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Financing Climate Policies through Climate Bonds–A Three Stage Model and Empirics*

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Abstract

The funding of climate mitigation and adaptation policies has become an essential issue in climate negotiations. Emissions trading schemes (ETS) and carbon tax policies are widely discussed as viable mitigation strategies, the revenue from which might then be used for adaptation efforts. In most current models, the burden of enacting mitigation and adaptation policies falls on current generations. This paper expands on a recent article by Sachs (2014) that proposes intertemporal burden sharing, suggesting that implementation of climate policies would represent a Pareto improving strategy for both current and future generations. In particular, this paper proposes that green bonds (also referred to as climate bonds) represent an immediately implementable opportunity to initiate Sachs' plan; the issuance of green bonds could fund immediate investment in climate mitigation such that the debt might be repaid by the future generations, those who benefit most from reduced environmental damages. The Sachs model is a discrete time overlapping generations model which we generalize and turn into a continuous time version exhibiting three major stages. We solve this three phase model by using a new numerical procedure called NMPC that allows for finite horizon solutions and phase changes. We show that the issued bonds can be repaid and the debt is sustainable within a finite time horizon. We also study econometrically whether the current macroeconomic environment is conducive to successfully phasing in such climate bonds.

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1 Introduction

The implementation of climate change oriented policies raises challenging questions concerning the manner in which policies and infrastructure will be financed. If one starts with the current climate stabilization policies that utilize emissions trading, carbon tax, and other regulatory measures to phase out fossil fuel energy and phase in renewable energy, the essential issue is the cost of mitigation and adaptation efforts. Most of the current measures show up as a cost for the current generation. In this paper, we propose an intertemporal model that allows for burden sharing between current and future generations. Sachs (2014) suggests the use of long term bonds that reimburse the current generation's mitigation and adaptation costs, and that are repaid by future generations through taxation. This funding strategy can be, as Sachs (2014) shows, welfare improving.

The potential high cost of action for current generations is implicit in the typical Integrated Assessment Model, or IAM, (Nordhaus 2008), in tipping point models, as well as in more complex mitigation and adaptation models that are based on the IAM. Sachs (2014) proposes an innovative intertemporal financial approach that might help to guide the development of a new framework employing the IAM, as well as tipping point models, such as Greiner et al (2010), and the infrastructure models against climate risk, such as Klasen et al (2015) and Maurer and Semmler (2015).

Here, however, we propose a simple model, based on Sachs (2014), that uses a discrete time framework with overlapping generations. In the original two period model, the current generation undertakes climate change efforts financed through long maturity bonds. The current generation remains financially as well off as without mitigation while improving environmental well-being of future generations. In fact as Sachs shows, this intergenerational tax-and-transfer policy turns climate change mitigation and adaptation policies into a Pareto improving strategy for both generations.

The bonds proposed by Sachs (2014), and this paper, do not mature for a number of generations. While such long term investment is out of the ordinary, evidence in Aretzjkie et al. (2016) shows that possible funding is consistent with investment strategies of sovereign wealth funds, pensions funds, insurance companies, and mutual funds. Such institutions have nearly $100 trillion in combined assets under management.[1] Moreover, in the current low interest rate environment, sovereign wealth funds and central banks have accumulated large excess savings of approximately $15 trillion. This is to say that

[1] For more details of the available funds looking for investment, see Aretzjkie et al (2016)

there is an enormous amount of wealth, far surpassing the US nominal GDP (about $18 trillion in 2015), which represents potential investment in long term climate projects.

We thus set up a growth model with three stages where climate policies are funded through the issuance of green bonds, and where future generations repay the bonds while reaping the benefits of the enacted climate mitigation policies. Where Sachs (2014) proposes a discrete time model, we use here a continuous time model which embeds the stages of the Sachs overlapping generations model into a continuous time version. The integrated multiple stage climate model helps to analyze how public finance can help, through green bonds, to fund climate policies that phase out fossil fuel energy and phase in renewable energy.

We propose a model in three stages. The first stage represents business as usual (BAU), with damage to the environment a byproduct of the production process. In a second stage climate policies are carried out through private agents in a market economy, but those agents are reimbursed for their effort by the issuance of green bonds. Sovereign debt may rise as environmental and climate effects are reduced to a sustainable level. Finally, in the third stage, the future generation pays back the bonds through an income tax. The latter generation does not experience elevated climate damages and their welfare is improved. After this period, once the bonds are repaid and greenhouse gases (GHG) are stabilized at a low level, the income tax can be reduced.

To solve, calibrate, and test such a new model of climate change policies with stages and regimes in continuous time, and to show that such a debt augmented growth model stays within the bounds of a sustainable fiscal policy, the project employs a new method, nonlinear model predictive control (NMPC), that solves complex dynamic systems with different nonlinearities for a finite decision horizon. This algorithm helps solve those intertemporal models with finite horizon and with regime changes. The different stages over the long long horizon mode are linked, and give us piecewise solutions, where the next initial state uses the information from the previous stage. This gives us sufficient information of what might happen over the entire solution paths.

In order to make the model empirically applicable, we also examine how the terms of public financial instruments such as green bonds are determined. There are a wide variety of green bonds of different maturities issued by a variety of institutions, both public and private. Since we are discussing here bonds of long maturity, relevant literature comes from the discussion of stretching the maturities of public bonds that started with the controllability of public debt; see Cole and Kehoe (1998), Arellano, et. al. (2013), and

Bocola and Dovis (2015). Thus we will have to add a thorough exploration of the existing climate bonds, their maturity structure, their institutional issuers and backing, when we suggest to phase in the new green bonds corresponding with our model.

