Financing Climate Policies through Carbon Taxation and Climate Bonds –Theory and Empirics

Arkady Gevorkyan* Michael Flaherty† Dirk Heine*‡ Mariana Mazzucato†§
Siavash Radpour¶ Willi Semmler‖

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Abstract

As the funding of climate change mitigation and adaptation policies have become increasingly relevant to climate negotiations, emissions trading schemes (ETS) and carbon tax represent two of the most viable policy tools. Both types of policy incentivize reductions in greenhouse gas (GHG) emissions through market mechanisms, and both also have the potential to raise revenue that might be used for additional climate change policies. In most current models, the burden of enacting mitigation and adaptation policies falls primarily on current generations. In practice, the necessary sacrifices required to internalize environmental damages face tremendous political opposition. Increased taxes or increased regulation are asserted as detrimental to potential economic growth, and these policies are particularly difficult to implement as world economies emerge from the financial crisis and recession of 2008. This paper studies the interaction of carbon taxes, emissions trading schemes, and climate bonds as policy instruments. Furthermore we also explore a private-public partnership to fund climate policies, where public investment crowds in private risk averse investors. In order to model those issues we set up an intertemporal model, related to Sachs (2014), that proposes burden sharing of current and future generations. The model includes as funding sources both a carbon tax and climate bonds, which can be used for further mitigation policies as well as adaptation efforts. The issuance of climate bonds contributes to immediate investment in climate mitigation, but the bonds would be repaid by future generations in such a way that those benefitting from reduced environmental damages share in some of the burden. We examine a three phase model by using a numerical procedure, NMPC, that allows for finite horizon solutions and phase changes. We show that the issued bonds can be repaid and that the debt is sustainable within a finite time horizon, and moreover that carbon taxes can complement green bonds and expedite the transition to sustainable practices. We also study econometrically whether the current macroeconomic environment is conducive to successfully phasing in such climate bonds when climate bonds interact with carbon tax and ETS as instruments.

*New School for Social Research, Department of Economics, 6 East 16th Street, New York, NY 10003. e-mail: gevoa020@newschool.edu

†New School for Social Research, Department of Economics, 6 East 16th Street, New York, NY 10003. e-mail: flahm788@newschool.edu

‡World Bank - Global Climate Change Policy Team, 1818 H Street NW, Washington, DC 2043. e-mail: dheine@worldbank.org

§R.M. Phillips Professor in the Economics of Innovation, SPRU University of Sussex, SPRU - Jubilee Building Room 384 University of Sussex Brighton BN1 9SL. e-mail: M.Mazzucato@sussex.ac.uk

¶New School for Social Research, Department of Economics, 6 East 16th Street, New York, NY 10003. e-mail: radps229@newschool.edu

‖Henry Arnhold Professor New School for Social Research, Department of Economics, 6 East 16th Street, D-1123, New York, NY 10003. e-mail: semmlerw@newschool.edu

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1 Introduction

Anthropogenic climate change is an extraordinary problem which will require extraordinary effort to manage. This effort must include the hard sciences, the social sciences, and effective policy making, as well as a shared commitment from the global community at large. Last year (2015) was the hottest year on record, dating back to 1880, and the year before (2014) is the next hottest. As of July, this year (2016) is shaping up to be even hotter; each of the seven months thus far (with the exception of June, which was equally hot) have been significantly hotter than the corresponding months of 2015.

That climate change is driven by mankind's fossil fuel use and land use is beyond debate at this point; there is near consensus in the global scientific community. The use of fossil fuels - coal, oil, gas - allowed for tremendous advances in technology, industry, and transportation over the last couple centuries, but it was carried out for the most part without concern for its environmental effects. In economic terms, the global use of fossil fuels created an externality. The production, distribution, and use of fossil fuels impacts households and businesses (in this case, the entire global community) in ways that are not accounted for in their market prices. Any long term plan aimed at addressing climate change must then, in one way or another, internalize the external costs of fossil fuel emissions. Above and beyond the costs associated with sourcing, mining, transporting, and selling these fuels, the market must incorporate the costs incurred by the global society as byproducts of the fuel's use.

Environmental regulations have been used to address certain pollution externalities to varying effects for decades, and carbon taxes have been used to disincentivize GHG emissions since the 1990s. Green bonds (or climate bonds) represent a fairly new development in the sustainable investment toolkit and are becoming increasingly popular in the financial word. Green bonds are typically issued for a specific project or activity which would mitigate climate change contributors or adapt a community to the effects of climate change. Green bonds, issued by both government entities and private businesses, have proven to be valuable, profitable, and low-risk financial instruments around the world. Countries actively involved in addressing climate change must utilize a multitude of market-based and regulatory-based policies. Direct regulation, carbon taxes and ETS represent the most widely used policies aimed at mitigating the effects of climate change.

This paper introduces a new theoretical model that examines the effectiveness and welfare improving effects of a combination of climate strategies. We first survey a number of current climate policies that have already been implemented in countries around the globe. We are then able to elaborate on the pros and cons of different climate policies. Furthermore, we review the financing methods and sources necessary for a widescale transition to more sustainable energy. The primary purpose of our study is to reflect on an economic framework that facilitates a transition to a lower carbon economy and to explore the policy tools that would best achieve this. We model three scenarios representing three different levels of mitigation effort: (1) a business as usual (BAU) model with damages to the environment resulting from the externalities of economic activities; (2) a scenario incorporating green bond investments and an intertemporal sharing of the cost of mitigation; (3) a scenario with green bond financing in addition to a carbon tax. The effectiveness of such climate policies and welfare effects will be studied. Furthermore, in the empirical section, we investigate how various climate policies such as ETS, carbon tax and climate bonds perform given specific macroeconomic environments. The main empirical method utilized is a panel vector autoregressive model (PVAR).

The remainder of the paper is organized as follows. Section 2 provides a general review of various carbon emissions mitigation strategies and provides historical and contextual background for ETS, carbon taxes and climate bond issuing. Section 3 explains theoretically how carbon taxes can work alongside other climate policies such as ETS and climate bonds. Section 4 reviews the current state and prospects of funding toward a new type of energy generation. In section 5, we explore the financing issue in a three phase model of climate change, incorporating both carbon tax and climate bonds as funding sources, and in section 6 we review the numerical results of different scenarios. Section 7 provides a empirical analysis of the prospects of the interaction of climate bonds with various types of carbon pricing - namely carbon taxes, emissions trading schemes, or some combination of both. Section 8 concludes.

2 Regulation and financing instruments

A number of policy tools have been implemented or proposed in the effort to internalize the carbon emission externality. Some of the most tempting policies are so-called command and control regulations that specify an emissions limit or related restrictions. While these are likely to induce the desired environmental benefit, they tend to come at high economic cost, they may create market distortions, and they may open up the possibility of black markets. For these reasons, most economists prefer market-based policy tools in addressing the emissions externality. A market-based regulatory policy would discourage the use of products with strong externalities, while simultaneously encouraging the substitution of more sustainable technologies. Such policies include emissions trading schemes (ETS) and carbon taxes. These preserve market incentives and allow for businesses and consumers to find efficient solutions on the road to sustainability.

Taxing in order to internalize climate-change-related externalities comes in a number of varieties and can be directed at either the supply side or the demand side of fuel usage. In recent research, Asheim (2012) and Harstad (2012) review the potential for supply side tax policies. A supply side tax would be implemented at the point of extraction, and thus applies to a smaller number of agents. Additionally, it allows flexibility in the application and roll-back of emissions taxes -

as emissions targets are met and as emitters begin implementing more sustainable technologies, supply side taxes can be rolled back and adjusted more readily than demand side emissions taxes, which would generally need to be more or less permanent. Demand side emissions taxes, on the other hand, would apply to a far larger number of agents - any business or individual who uses fossil fuels. This type of tax would be reflected in higher gasoline prices at the tank, higher energy costs for households, and higher input costs for businesses; each of these agents would then be able to determine how to adjust to rising prices, whether it be reduced usage or substituting a more sustainable technology. Emissions taxes, be they supply side or demand side, have the additional benefit of being revenue generators. Not only do they discourage the use of dirty fuels through the price mechanism, but they generate tax dollars which may be used in a variety of ways.

2.1 The incentives and structure of the carbon tax

There are a number theories on where along the distribution chain a carbon tax should be levied. Asheim (2012) argues for the upstream taxation of fossil fuels, such that it affects supply decisions rather than demand decisions. Weitzman (2014) suggests collecting the tax at the chokepoints where problematic fossil fuels are first entering an economy. This allows individual countries to retain the tax revenue while maintaining a reasonably small number of taxable agents. Herber and Raga (1995) agree that it is nearly impossible to tax each actual unit of carbon emission, though that would be the economically efficient place to levy the tax. Instead, they posit that the tax could effectively be levied at the mining/importing stage or at the point where fuels are sold to households and businesses.

