it also does not rely on data belonging to a particular type of distribution.

We apply the CART method in R with the rpart command to predict bond volatilities based on four relevant categorical variables: (i) bond type (i.e., green or conventional), (ii) sectors, (iii) maturities, and (iv) ratings. Based on these variables we find that the top discriminating factor is sectorial classification: the sectorial affiliation matters most when it comes to predicting high bond volatilities. Using this command in conjunction with our data set on conventional and green bond (from 2017 to 2020) yields a huge tree (see Figure 5). For better readability, we separately depict the left branch (which includes the energy and utilities sector) below in Figure 6 and the right branch (which includes the finance and government sector) in 7.

These figures show that bonds in the energy and utilities sector have higher volatilities than those in the finance and government sector. Additionally, the CART analysis validates our prior findings that green bonds are associated with lower volatilities than conventional bonds. The CART results in Figures 5, 6, and 7 show a decision tree that ranks the sectorial specification as the most important property regarding the volatility prediction. Bonds from the energy and utilities sector open the top left branch, which means that bonds in these sectors will predict higher volatility than bonds in other sectors (i.e., the finance and government sector). A bond in the energy (and utility) has a higher predicting power for volatility (graphically: energy is listed as the top classifier). Another good validation of our results is that bonds that are categorized as green are mostly shown to the right of conventional bond branches, which means that being a green bond predicts in most cases lower volatilities than being a conventional bond.

The only case where we observe the opposite is for government bonds (see bottom right) - but also Kapraun and Scheins (2019) found an opposite trend for green bonds when they looked at the government sector. For most of the decision nodes, we also see that non-investment grade bonds predict higher volatilizes than investment grade bonds, which is analogous to the comparison of long-term bonds and short-term bonds. This CART analysis was done across all currencies, but currency-specific CART analyses for the USD and EUR confirm the general findings: we see that (i) the energy sector also appears as a high volatility classifier for both currencies (not necessarily as the top one but still appearing as a high-volatility predictor), and that (ii) the bond type category shows lower volatilities for green bonds in the USD case but does not appear as a strong predictor for the EUR case (a currency anomaly that we already see in respect to the multivariate regressions)

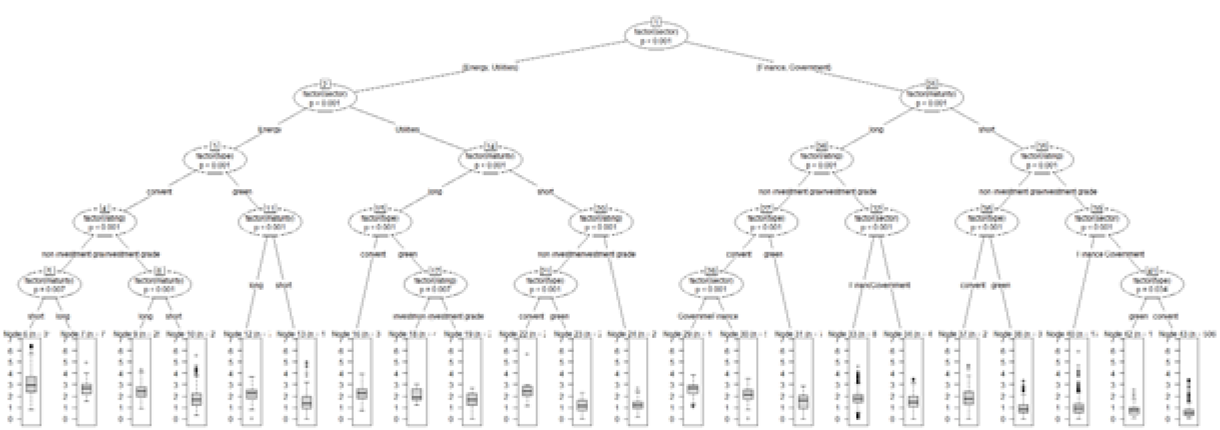

Figure 5: Analysis 3 - CART results (big chart)