A major empirical concern will be determining the drivers of long term bonds when issued and traded in the financial markets. Public finance literature, see Arellano et al (2013), has pointed out several determinants for the issuing of long term bonds. The main macroeconomic drivers of long maturity bonds appear to be interest rates, inflation rates and output. Higher inflation rates, for example, seem to reduce the issuing of long term bonds significantly. High interest rates also give incentives to reduce the duration of bonds. Decreased output and income is also associated with reduced long maturity bonds issuance. In section 5, using econometric analysis of currently issued green bonds, we consider the various determinants of the maturity structures of bonds, in particularly the drivers of long term bond issuance. We establish that the current macroeconomic environment appears to be conducive to issue long maturity climate bonds.

The remainder of the paper is structured as follows. Section 2 elaborates on issuing and trading of existing climate bonds. Section 3 presents our three stage model. Section 4 presents the numerical results using NMPC solution procedure. Section 5 presents some econometric results. Section 6 concludes. The algorithm used here is briefly summarized in the appendix.

2 Climate Change and Climate Bonds

Since the green bonds suggested here have to be phased in to existing markets, we next present a short review of the issues involved in financing mitigation and adaption efforts using green bonds. Crucial issues include the current climate trends and impacts, the investment requirements, the maturity of bonds, and the structure and the issuers of such bonds. This will be the background information needed for the following sections.

2.1 Challenges of Climate Change

The rapid development and industrialization, subsequent to the industrial revolution of the late-18th-early-19th century, has given rise to enormous growth in population, income and consumption. Fossil fuel combustion and energy production has allowed for innovations in all sectors of the economy, transportation and services. The technological development in agriculture has allowed for persistent population growth. The confluence of technological development with population, output, and consumption growth has made the human footprint on Earth undeniable. The constraints of arable land and food supply seem to no longer apply, at least in several parts of the world. Of course, the side effect to most of these developments is the damages caused to the environment. Fossil fuel combustion, livestock management, and new technology in land use all contribute to greenhouse gas (GHG) accumulation and radiative forcing. Additionally, there are the effects of direct pollution and pollutant runoff on natural ecosystems.

Population has grown approximately sixfold over the last 150 years, greatly magnifying human impacts on the environment. In addition to population growth, income growth has lead to higher and higher levels of output and consumption. Increased purchasing power has contributed to a surge in GHG in nearly all CO2 intensive sectors - agricultural production, energy production, transportation, and so on. Not surprisingly, growth in GHG emissions have run alongside output and population growth.

According to the most recent IPCC report, average global temperatures have risen 0.85 degrees Celsius since 1880. IPCC (2015) suggests that the period 1983 –2012 was likely the warmest 20 year period in the last 1400 years. The trajectory of future global temperatures then is highly dependent on the extent to which greenhouse gas emissions can be significantly reduced in a timely manner. It is impossible to attribute any specific event to climate change, but its impact is confirmed in the local frequency of storms, as well as trends in sea level rise, coastal flooding, droughts, heat waves, and other weather extremes. Atmospheric temperature change is perhaps the most obvious effect of the changing climate, but additional impacts will likely include changes in global water cycles, deterioration of air quality, oceanic warming, shrinking of sea ice cover and deterioration of snow cover and glaciers, sea level rise (due to both thermal expansion and ice-sheet/glacial runoff), disruption to carbon cycles likely leading to increased ocean acidification, and disruption to overall climate stability.

The causes of climate change are numerous, but the anthropogenic effect cannot be overstated. The exponential growth in economic output and population growth subsequent to the Industrial Revolution of the eighteenth and ninetheenth centuries has led to a dependence on fossil fuels and other exhaustible resources. Greenhouse gas emissions are tied directly to energy generation, industrial production and services, transportation, food production, and other means of welfare improvements, and the reduction thereof must ultimately require the development of effective climate mitigation and adaptation policies, including the creation of alternative energy sources.

2.2 Investment needs

The investment needs are large but attainable. Mackenzie (2009) estimates that it is necessary to invest $10 trillion in green technologies by 2030 in order to achieve the 450 parts per million CO2 level that is thought to be "moderately safe". As mentioned in the introduction, the wealth that might be used to fund such projects does exist; It is a matter of incentivizing the proper investments. The World Bank (2015), for example, suggests tapping into the $80 trillion bond market in order to fund new "roads, airports, buildings, water systems and energy supplies" that can stand up to rising global temperatures and extreme weather patterns.

There remains much debate on the validity and possibility of abatement investment. There are varying estimates of the volume of green investment needed, but it is widely understood that current investment is well below suggested targets. According to Clapp (2014), meaningful mitigation requires roughly $100 billion in annual green investment in needed by 2020 in order to achieve an abatement path consistent with a moderate rise in average global temperatures. Bank of America-Merrill Lynch estimate the total investment by 2035 needs to be $53 trillion in order to ensure a carbon emissions trajectory consistent with 2 degree Celsius rise in temperatures. Beyond 2 degrees Celsius there estimated strong damaging impacts on the economies, eco-systems and human health.

One of the major issues stalling the implementation of green development is funding concerns. Currently, the United States and other developed economies are highly dependent on the use of fossil fuel energies. Not only is it costly to develop a new renewable energy sources, energy transportation grids, and infrastructure network, it requires either forgoing use of entrenched technologies and infrastructure. The current generation must give up its reliance on certain resources, but this can be partially funded by intertemporal fiscal policies. The cost of moving toward a green economy is comprised of both the direct accounting costs and the opportunity costs of forgoing lower-cost fossil-fuel based energies. There needs to be a significant government role in setting the standards, enforcing regulations, and facilitating and encouraging less carbon intensive activities. However, governments will not be able to shoulder the burden alone - in part due to the large investment required and in part due to the polarizing, back-and-forth nature of politics. There is also, then, a significant role for the participation of private parties and international organizations.