To have the intended environmental effect, carbon tax should be levied on the unit of emission rather than on value. A carbon tax should also be proportionate to the carbon content of the particular fuel type. For example, coal has a higher carbon content than natural gas, so a well-proportioned carbon tax would levy a higher rate on coal than on gas. Not only, then, does the carbon tax encourage substitution away from fossil fuels entirely, but within the scope of fossil fuels it encourages the usage of relatively cleaner fuels. This may ultimately be critical for the intermediate stages, transitioning from carbon-based fuels to renewables. Fairly obviously, emissions taxes should not be levied on alternate energies, as this distort the benefits of substituting away from the fossil fuel in the first place.

One of the numerous benefits of a carbon tax over a tradable permits scheme is that it generates revenue for the implementing government. Marron and Morris (2016) identify the four viable uses of carbon tax revenues: offsetting the burden of the carbon tax, additional greenhouse gas emissions reduction efforts, mitigating and adapting to the effect of climate change, and general budgetary usage. Carbon taxes run the risk of being regressive, meaning that relatively poor households pay a larger share of income for increased fuel prices compared to their richer counterparts. To minimize the potential regressiveness of the carbon tax, revenues could be used to bolster the most vulnerable members of society. Alternatively, tax revenues could be used to subsidize further sustainability efforts. According to Acemoglu (2012), carbon taxes alone are distortionary, dealing solely with the current generation's environmental externality but neglecting those of future generations. Acemoglu therefore suggests a carbon tax be paired either with a research and development subsidy or with a complementary profit tax on the dirty energy sector.

Meanwhile, Marron and Morris (2016) maintain that the best sustainability spending projects are going to be those that complement the carbon tax without overlapping; that is, filling the gap policies are preferred to belt and suspenders policies that double up on a particular target, with diminishing usefulness. A third use of carbon tax revenues, explored by Chancel and Piketty (2015), is investment in climate change management and adaption. That is, given that some amount of change in underway and unstoppable, it might be expedient to invest in the policies and tools necessary to adapt effectively. Such policies will need to be undertaken regardless of revenue source, and there is nothing intrinsically tying the long term adaptation goal to the immediate capture of carbon revenues. Finally, carbon revenues may be used to fund general budgetary purposes, unrelated to climate change or fossil fuel reductions. In doing so, policymakers can focus on other economic targets such as fostering economic growth or political stability.

2.2 Carbon tax, climate bonds and the uses of revenue

A number of carbon taxes have been implemented over the past several decades, and an even larger number have been proposed by policymakers around the globe. This section briefly summarizes some of the notable tax policies, both at the national and local level. Here we review the timeline of implementation, their effectiveness in reducing carbon emissions, and the ways the tax revenues have been used.

National carbon taxes

The first wave of national carbon taxes were adopted by the Scandinavian countries in the early 1990s. Finland and the Netherlands implemented carbon taxes in 1990, Sweden and Norway followed suit in 1991, and Denmark implemented a tax in 1992. In subsequent years, few national carbon taxes have been implemented, as popular policy talks shifted focus to emissions trading schemes around the turn of the millennium. Nonetheless, Great Britain instituted a national carbon tax in 2001, as did Ireland in 2010. Australia and New Zealand have both faltered in their efforts at implementation; Australia's carbon tax lasted the two years 2012-2014, while New Zealand's never left the planning stage and was abandoned in favor of a permit trading scheme. A number of countries including France and Chile have passed carbon pricing legislation but have not yet implemented the tax. Several more countries have carbon tax proposals under legislative review.

The early implementation of carbon taxes in the Scandinavian countries allows some insight into the effectiveness of the carbon tax in curtailing overall CO2 emissions. Sumner (2009) summarizes the environmental benefits of implemented carbon taxes. Finland's carbon tax is estimated to have reduced CO2 emissions by approximately 4 million metric tons in the years 1990-1998. The Netherlands' tax is estimated to have reduced annual CO2 emissions by 1.7-2.7 million metric tons by the year 2000, roughly of 3.6-3.8 million metric tons by 2010, and upwards of 4.6-5.1 million metric tons by 2020. Norway's carbon emissions, contrary to the general trend, have increased significantly, due in large part to the skyrocketing GDP of the same period. In Sweden, CO2 emissions had fallen by about 9 percent over the period 1990-2006. Finally, in Denmark, industrial emissions had decreased roughly 23 percent through the 1990s. Implemented more recently, there are nonetheless positive trends stemming from Irish carbon tax as well. According to Converey (2012), auto gasoline dropped 21 percent in the years 2008-2011 and auto diesel fell 13 percent over the same period.

Almost all national carbon tax revenues are directed towards the general government budget or towards reducing the burden of other taxes (Sumner 2009). Finland, Norway, and Sweden direct carbon tax revenues largely towards general government budgets. The Netherlands, the United Kingdom, Ireland, and Denmark favor policies which either reduce other taxes or rebate the revenues to affected industries. The Netherlands also directs a notable amount of revenue towards climate mitigation policies. (Sumner 2009 and Converey 2012)

Local carbon taxes

In addition to the carbon taxes adopted nationally, several states, provinces, and localities have enacted their own carbon taxes. The city of Boulder, CO enacted one such tax in 2007, as did the Canadian province of Quebec. British Columbia and nine counties in California's Bay Area (the so-called Bay Area Air Quality Management District, or BAAQMD) enacted carbon taxes in 2008. While most national tax revenues were diverted to the reduction of other taxes or to the governments' general funds, locally collected carbon tax revenues tend to be earmarked for climate mitigation programs.

Issuing of long maturity bonds

Regardless of the use of funds, carbon taxes policies can be designed to complement to other long-term green investment. Sachs (2015) and Flaherty, et al (2016) show that the growing use of green bonds paves a path forward in sustainable investment, whereby the burden of climate change mitigation and adaptation spending is shared between the current generation and future generations which stand to benefit most from today's investment. As this paper will show, carbon taxes incentivize a more rapid uptake in greener, more sustainable technologies, and this removes some of the uncertainty around investing in corresponding businesses and projects. Later sections address the theory of joint carbon taxes and green bonds policy and show that given reasonable assumptions, carbon taxes implemented concurrently to green investment leads to a more sustainable economy faster than investment alone. In section 4, we examine what is or can be done to finance green energy technology on a large scale.

3 Principles of carbon pricing and climate bonds

The fundamental purpose of carbon pricing is to make consumers and producers of polluting goods take into account the costs which this pollution imposes on the society as a whole. Carbon pricing policies, such as carbon taxes or emissions trading schemes, can also be used alongside climate bonds in order to reap a more beneficial environmental outcome. Here, we review the efficiency benefits from including such carbon pricing in a joint policy with climate bonds.

Internalization of externalities

A root motivation for cost internalization is that, to have free economic markets, all exchanges in the economy should be voluntary, between freely consenting trade partners. Third parties must not be forced to pay for external costs arising from transactions. Market economies are supposed to reward those who create net values rather than those who merely redistribute values in zero-sum or negative-sum games. When the production of a good causes pollution, the costs of that pollution must, therefore, be paid by those taking the decision to produce and consume the product rather than by unrelated third parties. Otherwise, producers and consumers would be able to forcibly redistribute welfare from those third parties to themselves. Without bearing the full costs of their actions, such producers and consumers have an incentive to carry out transactions even when those transactions cause a net harm to society after factoring in the external costs borne by their victims. To safeguard the core principles of liberty and net value-creation, economic agents must, therefore, bear the full costs of their own actions. Pricing carbon emissions contributes to this cost internalization.

Carbon pricing can be achieved through different means, including taxes, emissions trading schemes and the private enforcement of property rights in courts. The last option looks appealing, as it avoids direct government intervention. Regrettably, it does not provide an efficient remedy in most cases. Recall that when the production of a good creates pollution harming a third party, this person might in principle take the producer or consumer of the good to court to reclaim the damages. Unfortunately, even in modern economies with well-defined property rights, the transaction costs of legal proceedings would be prohibitively high for the vast majority of pollution cases, in particular for greenhouse gases. CO_2 has a vast quantity of emitters, whose scentless effluences mix invisibly and spread globally. The location of most damages is outside the jurisdiction from where each emission occurred, and the global warming caused by a molecule of CO_2 occurs for about 100 years after the time of emission (Stocker et al., 2013). The polluters and their victims hence do not know each other, mostly live under different court systems, and partly in different time periods. For practical purposes, it is largely impossible for victims of climate change to take those harming them to court.

Limits of enforcing liabilities

While the private property rights solution does not in itself provide a viable solution, it can nevertheless greatly inform public policy. Following the Normative Coase Theorem (Parisi, 2007), the government should choose a carbon price that coincides with the price which freely negotiating emitters and victims of climate change would have reached if they were able to meet in an ideal court setting. Rational, private parties, bargaining on a level playing field, would set the carbon price at the level of the marginal damage that the carbon emissions cause to the victim. This rate, which would be reached through the first-best bargaining process (Coase, 1960), coincides with the definition of an optimal environmental tax (Pigou, 1932).