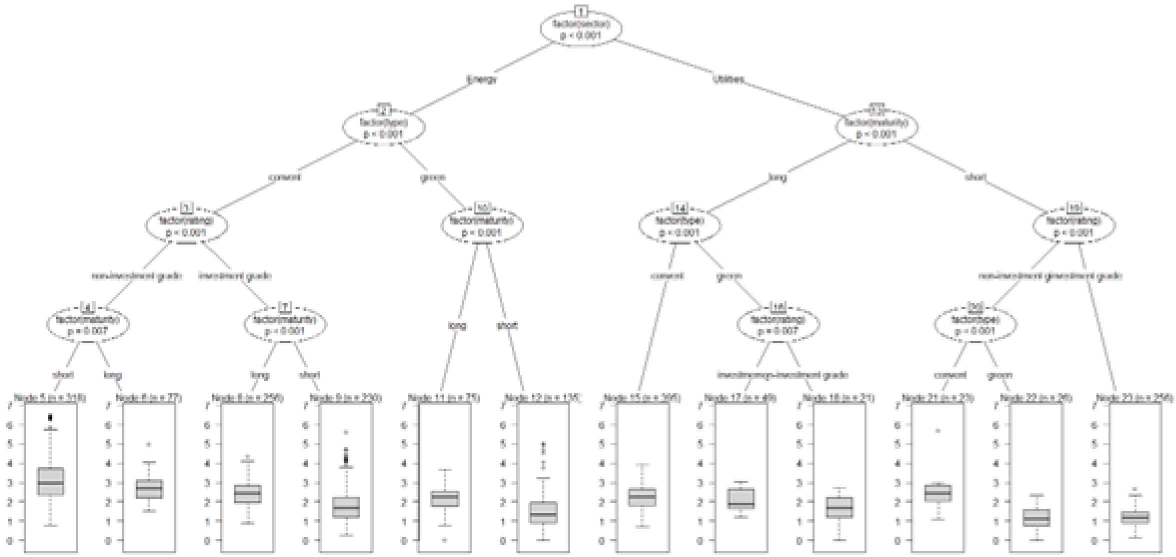

Figure 6: Analysis 3a - CART results, left branch (energy and utility sector)