Sachs (2014) suggest that the financial burden of climate mitigation might be shared with future generations. Rather than the current generation financing the reallocation of resources, today's policymakers can generate funds for abatement and climate investment through the issuance of public debt that will be repaid through the taxation of future generations. In this way, necessary mitigation steps can be taken immediately without greatly sacrificing the well-being of today's generation. While it is a fairly new instrument, the Green Bond is proving to be a quite useful tool in the green investment strategy: according recent articles in Financial Times (2016) and Moody's (2015), green bond investment in 2015 has already exceeded $40 billion and is expected to continue on an upward trajectory as investors continue to put their wealth into environmentally sustainable projects.

2.3 Maturity Structure of Climate Bonds

A green bond works like any other bond; the primary difference is that it is necessarily funds objectives related to encouraging environmental sustainability. Bonds are often issued for infrastructure projects when raising large investment is necessary. This is particularly reasonable during periods excessive savings. A bond issuer sells the bond to an investor, with an agreement that the bond issuer will repay the principal debt plus a premium at a predetermined maturity date. Repayment might occur all at once, as is the case with bullet bond plans, or might take the form of regularly scheduled payments. An example of bond as intertemporal finance tool is the currently-under-construction Tappan Zee Bridge in New York. The construction of the bridge represents an infrastructure project funded in part through bond issuance. With an expected construction cost of $3.9 billion, much of the investment will come from bond sales which will ultimately be repaid through tolls levied when the bridge is open for use. This spreads the cost of the project over time - future generations, who benefit from the use of the new and improved Tappan Zee Bridge ultimately help to fund the project as their tolls are used to repay the debt.[2]

The time horizon of green bonds should presumably be much longer than those of traditional, or non-climate-related, bonds. It does not seem to be sufficient to delay the

[2]For more details on the Tappan Zee Bridge project see Klaske and Kopott (2013) and New York State Thruway Authority (2013).

repayment of bonds 5 -10 years, as the climate benefits of investment will not be realized in such a short time period. The maturity structure of climate bond should be longer, as instruments, particularly if the financial return is not always comparable with investment alternatives. Recall the Sachs proposal: to institute immediate mitigation effort that can be, at least partially, funded by the people that will enjoy the less-damaged climate system in the future.To that end, the phasing in of long maturity bonds into the current bond market is a major issue and will be studied more specifically in section 5.

2.4 Types of Green Bonds

The defining characteristic of a green bonds is its stated focus on improving environmental and climate outcomes. As going 'green' offers some marketing cache, it is necessary to establish guidelines delineating green practices and green targets. That is, in order to identify and utilize those bonds that truly have an environmental impact, and are not just cashing in on the green movement, it is necessary to vet the particular projects and proposals funded. Ceres (2014) has composed a set of green bond principles that suggest a set of practices for various stages of green bond lifespan including: the use of proceeds, the process for project selection, the management of proceeds, and project reporting. Suggested green projects include those likely to make significant impact on climate outcomes: renewable energy, energy efficiency (including energy-efficient buildings), sustainable water management, sustainable land use, biodiversity conservation, clean transportation, and clean water and protection of coastal or other areas from flooding and destruction. Besides determining the optimal projects, bond issuers should strive for transparency in meeting the stated environmental and climate outcomes. To this end, Ceres recommends the use of performance indicators that would measure the impact of a particular investment - measured in terms such as GHG reduction reduced vehicle miles travelled.

Kaminker and Stewart (2012) describe three categories of green bonds: government-backed bonds, asset-backed bonds, and covered bonds. Government backing generally takes the form of a municipal government investing in a renewable energy projects. Asset-backed securities are similar to traditional bonds, but their debt repayment is financed by a particular revenue stream, such as highway/bridge tolls or a surcharge on home energy use. Covered bonds are a type of asset-backed security that are also guaranteed by the issuing agency. The repayment mechanism of green bonds, then, depends to some extent on which of these categories the bond falls into. Whether there are different drivers of the maturity structure of the different types of bonds will be discussed further in section 5.

2.5 Issuers of Green Bonds

Agencies issuing green bonds fall into three general categories: private business, governments and municipalities, and multinational institutions. While each institution's goal is raising funds for green investment, the particular bond characteristics tend to vary by type of issuer. For instance, generally speaking municipal green bonds have longer time horizons than bonds issued by private business. Table 6 provides examples of some of the properties that characterize the three issuer categories.

Since the first Green Bond was issued by the World Bank in 2007, numerous institutions both public and private have come to recognize the revenue-raising opportunity embodied therein which can substantially help to fund climate policies. The World Bank has played a lead role in the development and utilization of green bonds over the last several years. In addition, numerous municipalities in developed and developing countries have turned to green bonds as a means of raising funds. Some banks and other financial institutions have also taken note, and have come to include green bonds as part of their offerings. As concerning the issuers of bonds, we will also discuss in section 5 the factors driving the maturity structure of bonds as placed by the different issuers of bonds.

3 A Three Stage Continuous Time Model

As discussed above, the use of fossil fuel energy results in large levels of greenhouse gas emissions. The long-term well-being of the economy, the eco-system and the planet requires immediate investment in climate mitigation measures. The needed investment is large but there is the potential to tap into currently unused financial resources. The current saving glut can make funds available. Yet, there is a lack of urgency in implementation since current policy making generations will be long gone by the time the harsher effects of climate change are felt. Moreover, increase of taxes, cap-and-trade, and fees and regulations are often seen too costly and not easily implementable.