We see that carbon prices at this Pigouvian level are the consequence of taking property rights seriously. They would also implement legal principles that governments across the world have endorsed but not enforced. UN member states all adopted the Polluter Pays Principle (Rio Declaration, Principle 16) as did the major economic fora.[1]

Besides carbon pricing, the internalization of environmental costs can also be achieved through regulatory instruments. Price-based instruments come at lower costs, however. One reason for this cost advantage is that environmental taxes and emissions trading schemes allow firms with different abatement costs to vary in the depth of their emission cuts. A profit-maximizing firm will reduce its carbon emissions down to the level where its private marginal cost for achieving these emissions reductions equals the carbon price. A firm that can abate cheaply will then undertake greater emissions reductions than a firm which finds reducing emissions expensive. As a result, firms equalize their marginal abatement costs rather than their abatement quantities. The emissions reductions then occur where they are cheapest, minimizing the economy-wide cost of climate change mitigation (e.g., Buchanan et al., 1975; Ackerman et al., 1985). Compare this outcome with carbon pricing with the counterfactual outcome under a regulation where each firm is mandated to achieve the same quantity of carbon mitigation. In this case, some of the cost advantages of the firm with the cheaper carbon mitigation opportunities remain unused, and the overall climate target is reached at greater cost.

[1] e.g., OECD Recommendation C(72)128, Art. 191 Treaty on the Functioning of the European Union.

A related cost advantage of carbon pricing over regulations is the scope of emission reduction opportunities (e.g., Aldy et al., 2010; Krupnick et al., 2010). For example, a carbon price provides power stations with an incentive to switch to cleaner generation fuels (input substitution effect) and reduce exhausts (abatement effect), while simultaneously providing an incentive to consumers to purchase goods using less electricity (output substitution effect)(e.g., Sterner et al., 2012). By contrast, a regulation mandating power stations to install emissions treatment equipment (such as carbon capture and storage or SO_2 scrubbers) forgoes most of these wide-ranging incentives. Achieving the same overall emissions reduction target with a greater number of mitigation opportunities lowers overall cost. Furthermore, the state becomes less intrusive, as a carbon price leaves private agents the freedom of choice how to achieve emissions reductions, rather than mandating a particular way of reducing them.

These cost advantages also hold over time. Consider a regulation which requires power plants to reduce their emissions below a certain benchmark value. Once a power plant achieves this standard, there is no incentive to keep improving. If, however, the regulation is replaced by carbon pricing, the power plants face a dynamic incentive to continue exploiting cost-efficient opportunities for further emissions reductions (ibid).

Possibility of government failures

Correcting market failures such as climate change bears the risk of making things worse through government failure (Tullock et. al (2002)). The government may, for instance, lack in- formation needed for efficient policy interventions. The size of this problem again depends on the choice of policy instruments. Consider first the case of regulations and then of carbon pricing. When the government decides for businesses whether a new clean technology should be introduced, both the costs of introducing the technology and its benefits at reducing emissions require analysis. With carbon pricing, by contrast, the government only requires information about the marginal damages of carbon emissions and not about the marginal costs of abating these emissions (Posner, 1992, p. 378f). The government leaves it to businesses to compare the benefits of emissions reductions (as expressed by the carbon price) and their costs. Policy can then be efficient even if the government lacks part of the information required for a cost-benefit analysis.

Carbon pricing also contains three further risks of government failure: missing administrative capacity, corruption, and informal sectors (cf. Liu, 2013). Besides the scarcity of information, government failure may also occur due to the scarcity of qualified administrators for enforcing the policy, corruption and the existence of informal markets. Consider again first how these problems feature for regulatory policy and then for carbon pricing. Regulatory policy may require large numbers of administrative officers for audits and policing. Public officials with the required technical knowledge may be scarce. Businesses may furthermore seek to avoid the costs for regulatory compliance with comparatively smaller costs for bribing auditors. Both this corruption problem and the scarcity of officials become worse for regulatory policies that need to be rolled out across large spaces, such as in remote regions and informal markets.

Carbon pricing, however, can circumvent many of these problems, by imposing a price signal where fuels enter the economy. There are much fewer pipelines, mine mouths, and ports where fuels enter into the economy than there are chimneys to police. The government can accordingly concentrate its supervision over a small number of officials who impose a carbon price at a few fuel entry points to the economy, and all subsequent activities combusting these fuels are covered by the climate policy. It is then private trade partners who pass the carbon price signal through the market, to the remote regions, to the informal activities, to all industries. Each private agent has an incentive to fully enforce the price signal towards his transaction partners, given the private incentive to pass on a tax incident, so the public policy receives voluntary private enforcers where it lacks public ones.

As a by-product of their environmental role, carbon pricing may generate public revenues. These revenues can be used to lower other taxes, either directly for example by reducing personal or corporate income taxes, or indirectly by financing a budget consolidation that would otherwise have required additional taxes. In either case, this revenue-recycling effect of carbon pricing produces another efficiency gain that is unavailable with regulations.

The need for climate bonds

Despite all these advantages of carbon pricing, other policy instruments have relevant roles to play. Carbon pricing does not solve the problem of adaptation to climate change. A carbon tax provides mitigation incentives; it only indirectly reduces the vulnerability of the economy to the remaining climate change, and it does not compensate victims. Addressing these policy changes requires public and private investments, which carbon pricing may help to fund, but which may equally be financed through climate bonds. Beyond adaptation, climate bonds can furthermore help finance technology transitions. Carbon pricing importantly contributes to green technology transitions, but because there are remaining technology market failures beyond those internalized by carbon pricing, the most efficient technology transitions use both carbon pricing and public supports to green investment. This support can take the form of climate bonds.

Besides considerations of economic efficiency, a further argument to combine carbon pricing with climate bonds is political feasibility. The introduction of carbon pricing continues to be slow, and this delayed policy action causes significant economic harm. Stabilizing the climate later in time, e.g. by continuing to delay the introduction of significant climate policy, is drastically more expensive than earlier action. Even though carbon pricing would be the most efficient climate policy, if that policy is currently politically unattainable, it is more efficient to use second-best policy instruments than to do nothing. Climate bonds appear politically more easily realizable.

Exactly in those situations where policymakers shy away from incurring short-term costs for long-term gains, bonds could make climate policy incentive-compatible. In the medium-term, the second-best role of climate bonds may then be even greater than the important role already justified by the potential of such bonds at supporting adaptation and technology transitions.

Interaction effects of climate policies

When carbon pricing and climate bonds are implemented jointly, there are interaction effects between them. These interaction effects vary depending on the type of carbon pricing used. There are two major options for implementing carbon pricing: emissions trading schemes and taxes. A large literature analyses their respective advantages here we focus only on these interaction effects.

The value of climate bonds rises when climate change mitigation projects have higher private returns. These returns, in turn, rise when there is carbon pricing. A sufficiently high CO_2 price in emissions trading schemes or taxes hence supports the successful market introduction of climate bonds as well. This is an opportunity as well as a curse: Climate bonds are only partly an alternative to carbon pricing if they require carbon pricing for their market success. On the other hand, if carbon pricing did take off, we can expect climate bonds to thrive as well.

This interaction effect between the value of climate bonds and carbon prices is more ambiguous in the case of emissions trading schemes than for carbon taxes. An emissions trading scheme sets a cap on emissions, and when climate bonds finance climate change mitigation projects for industries that are covered by the same emissions cap, there can be emissions leakage. The mitigation achieved through the bonds reduce the scarcity of emission permits under the cap, reducing those permits price, thereby inciting the displacement of emissions more than their net reductions. To prevent this unwanted effect, the size of the emissions cap needs to be reduced when climate bonds are introduced, but those adjustments may be politically impossible exactly in the situations when climate bonds are sought. If climate bonds have been introduced as a second-best policy to fill the policy gap left by political opposition to serious carbon pricing, the same political opposition would probably also prevent an adjustment of emissions caps.

Against this argument, optimists may point out that the introduction of climate bonds might change the political gridlock because it creates new vested interests. The holders of climate bonds have an interest in reductions of the caps of emissions trading schemes. Current lobbying by industries to loosen emission caps could then be counter-balanced by new lobbying from investors who seek to strengthen those caps. By that reading, the creation of climate bonds could both weaken and strengthen emission trading schemes. With a carbon tax, these outcomes are clearer. As the tax rate is stable irrespective of the deployment of climate bonds, there is no risk of climate bonds and carbon taxes undermining each other.

Another interaction effect between climate bonds and carbon prices works through price volatilities, see section 7. As for other bonds, green investment projects can more easily attract climate bond finance if their returns on in- vestment are less volatile. As the returns on investment for green investment projects depend on carbon prices, a more stable carbon price also creates a more stable return on investment and accordingly a greater demand for green bonds. Emissions trading schemes, with their greater carbon price volatility compared to carbon taxes, then do not maximize the potential of climate bonds, see section 7.