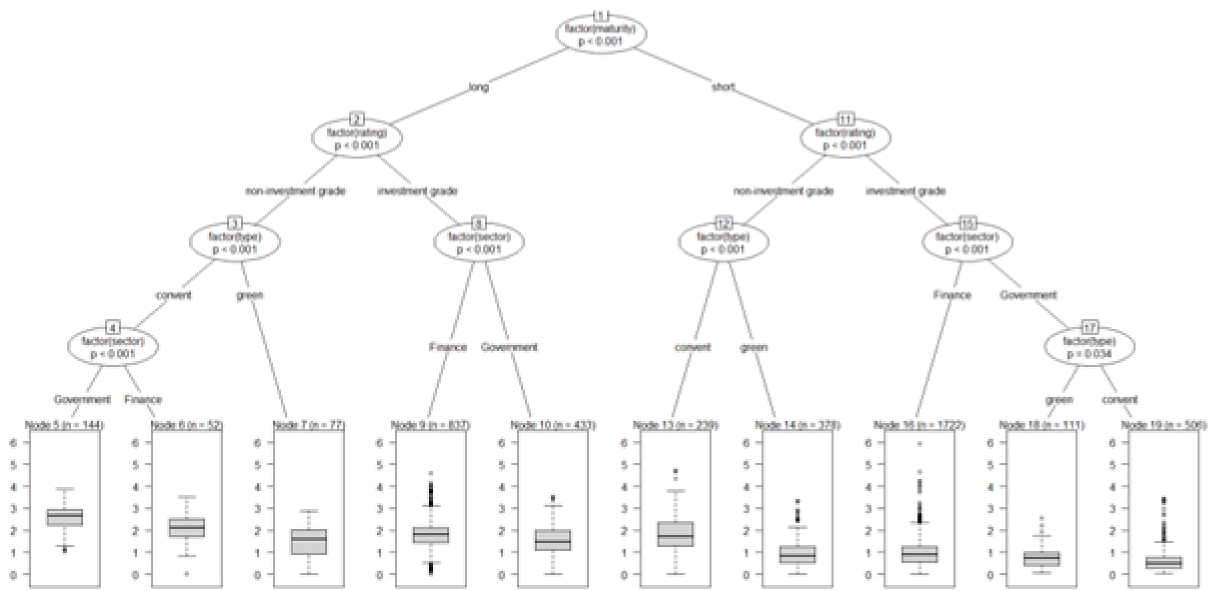

Figure 7: Analysis 3b - CART results, right branch (finance and government sector)

5.4 Energy sector analysis

In order to investigate differences between green and "brown" forms of investment we compare the bond performance of green and conventional bonds in the energy sector. Energy specific fixed income securities in Bloomberg are grouped into several subcategories but green bonds are mostly found under "Renewable Energy". All other energy subcategories are mostly fossil fuel related ("Pipeline", "Oil & Gas Services & Equipment", "Integrated Oils", "Exploration & Production", "Refining & Marketing", "Coal Operations"). For the energy specific analysis, we include all observations that are categorized under "Energy" in Bloomberg and add observations that are categorized as "Power generation". Since our sample does not include issuers who sold both types of bonds, in the green and "brown" energy universe, it is not possible to carry out a pairing analysis and control for issuer specific effects in the energy sector. Therefore, we run a non-matching analysis to compare the specificities of the energy sectors.

The regression setup is similar to sub-section 5.1 where the base model for the YTM regression includes nine different variables (X_1 bond type, X_2 volatility, X_3 liquidity, X_4 maturity, X_5 rating, X_6 coupon rate, X_7 amount issued, X_8 debts to asset, and X_9 date issued).[30] To further analyze the volatility specific effect we also add an interaction term that combines the bond greeness with its volatility measure ($X_{1,i} \cdot X_{2,i}$). The YTM rate is regressed on these explanatory variables, as defined by equation 15. The regression for the SRb is the same except for the volatility and the bond type x volatility explanatory variables.[31]

$$Y_i = \beta_0 + \sum_{k=1}^{9} \beta_k X_{k,i} + \beta_{10} X_{1,i} \cdot X_{2,i} + \epsilon_i \tag{15}$$

The regression results show that there is no clear evidence of a green premium for bonds in the energy sector. Table 8 shows no significant effects of the green dummy on yield to maturity rates. However, we do see that volatilities of green bonds are associated with lower yields (especially in the case of 260d volatilities as shown by models 1c and 2c, but also in the 90d case of model 1b). This suggests that the volatility risk premium for brown energy bonds is higher than for green energy bonds, or said differently, the volatility of brown bonds is associated with higher risk premia (higher yields) than in the case of green bonds. This is especially interesting, since Table 9 suggests weak evidence of higher Sharpe ratios for green bonds. It shows that in the general case (first three columns with no currency restriction, models 1a-3a) the bond specific Sharpe ratio (SRb) is higher by 27.2 bps for a green bond when the 30-day volatility is used for the SR calculation and by 9.8 bps in the 90-day volatility case; there is also a weak positive effect on the SR in the case of green bonds issued in USD in the 90 day case (see model 2b).

The evidence of higher SRb for green bonds is weak. However, it has to be noted that all significant green dummy effects are positive and that no negative effects of greenness on the SRb have been recorded.

[30] Since the subset of bonds for the energy sector offers less observations than our total sample we reduced the date issued control from a year-quarter combination to a yearly dummy.