Sachs (2014) suggests a solution to this conundrum in the form of intergenerational burden sharing. A green bond issued today and paid back at some future time period represents an opportunity to assign some of the cost of mitigation to those generations that will benefit most from its implementation. Rewriting the Sachs discrete time overlapping generations model in continuous time lets us study three distinct stages: (1) a business-as-usual (BAU) baseline model, (2) a model characterized by GHG mitigation funded by increasing public debt (i.e., the issuance of green bonds), and (3) a model of debt repayment coincident with low level GHG emissions and damages.

The solution procedure we suggest which is called NMPC (nonlinear model predictive control), see appendix and Gruene et al (2016), allows to solve models with finite time decision horizons, avoids the information requirements infinite horizon models require, can allow for limited information agents, and permits changes of stages and regimes in model variants.

3.1 Business As Usual

The baseline model consists of consumption smoothing households, as in standard models, choosing consumption in order to maximize utility over a continuous time horizon, subject to its budget constraint. Yet, the time horizon is finite. The budget constraint for the BAU model is characterized by the state equations for the growth of capital, K, and the accumulation of greenhouse gases, M. A logarithmic utility function is sufficient for our case assumed.[3] Future values are discounted at rate ρ.

$$Max_C \int_{t=0}^{N} e^{-\rho t} ln(C) dt$$

subject to

$$\dot{K} = D \cdot Y - C - (\delta + n)K$$

and

$$\dot{M} = \beta E - \mu M$$

where $K(0) = K_0$, and $M(0) = M_0$. Further information on parameters is summarized in table 1.

This stage represents a sort of laissez-faire approach to the climate issue. There is no mitigation effort, nor any other attempt to remedy the damages of climate change. Production is assumed to take the form of

$$Y = K^{\alpha}$$

with $\alpha \in (0, 1)$.

[3]The subsequent model variant is similar to Greiner et al (2010)

Following Greiner et al (2010) emissions are given by the function

$$E = (\frac{aK}{5A + A_0})^{\gamma}$$

where A_0 represent some exogenous mitigation that exists even in the absence of any conscious action towards mitigation, A represents abatement/mitigation efforts,K represents the level of capital, and γ represents an emissions growth rate. In the BAU stage, there is no abatement/mitigation effort, thus $A = 0$, and the equation simplifies to

$$E = (\frac{aK}{A_0})^{\gamma}$$

There is damaging effect of the stock of GHG emission on production. Greenhouse gas accumulation results in a damage function, $D(\cdot)$, to adversely affect output, Y. We assume a damage function, often used in integrated assessment models,

$$D(\cdot) = (a_1 \cdot M^2 + 1)^{-\psi}$$

with $a_1 > 0$, $\psi > 0$.

3.2 Greenhouse Gas Mitigation Stage - Building the Green Economy

In the second stage of the model, greenhouse gas mitigation is funded through the sales of green bonds. The basic characteristics of the model remain the same, however, the cost of abatement is factored into both the capital state equation and the emissions function, and a state equation is introduced to account for the accumulation of public debt. A representative household chooses consumption in order to maximize utility over a continuous time horizon

$$Max_C \int_{t=0}^{N} e^{-\rho t} ln(C) dt$$

subject to

$$\dot{K} = D \cdot Y - C - A - (\delta + n)K$$

$$\dot{M} = \beta E - \mu M$$

and

$$\dot{B} = r \cdot B + A$$

where the accumulation of public debt is a function of the cost of the abatement efforts, A, the interest rate, r, and the initial public debt, $B(0)$. A can also imply the cost of efficiency loss from replacing traditional energy sources by green energy. In this stage of the model, climate bonds are issued until time T, at which point greenhouse gas mitigation has brought down the GHG level to a lower equilibrium point (compared to the first model) as a result of abatement efforts and effectively reduced climate impacts on production.

Since the dynamics of demand for green bonds and their yield are not part of the model at this stage, we assume the allocated budget to the abatement effort, which is funded by green bonds, to be fixed at the given interest rate and let the process continue until we reach the equilibrium point of both capital stock and GHG level before switching to the next phase.

3.3 Debt Repayment Stage - Paying for the Green Economy

The third and final stage of the model consists of the repayment of green bonds using the extra output gained from higher capital stock accumulated as a result of lower GHG levels, and the existence of a green economy by continuing the abatement efforts. In the absence of notable damage from GHG, the output is reduced only by the taxation required to pay down the public debt and keep the abatement efforts in place.

$$Max_C \int_{t=0}^{N} e^{-\rho t} ln(C) dt$$

subject to

$$\dot{K} = Y(1-\tau) - C - (\delta + n)K$$

and

$$\dot{B} = r \cdot B - \tau Y$$

where τY is an income tax rate to repay the accumulated debt.

4 Numerical Solutions

To get a rough idea about the dynamics of the three models, we run a numerical simulation using NMPC. Instead of computing the optimal value function for all possible initial states, NMPC only computes single (approximate) optimal trajectories by solving the optimization with a finite horizon and using the initial steps of the solution as an approximation of the infinite horizon case.