4 Financing the shift in energy generation

The major mechanism of emission control will be a a shift in energy generations. There is basic research involved that is highly risky and requires some public private partnership, see appendix. We will discuss here in this section more the implementation and diffusion of new energy sources through some public and private funding. Public investments in innovation have been key in areas with high capital intensity, and with high technological and market risk. Such investments have often had the effect of crowding in risk-averse private business. Indeed, it can be argued that a green technology revolution will require a similar investment across the whole innovation chain that the ICT revolution had (Mazzucato, 2013), and for this to happen public investments must do more than fixing markets, they must actively shape and create them (Mazzucato, 2016).

A massive and rapid shift of energy generation to low-carbon energy sources has been recognized for decades to be a necessary condition for stabilizing atmospheric greenhouse gas concentrations (Caldeira, Jain, & Hoffert, 2003; Hoffert, Caldeira, Jain, Haites, & Harvey, 1998). However, the problem of financing the low-carbon transformation of the energy sector, the largest business on earth (Dangerman & Schellnhuber, 2013) is far from solved. The International Energy Agency (IEA) estimates that investment in low-carbon energy generation accounted for only 16 percent of total energy sector investments in 2013, or USD 260 billion out of 1.6 trillion and projected that for limiting the temperature rise to two degree Celsius, the annual low-carbon investment would have to triple to USD 790 billion until 2035 (IEA 2014, 20 and 44). Some urge that an additional stimulus of USD 1.5 trillion over the next decade into renewable energy R&D alone would be a minimum acceptable scale of finance for the problem (King, Stern et al. 2015, 25). Clearly, the danger of anthropogenic climate change requires that the volume of finance for low-carbon technologies rises considerably.

The mission to switch the energy supply to one of low-carbon is not simply a matter of deploying larger quantities of finance to build a new industry around innovative technologies. It must do this while facing the formidable challenge of competing with existing, low-cost fossil fuel technologies on their own turf for selling power. In theory, accounting for the external costs imposed by fossil fuels, greenhouse gas emissions, and air pollution would raise their price above that of the more mature renewable technologies. However, an appropriate price for carbon continues to elude policy makers (Wagner et al., 2015). Absent this correction, low carbon technologies are largely dependent on a variety of national support policies and on patient capital. Hence, finance providers must not only be convinced of providing finance for renewables whose performance record is far from fail-proof, they must also be convinced that the improvement in technology and cost is fast enough to ensure profitability with fully-developed fossil fuels while temporary public subsidies last. This incumbency effect of fossils on renewables makes the provision of finance even more challenging. [2]

In spite of all this, finance for renewables is quickly increasing. Bloomberg New Energy Finance (BNEF) estimates that investment into renewables along the innovation chain, from R&D to asset finance, has been rising sixfold over 11 years, from USD 45 billion in 2004 to 270 billion in 2014 in current USD at market exchange rates, which translates into an 18% compound annual growth rate. Even with subexponential growth (and Figure 1 shows a decreasing growth rate) the tripling of investment into renewables to USD 790 or a compound annual growth rate of 5.5 per cent from todays level, that the IEA advocates, appears feasible. Nor is this figure encroaching on scarce investment funds needed elsewhere: according to the (arguably imperfect but indicative) national accounts estimate of total the investment component of GDP compiled by the IMF, the current dollar value of investments in 2014 was over USD 19 trillion, a pool of which current renewable investment is 1.4 per cent and would rise to 4 per cent under the IEA scenario, holding the other magnitudes constant (IMF 2015).

And even with the current investment level, renewables accounted for 59 per cent of all new net energy capacity additions in 2014, meaning that most of the fossil energy investment is required to maintain the existing structures. The IEA forecasts almost two thirds of all net additions between 2015 and 2020 to be renewable energy, raising the renewables share in electricity provision from 22 to 26 per cent in only five years. Clearly, then, renewables are on an expansionary path and there is existing finance supporting the industry.

Conditioning asset finance on public or private ownership, Mazzucato and Semieniuk (2016a/b) find that almost 50 percent of global utility scale asset finance now originates in public financial institutions. As the two plots in Figure 2 depict, the share of asset finance provided by public sources (top plot) resembles the share of public funds for upstream renewable energy R&D (bottom plot), merely on a scale that is one order of magnitude larger.[3] This reveals that policy makers must not only focus on how to fix research or set incentives for public investment down-

[2]The only low-carbon technologies that are cost-competitive are hydro (dams) and nuclear. The former is limited to providing a few percent of total energy supply (Lewis 2007), and the latter - made cheap by large sums of public money invested - is hampered by political opposition both domestically (Germany, Japan) and internationally (nonproliferation concerns, e.g. Iran.)

[3]Renewable energy includes power from wind, solar, hydro, geothermal, biomass, and marine sources, and biofuels. Finance for hydro excludes large installations with capacity greater 50MW, typically funded by public agencies and banks.

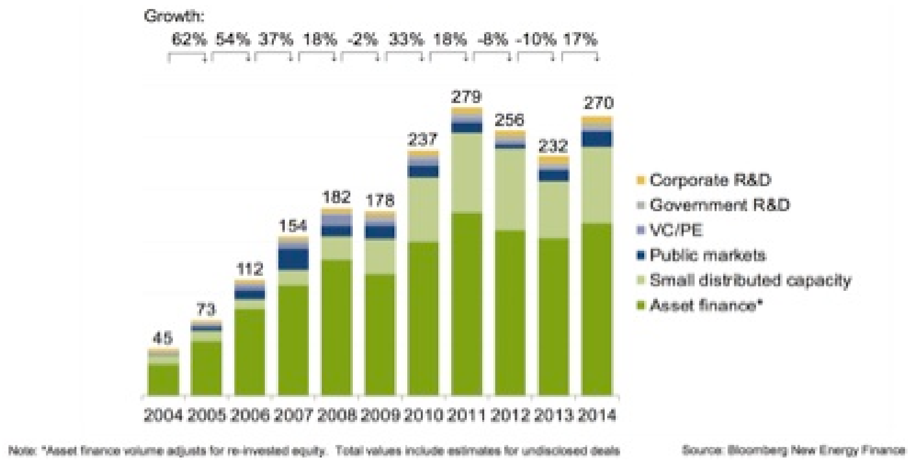

Figure 1: Total renewable investment (excluding grants).

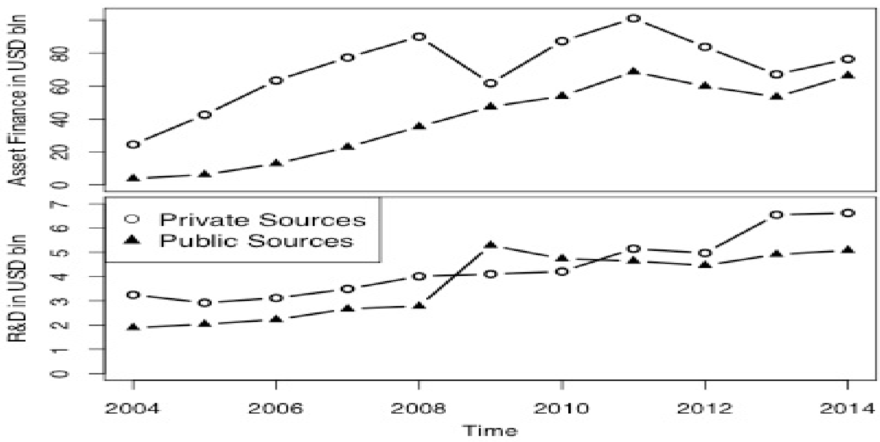

Figure 2: Private and public funds for renewable energy R&D (top) and utility scale asset finance (bottom).

Source: Mazzucato and Semieniuk, 2016a

stream, they must also come to grips with the fact that public decisions about green investment (austerity or green missions) have important consequences for the pace of green innovation and the energy transition.

Delving under the veil of total investments, a closer look at what is being financed by which types of financial actors reveals the implications of different types of finance for the direction of innovation. In Mazzucato and Semieniuk (2016a), asset finance for renewable energy deployment is classified into high-risk investments (more innovative) and low risk investments (less innovative, at the point of diffusion), depending on which technology is financed. In further work, Mazzucato and Semieniuk (2016b) show that there is a robust positive relationship between the share of private funds flowing into renewable asset finance that are invested in high risk technologies, and the share of these private high risk deals that have a public co-investor - typically a public bank that arranges the deal and carries out the preliminary risk analysis, before private lenders join the syndicate. In other words, public finance crowds in private finance.

They also show that the years 2009 through 2011 are outliers to that relationship, but these years instead coincide with massive public loan guarantees and grant programs underwriting private investments as part of post-crisis government stimuli. The distinction of what is being financed shows that policy makers allocating funds to green innovation have an influence over the direction of this innovation, and need to consider which direction is desired. In the case of renewable energy diversified supply is often recommended by scientists (Jewell, Cherp, & Riahi, 2014). If this becomes a policy goal, path dependency from scale effects suggest that high-risk investments into less advanced renewable technologies need to be ascertained with public investments. Needless to say, these results lead to more granular questions about what types of public actors and what types of private actors are shouldering the risky investments.