[31] Our energy specific subset of data did not have enough observations to run regressions with the YAI rate.

Table 8: Analysis 4a - Energy sector regression: yield to maturity

	Dependent variable: Yield to maturity								
	(1a)	(1b)	(1c)	(2a)	(2b)	(2c)	(3a)	(3b)	(3c)
	30d	90d	260d	USD.30d	USD.90d	USD.260d	EUR.90d	EUR.90d	EUR.260d
Intercept	-3.011^{***}	-3.344^{***}	-3.513^{***}	-2.564^{***}	-2.807^{***}	-3.433^{***}	-4.222^{***}	-5.067^{***}	-3.982^{***}
	(0.221)	(0.288)	(0.279)	(0.258)	(0.292)	(0.355)	(0.970)	(1.271)	(0.746)
Green bond (dummy)	0.007	0.471	0.532	-0.163	0.210	0.666	0.843	1.928	0.789
	(0.328)	(0.428)	(0.429)	(0.443)	(0.404)	(0.558)	(0.721)	(1.324)	(0.432)
Volatility 30d	0.265^{***}			0.298^{***}			0.515		
	(0.018)			(0.020)			(0.283)		
Green x Volatility 30d	-0.091			-0.031			-0.355		
	(0.097)			(0.161)			(0.237)		
Volatility 90d		0.172^{***}			0.214^{***}			0.415	
		(0.019)			(0.022)			(0.283)	
Green x Volatility 90d		-0.169^{*}			-0.100			-0.570	
		(0.082)			(0.079)			(0.396)	
Volatility 260d			0.061^{***}			0.067^{***}			0.056
			(0.009)			(0.013)			(0.039)
Green x Volatility 260d			-0.110^{*}			-0.155^{***}			-0.062
			(0.049)			(0.039)			(0.067)
R^2	0.837	0.812	0.797	0.843	0.824	0.782	0.902	0.859	0.895
Adj. R^2	0.834	0.809	0.793	0.839	0.820	0.776	0.885	0.835	0.875
Num. obs.	653	640	534	485	503	386	77	76	70

Standard errors are heteroskedasticity robust. $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$

Note: The table shows regression results for Yield to maturity rates for Green and conventional energy bonds. The Green dummy is 1 if a bond is Green and 0 otherwise. Non-depicted regressors include Maturity (long term dummy), S&P Rating, Coupon rate, Amount issued in bnUSD, Debt to assets ratio, as well as Bid-ask spread and Yearly dummies for 2018 and 2019.

Table 9: Analysis 4b - Energy sector regression: Bond specific Sharpe ratio (SRb)

	Dependent variable: Bond specific Sharpe ratio (SRb)								
	(1a)	(1b)	(1c)	(2a)	(2b)	(2c)	(3a)	(3b)	(3c)
	30d	90d	260d	USD.30d	USD.90d	USD.260d	EUR.90d	EUR.90d	EUR.260d
Intercept	0.409^{***}	0.196^{***}	0.083^{*}	0.581^{***}	0.304^{***}	0.125^{***}	-1.165	-1.367^{**}	-0.555^{**}
	(0.117)	(0.057)	(0.036)	(0.099)	(0.041)	(0.037)	(0.739)	(0.417)	(0.185)
Green bond (dummy)	0.272^{*}	0.098^{*}	0.015	0.391	0.085^{*}	0.002	-0.119	-0.226	0.018
	(0.132)	(0.048)	(0.030)	(0.263)	(0.042)	(0.040)	(0.315)	(0.205)	(0.060)
R^2	0.250	0.253	0.252	0.312	0.385	0.285	0.612	0.569	0.648
Adj. R^2	0.239	0.243	0.239	0.299	0.374	0.268	0.558	0.507	0.593
Num. obs.	650	637	528	485	503	386	75	73	67

Standard errors are heteroskedasticity robust. $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$

Note: The table shows regression results for the Bond specific Sharpe ratio for Green and conventional energy bonds. The Green dummy is 1 if a bond is Green and 0 otherwise. Non-depicted regressors include Maturity (long term dummy), S&P Rating, Coupon rate, Amount issued in bnUSD, Debt to assets ratio, as well as Bid-ask spread and Yearly dummies for 2018 and 2019.