Parameter	Definition	Stage 1	Stage 2	Stage 3
n	population growth rate	0.02	0.02	0.02
α	output elasticity of capital	0.18	0.18	0.18
β	share of emission added to ghg	0.49	0.49	0.49
γ	capital elasticity of emission	1	1	1
δ	depreciation rate	0.075	0.075	0.075
μ	constant decay rate	0.1	0.1	0.1
ρ	discount rate	0.03	0.03	0.03
ψ	exponential damage factor	1	1	1
A	abatement effort	0	0.01	0.01
A_0	constant abatement parameter	0.0012	0.0012	0.0012
a_1	quadratic damage parameter	0.5	0.5	0.5
a	ghg emission scaling factor	0.00035	0.00035	0.00035
r	interest rate	0	0.03	0.03
K_0	initial capital stock	0.5	0.5	0.62
M_0	initial ghg level	0.5	0.5	0.03
B_0	initial debt	0	0	0.97

Table 1: Simulation Parameters and Initial Values

The initial values and part of model parameters at each stage are presented in Table 1.We run the simulation for each models separately while feeding the outcomes of the second model to the initial values of the third. The second and the third models are only separated for illustration purposes and one can easily integrate them to one model with changing the tax rate after GHG level reaches equilibrium.

4.1 First Stage - Business As Usual

We picked the initial values of both capital stock and GHG level below their equilibrium values to let the system grow initially. However, as a result of GHG accumulation, the final equilibrium value for capital stock is below the initial value of 0.5. This decline in the equilibrium value of capital stock (and therefore output and consumption) is what justifies abatement efforts and taxing future generations for abatement efforts previously undertaken. The simulation results of this stage are shown in figure 1.

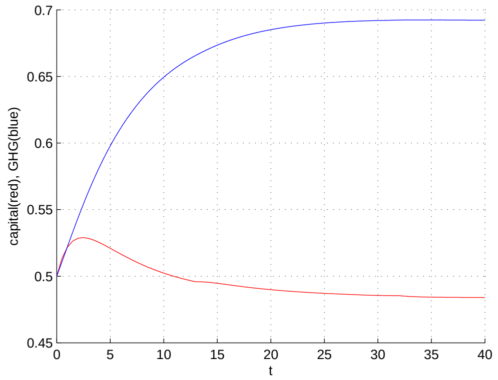

Figure 1: Stage 1 Simulation

4.2 Second Stage - Climate Policy

If, instead of allowing the GHG level to elevate, the government sells climate bonds to finance abatement effort, or to reimburse private agents for their abatement effort, we expect lower GHG levels and, as a result, larger capital stock and output. For a large enough A (1% in this simulation), the equilibrium level of GHG will be low enough to reduce the damage to an insignificant amount. As it is shown in figure 2, the second stage stops and the third stage is initiated when the changes in both GHG level and capital stock become smaller than $\epsilon = 0.001$. Notice that the main objective of this stage is reducing the GHG level, and therefore we do not need to optimize the length of the period or when to switch to the third phase.

4.3 Third Stage - Debt Repayment

In the third stage, we use the tax rate (τ) on the output to cover both abatement efforts and debt repayment. Figure 3 shows the simulation results of the third stage. The slight disturbance at the final stage of debt repayment is a result of non-linear solver trying to deal with the sudden change in the tax rate from 5% to A/Y when the debt is fully repaid.

As can be observed through the abatement effort in the second stage the GHG can be significantly reduced to a low stationary, and effectively harmless, level. Through bond

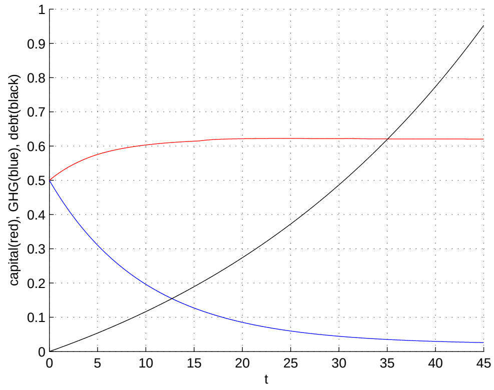

Figure 2: Stage 2 Simulation

issuance, debt is built up in the second stage, but repaid through the income tax imposed in the third stage. Subsequently, debt is reduced and and steered down so that economy reaches a low or zero level of debt. Throughout stages 2 and 3, the equilibrium capital stock is remains at levels above the BAU alternative. Seeing that it is theoretically possible to finance climate stabilization through green bonds, attention must then be paid to the feasibility of phasing in such financial instruments.

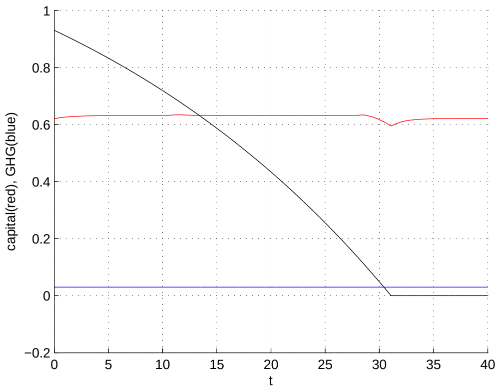

Figure 3: Stage 3 Simulation

5 Empirics– Phasing in Climate Bonds

From our previous analysis it follows that the bonds discussed above should be long maturity bonds. Thus, one must look at how long maturity bonds be phased in given the current financial market and macroeconomic environment. Understanding the conditions conducive to the issuance of long term bonds are critical in order best to suggest further green bond policy in today's market.[4] These drivers will be studied next through an econometric approach.