Due to the important role of public finance in crowding in risk-averse private finance, it is important for the policy mix to include both direct public investments, and indirect tax incentives. Carbon taxes alone will not create enough additionality: making private investment happen that would not have happened anyway (Mazzucato, 2016). In the following section, we introduce a dynamic multi phase model that allows to consider both policies.

5 Climate policies with burden sharing –Three scenarios

Significant increases on abatement and mitigation policies are clearly a necessary step towards sustainability. As we have seen, policymakers' best tool for abatement finance might be the selling of green bonds or the taxing carbon emissions, or perhaps some combination of both. In order to compare a situation of no abatement effort with various abatement strategies, we introduce a carbon tax to the model used in Flaherty, et al (2016) which is based on the idea of inter-generational burden sharing of Sachs (2014).

While carbon taxes (and other types of mitigation policies) put the burden on the current generation, green bonds issued today and repaid by the future generations transfer the costs of mitigation and adaptation to future generations. The model that follows presents three scenarios. The first presents the business-as-usual (BAU) case. No attempt at abatement or mitigation is made, greenhouse gas levels increase indefinitely, and capital grows initially but thereafter declines as damages from climate change are realized.

The second scenario explores the effect of green bonds, but does not institute any form of carbon tax policy. In this scenario, investment in green infrastructure is immediately undertaken and scheduled to be repaid by future generations. Here, greenhouse gas levels drop, capital continues to accumulate, and a debt burden accumulates in the first time period which is repaid by taxes taken out of later time periods.

The third and final scenario introduces a carbon tax to the green bond case. This resembles scenario 2, with the addition of a carbon tax included in the first stage. The second stage of this scenario is nearly identical to that of the second, as the carbon tax is small following the shift to greener energy sources. Ultimately, we argue that the third scenario more quickly reduces greenhouse gas emissions and allows for a higher steady state level of capital, while minimizing the debt repayment of the second generation, because bond repayment is phased in earlier.

The solution procedure we suggest which is called NMPC (nonlinear model predictive control), see 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.

Since the solver is based on optimization in a finite time horizon, which can approximate the infinite time horizon solution for continuous and smooth functions. It can also resemble the human decision making based on short term interests instead of optimization over the long run or infinite horizon. We want to note that current settings of our model and numerical solver does not allow yet to calculate the optimal levels of green bonds or tax rates, and an endogenous regime switching from one phase to another in order to achieve the long term goal of lowering the GHG levels in the most welfare improving manner.[4] However, it allows us to study dynamics of the economy by setting exogenous constant rates for carbon taxation and green bonds as policy variables.

5.1 First Scenario: Business As Usual

The baseline model, introduced in Flaherty et al (2016), is based on a representative household/Government optimizing consumption over a finite period to maximize utility over a continuous time horizon. The utility function and the budget constraint are similar to those of standard models with addition of GHG accumulation, M, and damage caused by GHG, D. Future consumption is discounted at rate ρ in a logarithmic utility function.

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

subject to

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

[4]For regime switching model of this type with an overall welfare evaluation, taking into account all regimes, see Orloff et al (2016).

and

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

where $K(0) = K_0$, and $M(0) = M_0$. The production is defined as:

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

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

Emissions, following Greiner et al (2010) with the addition of some abatement effort, are given by the function:

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

where A_0 represent some exogenous mitigation effort that exists even in the absence of any conscious action towards mitigation and γ affects the emission growth.

There is a 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 $a_1 > 0$, $\psi > 0$.

5.2 Second scenario: Financing the green economy by climate bonds

In the second scenario, greenhouse gas mitigation is funded through the sales of green bonds in the first stage, and the accumulated debt is repaid in the second stage. The basic characteristics of the model remain the same, however, the cost of abatement is factored into both the capital stock 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 finite time horizon.

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

subject to

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

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

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

Where A represents the abatement/mitigation efforts financed by green bonds during the first stage (and reimbursed in the second stage). During the first stage of the model, green bonds are sold to finance the GHG mitigation. Since the abatement/mitigation effort in the capital stock equation is reimbursed by the issued bonds, it does not appear there as a cost. The debt dynamics equation for the first stage is:

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

In this stage, public debt, B, is a function of the cost of the abatement efforts, A, the interest rate, r, and the initial public debt, $B(0)$. 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.

The second 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 preserving the green economy by continuing the abatement efforts. In the absence of notable damage from GHG, the consumption 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 τ is an income tax rate to repay the accumulated debt and maintain the equilibrium level of abatement/mitigation effort.

5.3 Third Scenario - Paying for the green economy by carbon taxes and climate bonds

The third scenario is similar to the second scenario, but it includes an additional carbon taxes during the first stage, showing up in the capital stock equation. The first stage equations for this scenario are:

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

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

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

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

where χ is the carbon tax rate. The carbon tax rate is set using an arc-tangent function:

$$\chi = b_1 \frac{2}{\pi} atan(b_2 M^2 - 0.01)$$

Since this model does not differentiate between brown and green capital, where brown capital produces higher amounts of emissions compared to the green capital, we can only tax the capital or its output as a whole. This is done with a changing (decreasing) tax rates to take into account that some capital stock may already represent green capital. The carbon tax suggested in this model is applied as a semi-flat tax rate on the output as long as the GHG level is higher than desired amount. The carbon tax income is spent solely on mitigation/abatement efforts.

The second stage of the model is the same as the second stage of the second scenario:

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

subject to

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

and

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

Notice that after the repayment of green bonds, total taxes,τY, would be equal to the cost of abatement efforts at the equilibrium, $A + \chi Y$, with a very small and negligibleχ. While the carbon tax rate is higher for the first generations which is facing higher levels of GHG and damages caused by that, future generations that pay almost nothing in carbon taxes and lose less output to the climate damage have to repay the green bonds and keep the level of abatement effort by paying a small amount of carbon tax.

6 Numerical solutions for the three scenarios

To get a rough idea about the dynamics of the three scenarios and their outcomes, we run numerical simulations using NMPC. The initial values and part of model parameters at each stage are presented in table6.We run the simulation for each scenario separately, but the results for the second and third scenario are presented together to make the comparison of the two policy sets easier.

Parameter	Definition	Scenario 1	Scenario 2	Scenario 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	0.005	0.005
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
b_1	Maximum Carbon Tax Rate	0	0	0.05
b_2	SGS sensitivity of Carbon Tax Rate	0	0	10
r	interest rate	0	0.03	0.03
τ	debt repayment tax rate (second stage)	0	0.055	0.055
K_0	initial capital stock	0.3	0.3	0.62
M_0	initial GHG level	0.3	0.3	0.03
B_0	initial debt	0	0	0

Table 1: Simulation Parameters and Initial Values

6.1 First Scenario - 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 0.3. This decline in the equilibrium value of capital stock (and therefore output and consumption as discussed in Section 5.1) is what justifies abatement efforts and taxing future generations for abatement efforts previously undertaken. The simulation results of this stage are shown in figure 3.

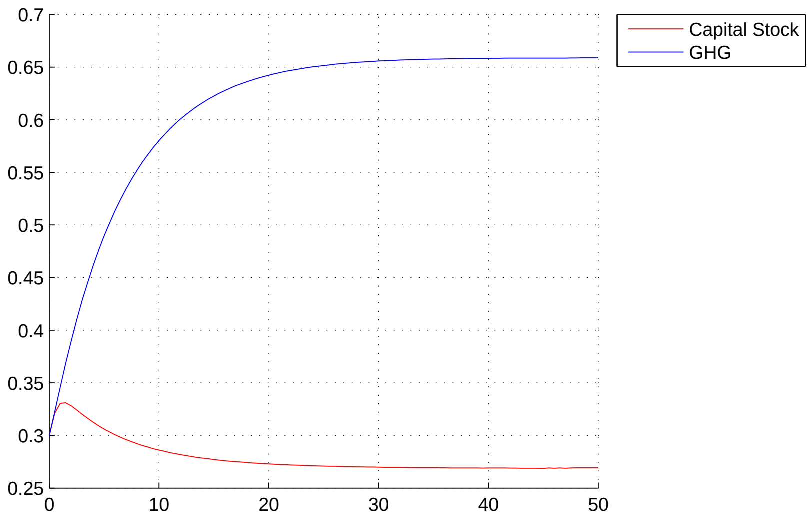

Figure 3: Stage 1 Simulation

6.2 Second and third scenarios - Climate policies

Figure 4 shows the effects of two policy sets introduced in the second and the third scenarios. In the second scenario, presented in the figure by dashed lines, the government sells green bonds and accumulates debt to finance the mitigation efforts during the first stage. As a result of this policy, the GHG level drops and equilibrium level of capital stock increases compared to the first scenario. The first stage stops and the second stage is initiated when the changes in both GHG level and capital stock become smaller than $\epsilon = 0.0001$. 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.[5]

Compared to the second scenario, the third scenario, presented by solid lines in the figure, starts with a sharper decline in the GHG level thanks to additional financing generated by carbon taxes. More taxes initially reduce investment and capital stock grows slightly slower than in the Third scenario (the difference is small to be shown in the graph), it starts to take over the investment of the second scenario as soon as GHG levels decline. While the fast decline of GHG levels and higher taxes in the third scenario have almost no effect on the equilibrium level of capital stock and a very small GHG, the main difference in the two scenarios is in the adjustment speed. Additional finances in the third model accelerates the mitigation process and the GHG level reaches its equilibrium level faster than in the second scenario. Faster adjustment means less accumulated debt, less accumulated interest, and faster repayment.