6 Conclusion

The model-driven results showed us that the fossil fuel based assets - in our case bonds - should, if the negative externalities are properly priced in, exhibit empirically low returns and possibly higher volatility. On the other hand, one would expect, for the green bonds, delivering positive externalities in the long-run, higher returns and lower volatility. The second type of assets should lead to superior asset and wealth accumulation as compared to the first type of assets. This should also lead -- as our dynamic portfolio model predicts -- to a change of portfolio holdings of the two types of assets.

Though we find heterogeneities for different currencies and sectors our empirical analysis concludes that green bonds show lower volatilities and achieve higher Sharpe ratios (in the paired as well as in the unpaired analysis) which reflects an improved wealth accumulating characteristic of green bonds. Especially the comparative performance of green vs non-green bonds in the energy sector shows the strongest differences with regards to volatilities and Sharpe ratios. Looking at the results of the regression analysis of paired bonds we also see significant and positive secondary market yield effects of green bonds. Yet, this effect is somehow ambiguous since unmatched yield to maturity rates show significant negative yield differentials of green bonds (the conclusion for primary market yields is due to a weaker data availability less clear).

There are certain reasons for the ambiguities and why there is still a gap between the model-driven results and the empirics in some instances: different preferences of market participants, only little information on the positive and negative externalities is integrated into the actual trading, the green bond market is still small and evolving market and a lot of learning is still going on.

Our empirical results, supported by previous findings of the literature, seem to show evidence of negative yield differential of green minus conventional bonds in the primary market, but positive yield differentials for a paired bond analysis in the case of the secondary market. Additionally our study shows that green bonds show a higher bond specific Sharpe ratio in several regression designs, which makes green bonds an interesting investment form. Especially due to lower volatilities, as identified with the CART and some cases in the regression analysis, green bonds can help to improve the portfolios of investors and help to achieve sustainable wealth accumulation. Also the energy sector specific analysis shows weak evidence of an improved Sharpe ratio of green bonds, which points towards better volatility discounted returns of green bonds compared to brown, i.e. fossil fuel based, bonds.

Generically, the higher potential of asset accumulation is shown by our model-driven results where certain preferences of individual bond holders (socially-oriented investors, ESG investors, and social impact investors) can allow the additional social returns to arise in the long run, however not necessarily showing up in the shorter run in the trading of assets, driven by short-termism and other forces. We can therefore have larger asset accumulation in the case of renewable energy assets, as compared to the case of fossil fuel energy, see the upper graph in Figure 2. On the other hand, there should be a (shadow) tax on fossil fuel energy which makes the return lower, see lower two graphs. This resembles earlier studies put forward in microeconomics as positive and negative externality effects which has been used in climate-oriented models by Acemoglu et al. (2012), but here now applied to bond prices and yields.[32]

We also want to note that here as in Semmler et al. (2020), by using the NMPC program, the returns for risky assets are made time dependent, but they can also be defined as impacted by stochastic shocks along their paths. Empirically estimated low frequency movements in returns are estimated and built into a dynamic portfolio model, see Chiarella et al. (2015, ch. 4). An outlook for a stochastic version of the model is also presented in Appendix B, but the results do not differ significantly from the deterministic version presented in Figure 2. One obtains, however, slightly different paths for the different realizations of the shock sequences.

Our approach can also be used to control sovereign debt as much as sovereign bonds are convertible into some equity. This is an important issue, since many observers express the criticism that issuing green bonds for climate protection will make the debt to GDP ratio rising leading to unsustainable debt. This does not need to occur if (shadow) tax rates are properly levied on returns from fossil fuel assets and aid to give incentives to create positive externalities of renewable energy. The use of convertible bonds, that turn into equity holdings when renewable energy firms are successful, aids to reduce debt of the sovereign issuer of bonds.