5.1 Panel Data Analysis

In order to look at the performance of green bonds and variables determining the issuing long term bonds, we construct a robust empirical model. We look at the green bonds issued by different institutions with different maturities as presented in Table 6 in the Appendix. The empirical specification for the different issuer of the green bonds is given by the following form:

$$\begin{aligned} y_{it} =& \alpha + \beta_{1t}(Tbr_{i,t}) + \beta_{2t}(infl_{i,t}) + \\ &+ \beta_{3t}(VIX_{i,t}) + \beta_{4t}(dolval_{i,t}) + \beta_{5t}(IPI_{i,t}) + \\ &+ dum_{it} + \varepsilon_{i,t} \end{aligned} \tag{1}$$

where the dependent variable is the bond price for individual green bonds, i and t refers to the type of the issuer and the time indexes. The error term is i.i.d and represented by ϵ_{it}. The model includes key determinants for bond prices: variables that represent risk, 3 month Treasury Bill rate (Tbr), inflation (CPI) ($infl$), Chicago Board Exchange Market Volatility Index (VIX), long US dollar futures index ($dolval$) and a measure of macroeconomic stability, such as industrial production index (IPI), with corresponding coefficient vectors: $\beta_{1i}, \beta_{2i}, \beta_{3i,}\beta_{4i}, \beta_{5i}$.

As a proxy for the short term interest rate is taken the 3 month Treasury Bill rate. Given such a short period of time, the federal funds rate hike by 0.25 bp in December 2015 produced a big spike in the short term interest rate as well. A rise in the interest rate according to the theory would drive the price of bonds down and also could signal the more riskier environment. Thus, a preference for short bonds would prevail.[5] Another variable that determines risk is the VIX and the dollar value. As a proxy for the dollar value, the Powershares Deutsche Bank US Dollar Bullish ETF (UUP) is taken. It represents the movement of the dollar appreciation and is often used as a good indicator.

[4]Our econometric study is inspired by Cole and Kehoe (1998), Arellano et al (2013,) and Bocola and Dovis (2015), who however only present stylized facts on drievers of long term bonds.

[5]See also Bocola and Dovis (2015).

The inflation rate (CPI) is expected also to be one of the key drivers for the maturities of climate bonds. According to the literature (Arellano et al, 2014) there is a negative relationship between the long term bonds and the inflation rates. Also, as the proxy for the macroeconomic stability and growth we include the Industrial Production Index. The important aspect of the regression is not causality per se, but the relationship among the explanatory variables and the price of the climate bonds. Therefore, the sign and the level of significance of each coefficient will be an important factors. As shown in equation 1 the dummy variable represents the long term maturity bonds (it takes the value of one for 5 year and greater maturity bonds). According to the goal of our study, such dummy plays an important role, helping us get information on long duration bonds.

Panel study tests are carried out for random-effect model following log transformation for several variables, as specified below. Next, we discuss the underlying data and summarize key empirical results. Our panel data is monthly, covering the period from October 2013 and January 2016, determined by data availability. The included data is unbalanced because for some explanatory variables the data for the month of January 2016 is still not available.

All the analyzed bonds in the empirical part are classified by the Bloomberg database as being green bonds. Also, we concentrated our research on only active bonds (that have not matured by February 2016) and all the bonds are denominated in USD. Time series on the price for those bonds is also obtained from the Bloomberg database. Monthly data on VIX, CPI index and 3 month Treasury Bill Rate is obtained from the US Federal Reserve Bank database. Industrial Production index was obtained from the OECD database. Finally, dollar value is gathered from the Yahoo Finance source.

Descriptive statistics for all variables used in the regressions are presented in Table 5.1.

5.2 Empirical Results

Overall, using pooled panel data has several advantages compared to conventional times-series analysis or cross-sectional data. This method allows us to look at the simultaneous effect on the bond price issued by different groups of institutions as well as different maturity bonds. However, if there is nonstationarity in the regression, it may result in an invalidated standard t-statistic. Thus, it is necessary to conduct a unit root test before estimating the regressions. Since our data set is unbalanced panel data, we use Im-Pesaran-Shin (IPS) and Fisher unit-root tests. The null hypothesis for both tests is the

Variable	Obs.	Abbrv.	Mean	Std. Dev.	Min.	Max
Government Agencies	72	govt.agency	101.07	1.93	99.16	107.89
Private Sector	72	private	100.15	1.11	98.71	105.37
Supranationals	116	supra	97.58	3.27	86.28	100.415
Interest Rate	116	interest	0.053	0.058	0.02	0.26
Inflation	108	inflation	0.64	0.23	-0.7	0.44
VIX	112	VIX	15.58	3.07	11.54	24.38
Dollar Value	116	dollar	23.65	1.79	21.26	26.08
Industrial Production	108	industrial	0.11	0.42	-0.9	0.9

Table 2: Summary Descriptive Statistics

Test	govt.agency	private	supra	interest	inflation	VIX	dollar	industrial
Im-Pesaran-Shin	0.0000	0.0078	0.0378	0.9695	0.0029	0.0324	0.0001	0.01
Fisher Type	0.0800	0.3575	0.0087	0.9577	0.0243	0.3594	0.4736	0.1499

Table 3: Panel Unit Root Tests

Note: First difference transformation helps exclude unit roots, result in stationary series, for all variables (not reported for brevity).

existence of the unit root, and an alternative hypothesis is that some panels are stationary (IPS) and at least one panel is stationary (Fisher). Table 5.2 presents the the p-values for both tests. Taking the first difference on data levels or log difference transformations helps correct for unit roots and ensure data stationarity. As such, the rest of the paper works with first difference and log first difference variables jointly. We also applied Hausman test to our model, which showed that should use the random-effects model.

Table 4 shows the estimation results for all of our regressions. The independent variable is the price of climate bonds grouped by the issuer type with corresponds to the Table 6 in the Appendix and also bonds divided based on their maturity. Model 1 shows the effect of explanatory variables on the time series of the price of four green bonds which are issued by government agencies. Model 2, accordingly, shows the relationship for the four green bonds issued by the private institutions. Model 3 shows results for the bonds issued by the supranational organizations. To provide a complete picture, we also estimate the same regression model for the climate bonds based on different maturities (irrelevant of the issuer now). For that we divided our sample of 12 bonds on two groups. First group (Model 4) would represent bonds that have 5 year or higher maturity and the second group (Model 5) would be represented by the green bonds with less than 5 year maturity.