Overall, comparing all three scenarios we can observe that the first scenario is the most costly

[5]This can be shown to be feasible, though with a different software, see Orloff et al (2016).

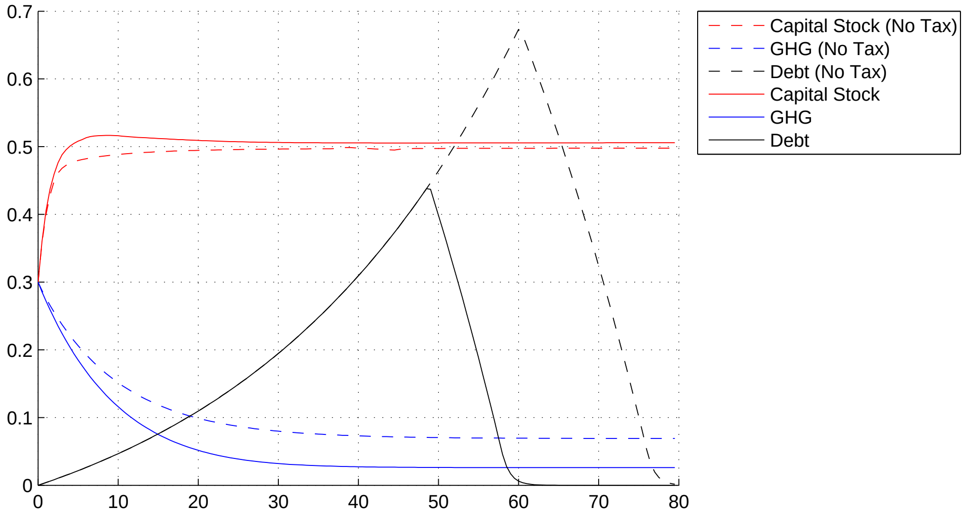

Figure 4: Stage 2 Simulation

one, and the third scenario, with carbon tax and bond issuing, seemed to be superior to the second one, where we have only bond issuing to finance mitigation and adaptation efforts.

7 Empirics of the interaction of climate policies

A particularly important issue is the phasing in of the aforementioned climate change policies - namely carbon taxes, green bonds, and possibly emissions trading schemes - given a particular macroeconomic environment. Here, we investigate first the change in the price of green bonds under various macroeconomic conditions. Then, we present the econometric results using a panel regression model, PVAR, allowing for a mix of policies.

7.1 Macro environment and climate policies

Successful implementation of sustainable climate change mitigation/adaptation policies requires some assessment of which economic conditions are conducive to ETS, carbon taxes and green bonds. We are particularly interested in what drives bond prices, as they are issued, and how that interacts with various climate mitigation policies. Analyzing the raw data, Figure 5 shows the change in the price of the climate bonds in the different environments.

Each curve represents the average of the price average of the 5 green bonds (classified by Bloomberg) issued in different countries, based on the climate policies that each country has. Table 2 represents the corresponding variance of the average of three groups of the prices of green bonds issued in the countries with different climate change policies. Results in the Table 2 and Figure 5 shows that green bonds issued in the countries where there is ETS only policy are experiencing higher volatility and an underperformance comparing to the other green bonds issued in countries where there is also a carbon tax introduced.

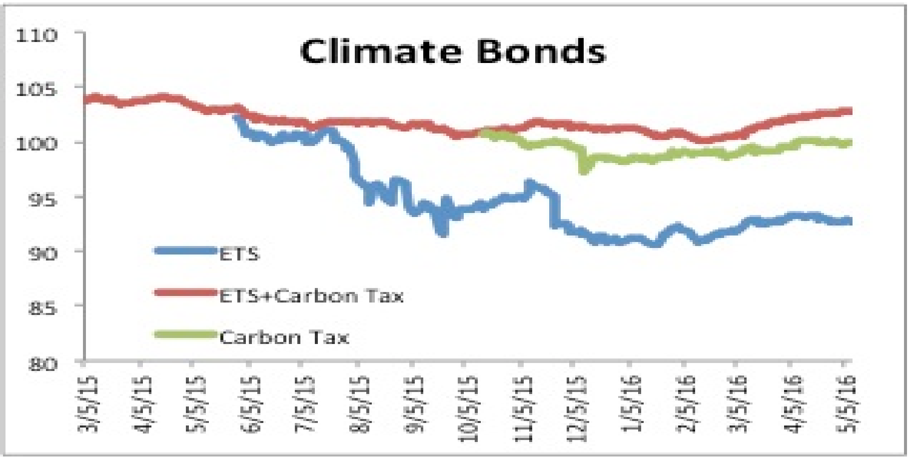

Figure 5: Climate Bonds in different environments

	ETS only	ETS and Carbon Tax	Carbon Tax only
Variance	10.72	1.08	0.41

Table 2: Variance of the green bonds

The main empirical methodology that we are using in our analysis is a panel vector autoregressive model (PVAR). Through this modeling procedure, we were able to identify that there is high similarity in the price performance of the climate bonds in the ETS only or carbon tax only policy environments.

7.2 Interaction of carbon tax, ETS and climate bonds

Section 3 explored the possible ways in which the various climate policy tools might interact. This section empirically explores the changing price of the green bonds when other climate change mitigation policies are implemented concurrently. The ultimate goal is to determine which environment provides the greatest benefit for the phasing of green bonds.

There are three main regressions that we use in estimating the prices of the green bonds. The first environment contains governments utilizing only emissions trading scheme policies (ETS). Another group of bonds represent the environment where the ETS policy is used in conjunction with carbon tax policy (CTETS). The last group of green bonds represent an environment with only carbon tax policies in place as mitigation tools (CT).

The researched green bonds are presented in the Table 3. A majority of countries utilize either ETS policy or CTETS policy as a means of mitigation. Very few countries adopt carbon tax policies alone as a single method. Such situation leads to only a few green bonds that were issued and researched in the countries with CT classification.

Monthly data is collected from October 2014 to June 2016 in order to perform a strongly balanced regression for the three different environments. Dependent and independent variables are described in the Table 4 with corresponding explanation, data sources, and expected signs in the estimations.

We follow Abrigo and Love (2015) and Love and Zicchino (2006) in setting up the panel-data vector autoregression (PVAR) analysis. PVAR combines the traditional VAR approach with the panel data analysis, which allows for the specific individual heterogeneity by introducing fixed effects μ_t. The empirical specification has the following form:

$$\begin{aligned} y_{it} &= \Theta_0 + \Theta_{1t} yield_{it} + \Theta_{2t} vix_{it} + \Theta_{3t} oil_{it} + \\ &\quad \Theta_{4t} tan_{it} + \Theta_{5t} industrial_{it} + \mu_t + \varepsilon_{it} \end{aligned}$$

where the dependent variable is the bond price for individual green bonds, i refers to the environment where the bonds were issued and t refers to 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, 10-Year Treasury Constant Maturity Rate, Chicago Board Exchange Market Volatility Index (VIX), USO United States Oil ETF as an indicator of the crude oil price movement, TAN Guggenheim Solar ETF as an indicator of the demand for the alternative energy companies and a measure of macroeconomic stability, such as industrial production index (*industrial*) for the individual countries where bonds were issued.

	Issue Date	Maturity Date	Maturity Period	Coupon Rate	Par Amount	Amount	Issue Price	Currency	Country of Issue
ETS only									
ABENGOA GREENFIELD SA AS	9/24/14	10/1/19	5	5.50	1000	265,000.00 (M)	100	EUR	Spain
HERA SPA	7/4/14	7/4/24	10	2.38	1000	500,000.00 (M)	99.46	EUR	Italy
KFW	7/22/14	7/22/19	5	0.38	1000	1,500,000.00 (M)	99.47	EUR	Germany
LANDWIRTSCH. RENTENBANK	8/20/13	8/20/20	7	1.46	100000	50,000.00 (M)	100.00	EUR	Germany
IBERDROLA INTL BV	4/24/14	10/24/22	8	2.50	100000	750,000.00 (M)	99.72	EUR	Netherlands
ETS and Carbon Tax									
CREDIT AGRICOLE CIB	9/24/13	9/24/20	7	0.68	1000000	5,410,000.00 (M)	100.00	JPY	France
ELECTRICITE DE FRANCE SA	11/27/13	4/27/21	8	2.25	100000	1,400,000.00 (M)	99.56	EUR	France
UNIBAIL-RODAMCO SE	2/26/14	2/26/24	10	2.50	1000	750,000.00 (M)	98.72	EUR	France
KOMMUNALBANKEN AS	11/21/13	11/21/16	3	0.75	2000	500,000.00 (M)	99.73	USD	Norway
BKK AS	10/6/14	10/6/21	7	1.61	1000000	2,000,000.00 (M)	100.00	NOK	Norway
Carbon Tax only									
DEVELOPMENT BK OF JAPAN	10/7/14	10/6/17	3	0.25	100000	250,000.00 (M)	99.63	EUR	Japan
JOHANNESBURG CITY	6/9/14	6/9/24	10	10.18	1000000	1,458,000.00 (M)	100	ZAR	South Africa