[32] Of course, as also Kapraun and Scheins (2019) argue, once the bonds are traded there might be a multiplicity of drivers of actual bond prices and yields, for example relevant are the actual activities in portfolio management, monetary policy and interest rates, varying risk premia, also for other assets, then the varying Distance to Default, and more.

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Appendix A - Fast fourier transform (FFT)

In Section 3, we use a Fast fourier transform (FFT) to estimate the green and fossil fuel returns applied to the dynamic portfolio model, as in Chiarella et al. (2016) and Semmler & Hsiao (2011). The FFT filters short-term shocks, estimating the coefficients of a sine-cosine function that represents the asset performance - see eq. A.1. In Section 3, it generates low-frequency movements using the monthly annual total returns for green and fossil fuel monthly returns from December/2015 to December/2020 for the US.

$$y(t) = \sum_{i=1}^{k}(a_i sin(\frac{2\pi}{\tau_i}(t-t_o)) + b_i cos(\frac{2\pi}{\tau_i}(t-t_o))) \tag{A.1}$$

As described by Semmler & Hsiao (2011), the first step to apply the FFT method is to de-trend the real returns for each index in the time series. We thus subtract a linear trend from the real returns:

$$Detrendedreturns = realreturns - (b_1(t-t_0) + b_2) \tag{A.2}$$

The linear trend coefficients ($b_1$and b_2) are obtained by a polynomial curve $p(x)$ of degree 1 that returns the best fit (in a least-square sense) for the real returns data. The values for t and $t_0$depend on the period covered by the time series. The FFT method picks up the periods with the highest power (τ_i). We obtain then the coefficients a_i and b_i for the harmonic fit for the different values of k and the τ_i for the different periods (in months), as in eq. A.1.

The harmonic regression model is estimated for different values of k, from 1 to 6, which represents different frequencies - from low to high frequency data. For our analysis, we select the estimation with the lower sum of squared errors (see estimations in Figure A.1). We select $k = 4$ for green bonds and $k = 1$ for fossil fuel bonds.

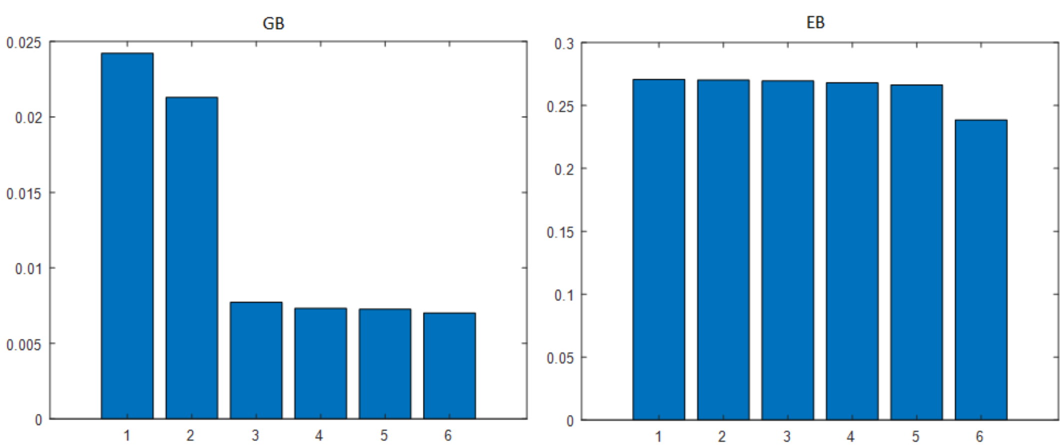

Figure A.1: Harmonic estimations: Sum of squared errors for green bonds (GB) and fossil fuel bonds (EB) in the US