	(1)	(2)	(3)	(4)	(5)
Interest	-0.0023**	-0.0021***	-0.0048	-0.0029***	-0.0007***
	(0.0014)	(0.0006)	(0.0047)	(0.0007)	(0.0001)
VIX	0.0056***	0.0014	0.0071**	0.0111***	-0.0001*
	(0.0025)	(0.0059)	(0.0044)	(0.0037)	(0.0001)
Inflation	-0.0049*	-0.0082**	-0.0021***	-0.0176***	-0.0027**
	(0.0070)	(0.0045)	(0.0009)	(0.0050)	(0.0013)
Dollar	0.0692	0.1712**	0.1124*	0.2286***	0.0087***
	(0.0813)	(0.0989)	(0.0869)	(0.0678)	(0.00265)
Industrial	0.0008	-0.0006	0.0050*	0.0032*	-0.0007
	(0.0023)	(0.0021)	(0.0036)	(0.0023)	(0.0001)
Dummy	0.0012***	-0.0003***	0.0023***		
	(0.0001)	(0.0001)	(0.0007)		
Constant	-0.0009	-0.0011	-0.0051**	-0.0008	0.0009
	(0.0008)	(0.0007)	(0.0024)	(0.0006)	(0.0013)
Observations	60	60	64	90	102

Table 4: Panel Study Results: Group Issuer

Note; Robust standard errors are in brackets. ***,**,* Indicate 1%, 5% and 10% significance levels, respectively

The results can be summarized as follows. Increasing interest rates have a negative effect on the green bonds issued by the different government agencies and private companies, and the negative effect is even stronger for long bonds. The inflation variable also has a negative sign for all three groups but more significant for the bonds issued by the supranational institutions in Models (1)-(3). Similar sign and significance for interest rate and inflation seen for both short and long term maturity bonds in Models (4) and (5). This corresponds with the existing literature findings, where an increase in inflation and interest rates have a negative effect on the longer term maturity bonds.[6]

Since all the researched bonds are denominated in the USD, then value of the dollar and its appreciation has a positive significance on the green bonds issued by the private sector

[6]See Arellano et al. (2014) and Bocola and Dovis (2015).

and supranationals and bonds with different maturities. Indicator of the risk and distress in the environment can be observed by the change in the VIX values. From Table 4 we can see that VIX is highly significant for green bonds issued by the government agencies (1) and supranational institutions (3), whereas insignificant for the private sector (2). Such result may be due to the rising risk, entailing that investors tend to buy low risk assets such as government/supranational green bonds. Also, as the environment becomes more risky and volatile, investors tend to purchase long term green bonds (4) and selling short term ones (5). Such scenario is somewhat contradictory to the common view that with more volatility the short term bonds appreciate faster. The potential explanation for such finding is similar as for Models (1) and (3). Long term bonds are usually represented by the government institutions or supranational organizations. Thus, even though being long term they still have a low risk on defaults.

According to the dummy variable, green bonds issued by the governmental agencies and supranational institutions with the long term maturities rise in the price faster (by $0.0012 and $0.0023, accordingly) than short term green bonds issued by those institutions. On the other hand, bonds with long term maturities issued by the private sector depreciate by $0.0003 faster comparing to the bonds with short-term maturities issued by the companies. By representing the long term bonds, the dummy variable results are minimal in the dollar amount but are still statistically significance and show the opposing signs between public and private sectors. Such results are important for our analysis.

Overall, Table 4 presents the results for the climate bonds that are consistent with the literature on conventional bonds. The scenario is not unique for the bond market analysis. However, application of the traditional factors that have an effect on the performance of the long term and short term maturity green bonds have not been done in the literature before. So this empirical section is a reconfirmation of the basic qualities of the climate bonds with their special characteristics which are that with low inflation rates and low interest rates, as well as with increasing instability, investors are still willing to purchase the long term bonds. Thus these factors, which currently dominate macroeconomic trends are quite conducive to phase in climate bonds.

6 Conclusions

We follow here a sketch of a model that Sachs (2014) has proposed on funding the cost of climate change. Though Sachs uses a discrete time framework with overlapping generations, we turn his model into a continuous time model where current climate policies are financed through long maturity bonds. We show that the current generation remains financially as well off as without mitigation while improving environmental well-being of future generations. The intergenerational tax-and-transfer policy turns climate change mitigation and adaptation policies into a Pareto improving strategy for both generations. Since the costly burdens borne by the current generation is implicit in most current work on the macroeconomics of climate change, the proposed Sachs model proves truly innovative in its use of intertemporal burden-sharing, the insights of which might help to guide the development of new frameworks beyond the IAM. More complex models would need to include the financing aspects of climate policies. As we also show the current macroeconomic environment of low interest rates, low inflation rates, high short term volatility and strong value of the dollar seems to be conducive to phasing more long-term green bonds into the financial markets.