Table 3: Structure of the sample Green Bonds by country of issuance

Variable	Description	Source	Expected sign
Dependent variables			
ets	Green bonds that introduced in the countries with ETS policy only	Bloomberg database	
ets_carbon	Green bonds that introduced in the countries with ETS and Carbon Tax policy	Bloomberg database	
carbon	Green bonds that introduced in the countries with Carbon Tax policy only	Bloomberg database	
Independent variables			
yield	10-Year Treasury Constant Maturity Rate Percent, Monthly, Not Seasonally Adjusted	FRED St.Louis	(-)
vix	VXX iPath S&P 500 VIX ST Futures ETN	Yahoo Finance	(+)/(-)
oil	USO United States Oil ETF	Yahoo Finance	(+)/(-)
tan	TAN Guggenheim Solar ETF	Yahoo Finance	(+)/(-)
Industrial	Industrial Production Index	OECD Database	(+)

Table 4: Variables, data sources and expected signs

The 10-Year Treasury Constant Maturity Rate (yield) is used as a proxy of the volatility of the interest rate. It is expected that the price of the bonds in the different environments would move in the different direction with the yield, therefore the expected relationship is negative. With the environment of negative interest rates extant in Europe, it is expected that the price of the green bonds would benefit, regardless what climate change policy the country has.

All the analyzed bonds in this analysis are classified by the Bloomberg database as being green bonds. Also, we have concentrated our research on only active bonds (that have not matured by June 2016). Time series on the price for those bonds is also obtained from the Bloomberg database. Descriptive statistics for all variables used in the regressions is presented in Table 5. It is necessary to conduct a unit root test before estimating the regressions. We use Im-Pesaran-Shin (IPS) and Fisher unit-root tests in our estimations. The null hypothesis for both tests is the 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 6 presents the p-values for both tests. Taking the first difference on data levels or log difference transformation 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 next look at the empirical results of the estimated regressions and importance of the different environments on the price change of the climate bonds.

Variable	Obs.	Mean	Std. Dev.	Min.	Max
ETS	104	96.33	25.62	7.25	112.98
ETS_carbon	104	103.68	4.98	95.35	114.73
carbon	41	100.60	2.90	92.88	109.32
yield	104	2.12	0.20	1.78	2.53
vix	104	23.48	5.89	13.57	36.87
oil	104	17.02	6.40	9.00	34.41
tan	104	32.82	7.51	22.01	47.00
Industrial	104	100.87	8.80	86.90	114.10

Table 5: Summary Descriptive Statistics

Test	ets	ets_carbon	carbon	yield	vix	oil	tan	industrial
Im-Pesaran-Shin	0.6625	0.4093	0.0806	0.4553	0.3525	0.0000	0.9764	0.0004
Fisher Type	0.6247	0.5966	0.0291	0.5714	0.7705	0.0080	0.9936	0.0124

Table 6: Panel Unit Root Tests

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

7.3 Empirical Results

Using PVAR allows us to look at the simultaneous effect on the bond price issued in different countries with different environments. Also, with the use of this method we can determine the impact of the shock of different variables on the price of the green bonds.

We proceed to estimate variants on the baseline model presented by equation 1 for three groups of green bonds issued in different environments. For ETS policy and CTETS policy environments, five green bonds were used in the estimations. For the CT policy environment, two green bonds were considered due to unavailability of the sufficient time series data on those bonds. Results of the regression analysis for ETS only environment is presented in the Table 7. Table 8 shows the results for the CTETS environment and for the CT policy only.

The Hausman test for partial and complete specification of the baseline model indicated the use of the random effects. The four extensions of the baseline model are reported for each environment (besides CT policy only), with the last model being most inclusive and informative for our purposes.

Table 7 shows the estimation results for the green bonds issued in the ETS policy environment. Presented results show that all the independent variables have positive significance on the climate bonds issued in the countries that have ETS policy. Such findings were not expected and can be attributed to the positive significance of the yield on the price of green bonds. VIX and oil have positive significance on the price change of the green bonds since those variables can represent the risk factor in the environment. Thus, when the environment becomes riskier, investors flock into green bonds as alternative, lower-risk assets. With the development of the economy and growth of the industrial production, the price of the green bonds is growing as well.

Corresponding impulse response functions (IRF) show that the positive shock in the industrial production index of individual countries have a positive effect on the green bonds and then the impulse fades in. Similar reaction can be observed when there is a shock in the yield on the price of green bonds. IRF's for the green bonds issued in the ETS environment is presented in the Figure 6.

	(1)	(2)	(3)	(4)
Yield	0.1165***	0.1253***	0.2365***	0.2308***
	[0.0253]	[0.0097]	[0.0079]	[0.0429]
VIX	0.0053	0.0015	0.0214***	0.0179**
	[0.1004]	[0.0035]	[0.0019]	[0.0102]
Oil		-0.0306***	0.0263***	0.1428***
		[0.0069]	[0.0069]	[0.0216]
tan			0.0833***	0.0786***
			[0.0438]	[0.0228]
Industrial				1.427***
				[0.3402]
Constant	-1.363***	-0.1251***	-0.1115***	-0.1173***
	[0.0179]	[0.0123]	[0.0092]	[0.0302]
Observations	74	74	74	74
Number of panels	5	5	5	5

Table 7: Panel Study Results: Green Bonds issued in the ETS policy environment
Note; Robust standard errors are in brackets. ***,**,* Indicate 1%, 5% and 10% significance levels, respectively

Results for the CT policy environment are presented in Table 8, Models (5) and (6). Due to the limited number of observations the baseline model did not produce the comprehensive results for all the variables. But it's important to note that obtained results highly correlate with the ETS policy only results, from Table 7.

IRF for the CT environment green bonds is presented in the Figure 8. As we noted, the analysis is very close to the analysis of the bonds in the ETS only environment. First there is a positive