Appendix B - Outlook for a Stochastic version of the portfolio model

In Sections 3 and 4, we solve the dynamic portoflio maximization problem using NMPC for a deterministic case only. There, a time varying mean, obtained by some harmonic estimations, are driving the returns. Nevertheless, actual external shocks and financial market risks also matter for the investment decision and the solution paths. Our empirical studies in Section 5 show that green bonds tend to be less volatile, which impacts the return-risk ratio (Sharpe ratio) and thus the attractiveness of green bonds vis-a-vis fossil fuel bonds. To address those risks, we introduce a stochastic version of the model using a NMPC algorithm for a stochastic case. This is done by using an adjusted version of the model presented in Section 3, including a new state equation - $x_3(t+1)$ - that generates shocks to the wealth dynamics - $x_1(t+1)$ - which allows us to simulate financial market risks. We get, however, similar results as for the deterministic case.

The pay-off function of portfolio decision in discrete time form, subject to constraints, looks like the following:

$$E(\max_{\{u_s, c_s, \pi_s\}} \sum_{t=0}^{N-1} \delta^{(s-t)} F(c_s W_s, u_s W_s)) \tag{B.1}$$

s.t.

$$\begin{aligned} x_1(t+1) = x_1(t) + (\pi_t r^{e^{\prime}}_{t_{green}} x_1(t)_t + (1-\pi_t) r^{e^{\prime}}_{t_{fossilfuel}} x_1(t) - (u_t + c_t) x_1(t) - X(\Pi_t, W_t)) \\ + (\psi + \delta log(x_3(t)) x_1(t)) \end{aligned} \tag{B.2}$$

$$x_2(t+1) = x_2(t) + 0.2 \tag{B.3}$$

$$x_3(t+1) = e^{\bar{\rho} log(x_3(t)) + \sigma z} \tag{B.4}$$

We rely on a new objective function with the discount factor δ and add a new state variable x_3, now representing the exogenous shocks given by z (an i.i.d. random variable), amplified by σ (the standard deviation) and depending on $\bar{\rho}$ (the persistent parameter for shocks). Those shocks impact the portfolio performance, impacting the dynamics of $x_1(t+1)$ through the term $(\psi + \delta log(x_3(t)) x_1(t))$.[33]

We solve this new model employing the parameters used for the simulations presented in Figure 2, considering a standard deviation (σ) equals to 0.05. For the case with $\alpha = 0.034$, the model behavior is similar to the case of the deterministic model (Figure B.1).

[33] The new parameters are set as follows: $\bar{\rho}$=0.9; $\psi = 0.01$; $\delta = 0.05$.

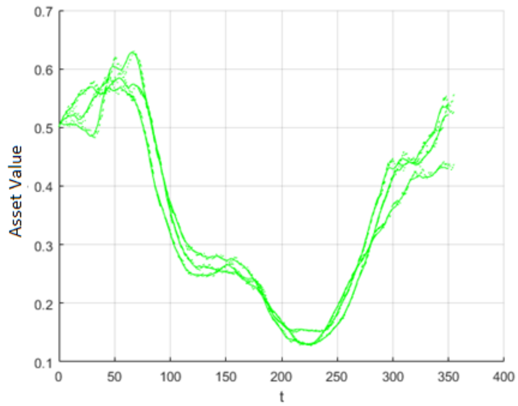

Figure B.1: Stochastic version of the model shown in Figure 2 ($\sigma = 0.05$; $\alpha = 0.034$)

However, the stochastic model is based on a discrete-time system and is solved with small steps which demands more iterations to reach a similar outcome. Nevertheless, the use of the deterministic case, as shown in Figure 2, is a good proxy for the market dynamics. In the stochastic case, there are additive market shocks which can generate multiple paths for the evolution of portfolio wealth. Yet, the overall direction of outcomes shows close similarity to the deterministic case showing now, however, different paths for the different realizations of shocks.