Appendices

1. Nonlinear Model Predictive Control (NMPC)

For the numerical solution of the optimal control problem we do not apply here the dynamic programming (DP). Though the DP method has the advantage that a global solution to the optimal control problem can be found, by first computing an approximation to the optimal value V and then the optimal control, and its time path, is computed from V. The main disadvantage of DP, however, is that its numerical effort typically grows exponentially with the dimension of the state variable. Hence, even for moderate state dimensions it may be impossible to compute a solution with reasonable accuracy.[7] A remedy to this problem can be obtained by using nonlinear model predictive control (NMPC).[8] Instead of computing the optimal value function for all possible initial states, NMPC only computes single (approximate) optimal trajectories. In order to describe the method, let us abstractly write the optimal decision problem as

$$\text{maximize} \quad \int_0^\infty e^{-\rho t}\ell(x(t), u(t))dt,$$

[7]Another algorithm that solve dynamic decision problems with infinite horizon is DYNARE

[8]For a details, see Gruene et al. (2015).

where $x(t)$ satisfies $\dot{x}(t) = f(x(t), u(t))$, $x(0) = x_0$ and the maximization takes place over a set of admissible control functions. By discretizing this problem in time, we obtain an approximate discrete time problem of the form

$$\text{maximize} \quad \sum_{i=0}^{\infty} \beta^i \ell(x_i, u_i), \tag{2}$$

where the maximization is now performed over a sequence u_i of control values and the sequence x_i satisfies $x_{i+1} = \Phi(h, x_i, u_i)$, Here $h > 0$ is the discretization time step, $\beta = e^{-\rho h}$ and Φ is a numerical scheme approximating the solution of $\dot{x}(t) = f(x(t), u(t))$ on the time interval $[ih, (i+1)h]$. For details and references in which the error of this discretization is analyzed we refer to Gruene et al (2015).

The idea of NMPC now lies in replacing the maximization of the infinite horizon functional (1) by the iterative maximization of finite horizon functionals

$$\text{maximize} \quad \sum_{k=0}^{N} \beta^i \ell(x_{k,i}, u_{k,i}), \tag{3}$$

for a truncated finite horizon $N \in \mathbb{N}$ with $x_{k+1,i} = \Phi(h, x_{k,i}, u_{k,i})$ and the index i indicates the number of the iteration, cf. the algorithm below. Note that neither β nor ℓ nor Φ changes when passing from (9) to (10), only the optimization horizon is truncated.

Problems of type (10) can be efficiently solved numerically by converting them into a static nonlinear program and solving them by efficient NLP solvers, see Gruene et al (2015). In our simulations, we have used a discounted variant of the MATLAB routine `nmpc.m` available from `www.nmpc-book.com`, which uses MATLAB's `fmincon` NLP solver in order to solve the resulting static optimization problem.

Given an initial value x_0, an approximate solution of (9) can now be obtained by iteratively solving

(2) as follows:

(1) for i=1,2,3,...
(2) solve (2) with initial value $x_{0,i} := x_i$ and denote the resulting optimal control sequence by $u^*_{k,i}$
(3) set $u_i := u^*_{0,i}$ and $x_{i+1} := \Phi(h, x_i, u_i)$
(4) end of for-loop

This algorithm yields an infinite trajectory x_i, $i = 1, 2, 3, \ldots$ whose control sequence u_i

consists of all the first elements $u^*_{0,i}$ of the optimal control sequences for the finite horizon subproblems (10).

Under appropriate assumptions on the problem, it can be shown that the solution (x_i, u_i) (which depends on the choice of N in (2) converges to the optimal solution of (9) as $N \to \infty$. The main requirement in these assumptions is the existence of an optimal equilibrium for the infinite horizon problem (9). If this equilibrium is known, it can be used as an additional constraint in (10), in order to improve the convergence properties, see Gruene et al. (2015).

However, recent results have shown that without a priory knowledge of this equilibrium this convergence can also be ensured, see Gruene et al. (2015), and this is the approach we use in the computations in this paper. It should be noted that the original work on the NMPC, see Gruene and Pannek (2011), treats averaged instead of discounted infinite horizon problems. However, Gruene et al (2015) show that the main proofs carry over to the discounted case. In any case, the solution generated by NMPC will always provide a lower bound for the true optimal solution. Note that this procedure also allows for irregular impacts on the dynamics of the state variables as well as regime switches.[9]

[9]Note that in DSGE models regime switches are also perceived as something likely to occur which some literature starts to explore now.

2. Summary Table of Issuers and Bond Types

	Issue Date	Maturity Date	Maturity Period	Coupon Rate	Par Amount	Amount	Issue Price	YTM
Government Agency								
Kommunalbanken AS	11/21/13	11/21/16	3	0.75	2000	500,000.00 (M)	99.73	0.843
Export-Import Bank of Korea	2/27/13	2/27/18	5	1.75	1000	500,000.00 (M)	99.67	1.819
Export Development Canada	1/30/14	1/30/17	3	0.88	5000	300,000.00 (M)	99.97	0.884
Overseas Private Investment Corp.	9/24/14	9/15/29	15	3.28	1000	47,300.00 (M)	100.00	3.280
Private Sector								
Bank of America	11/21/13	11/21/16	3	1.35	1000	500,000.00 (M)	99.97	1.359
Regency Centers LP	5/16/14	6/15/24	10	3.75	1000	250,000.00 (M)	99.48	3.812
Vornado Realty LP	6/16/14	6/30/19	5	2.5	1000	450,000.00 (M)	99.62	2.581
Anstock II ltd	7/24/14	7/24/17	3	2.125	1000	300,000.00 (M)	99.72	2.221
Supranationals								
IBRD	7/12/12	7/12/22	10	1.5	10,000	5,000.00 (M)	99.10	1.50
African Development Bank	8/31/12	8/25/22	10	1.83	1,000,000	20,000.00 (M)	100.00	1.830
International Finance Corp	2/22/13	5/16/16	3	0.5	1,000	1,000,000.00 (M)	99.80	0.562
African Development Bank	10/18/13	10/18/16	3	0.75	1,000	500,000.00 (M)	99.71	0.750

Table 5: Green Bonds

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