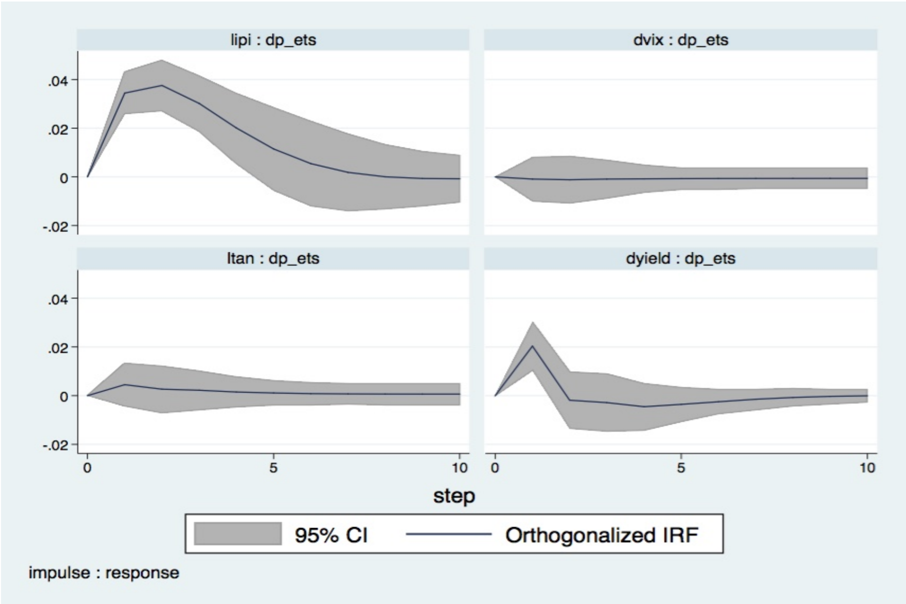

Figure 6: Climate Bonds in ETS policy environment

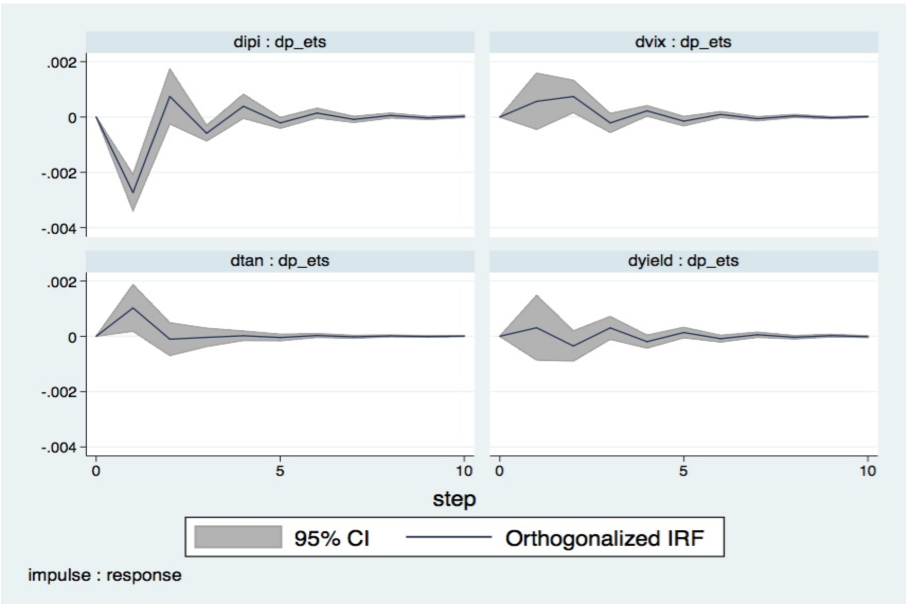

Figure 7: Climate Bonds in CTETS environment

	(1)	(2)	(3)	(4)	(5)	(6)
Yield	0.0024	0.0014***	-3.8712	-0.0109***	0.0067	0.1383***
	[0.0069]	[0.0058]	[0.0043]	[0.0047]	[0.0154]	[0.0513]
VIX	0.0023	0.0024	0.0028**	0.0072***		0.3898*
	[0.0026]	[0.0024]	[0.0017]	[0.0017]		[0.2316]
Oil		-0.0050*	-0.0095***			
		[0.0032]	[0.0037]			
tan			0.0043	-0.0167***		
			[0.0045]	[0.0042]		
Industrial				-0.1632***	0.3437***	1.2667***
				[0.0398]	[0.1262]	[0.5124]
Constant	0.1299**	-0.0213	-0.1389***	0.7429***	-0.3906***	-1.0191***
	[0.0659]	[0.0468]	[0.0483]	[0.1119]	[0.0946]	[0.4433]
Observations	89	89	89	89	35	35
Number of panels	5	5	5	5	2	2

Table 8: Panel Study Results: Green Bonds issued in the CTETS policy and CT policy
Note; Robust standard errors are in brackets. ***,**,* Indicate 1%, 5% and 10% significance levels, respectively

impulse from the shock in the industrial production and then this impulse fades in. As in Figure 6 yield also has a positive impulse on the price of green bonds and then impulse fades in. We can conclude that the results based on the PVAR analysis for two types of environments are very similar.

Finally, Table 8 Models (1)-(4) present results for the baseline regression ran for the CTETS policy environment. We notice that yield has a positive significance for the price of green bonds in Model (2). However, with the introduction of *tan* and industrial production index in the Model (4) yield has a negative significance on the price of bonds. This finding corresponds to our expectations and make the analysis more complete. In the Model (4) it is also important to note index of alternative energy and industrial production index has a negative significance on the price of bonds issued in the CTETS environment. This could be explained that investors are not in the run to invest into alternative energy, when there are so many ways in order to invest in the climate change mitigation products.

From Figure 7, the IRF for the green bonds issued in the CTETS environment show that first there is negative impulse from the shock in the industrial production and then this impulse fades

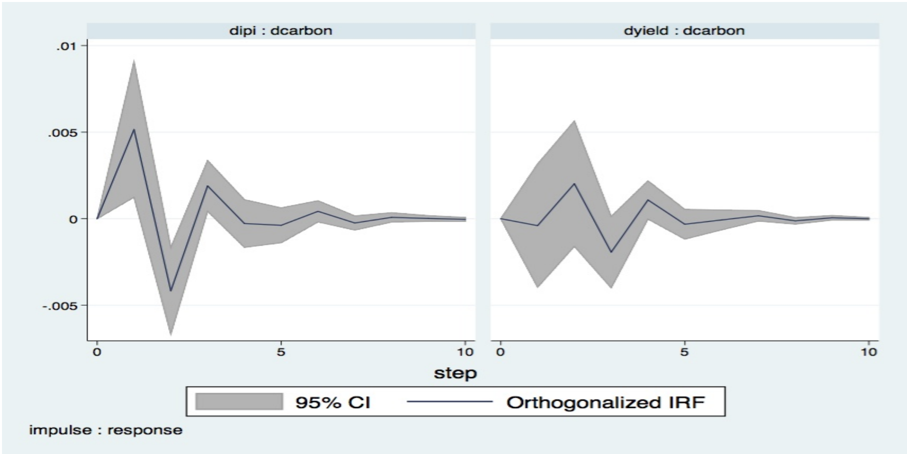

Figure 8: Climate Bonds in CT policy environment

in. Explanation of this could be that investors in the countries where CTETS implemented, invest in the other instruments (corporate bonds, equities, commodities, etc.) in the periods when the industrial production is growing. However, whenever there is a negative shock in the IPI then investors flock into climate bonds, being one of the safest instruments. This finding contradicts our expectations and contradicts to the results obtained for the ETS and CT environments.

Such difference in the obtained results between ETS/CT environments and CTETS environment can be explained by the fact that investors have more resources in order to invest into mitigation of the climate change. Having different policies such as carbon tax, ETS and green bonds, does not limit investment behavior to any specific way of investing into climate change. Thus, obtained results correspond to this logic and show very similar results for the change in the price of green bonds issued in the countries with only ETS or carbon tax policies.

Furthermore, having one policy towards mitigation of the climate change seems to be most beneficial for the price change and demand of the climate bonds. However, from Table 2 and Figure 6 we notice that green bonds issued in the countries with carbon tax policy only outperform green bonds issued in the other countries. Also, variance of the CT green bonds is the lowest comparing to the other researched climate bonds.

Overall, ETS and CT are the two environments that are the most favorable for the climate bonds (surging demand). Bonds issued in the carbon tax environment show the lowest variance and higher performance of their price. However, as we analyzed from the regulatory point of view the carbon tax environment is much more complete instrument for mitigating climate change than the ETS policy. Thus, we conclude that carbon tax environment is the most favorable for the issuance of the green bonds and the appreciation in their price.

8 Conclusions

Policies to mitigate and adapt to climate change must incentive a move away from GHG intensive economic activities as well as to provide funding for a transition to different sources of energy. This paper studies the interaction of carbon tax, ETS and climate bonds as policy instruments. We also explore a private-public partnership to fund climate policies and new forms of energy production. As to the source of funding of climate policies in most current models, such as the IAM, the burden of enacting mitigation and adaptation policies falls on current generations. In order to model new sources of funding we set up an intertemporal model, related to Sachs (2014), that proposes burden sharing of current and future generations. In contrast to Flaherty et al. (2016) the current model includes as funding sources both a carbon tax and climate bonds, which can be used for mitigation policies as well as adaptation efforts. The issuance of climate bonds aids to fund immediate investment in climate mitigation but the bonds could be repaid by future generations who may benefit from reduced CO2 emission and environmental damages. We examine three scenarios by using a new numerical procedure called NMPC that allows for finite horizon solutions and phase changes. We show that a scenario that uses a mix of policies, such as carbon tax and bond financing, is superior to other policy choices. 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 when climate bonds interact with carbon tax and ETS as instruments. We thus study how such climate policies perform given the specific macroeconomic environments we are facing now. The main conclusion is that a mix of policies should be used that give however an important weight to climate bonds as a viable financial instruments for climate policies as well for shifting energy production to large scale renewable energy generation.

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Appendix: New energy generation -Financing of innovations

The financing of innovation for new types of energy is costly, its outcome uncertain and it requires patience and commitment to projects sometimes for decades until profits begin to appear (O'Sullivan, 2005). As a result, finance for innovation has tended to be scarce, with private financial institutions often preferring short-term gains (Haldane 2016). There should be as Arrow has argued in earlier times, some state involvements in fundamental research on innovations. Such a view has given an importance to public financing for invention and innovation, beyond the usual market failure justification as discussed in sections 3 and 4. From the internet to nanotechnology, most of the fundamental technological advances of the past half century – in both basic research and downstream commercialization – were funded by government agencies, with private businesses moving into the game only once the returns were in clear sight. For example, all of the new technologies behind the iPhone were funded by the state, including the Internet, GPS, touchscreen display and the voice-activated Siri personal assistant[6]. The story here is in fact of an 'entrepreneurial state' (Mazzucato, 2013).

Such active public investments were not geared only to government funding of 'basic' upstream research, a typical 'public good' in market failure theory. US government agencies funded both the basic and applied research and, in some cases, went as far downstream as to provide early-stage risk finance to companies deemed too risky by the private financial sector. In its early years Apple received $500,000 from the Small Business Investment Corporation (SBIC), a financing arm of the US government. Likewise, Compaq and Intel received early-stage funding (to set up the companies), not from venture capital but from the public Small Business Innovation Research (SBIR) programme, which has been particularly active in providing early stage finance to risk-taking companies. And across the world, public finance has played an entrepreneurial role in countries like Israel (Breznitz, insert), China (insert), and other emerging countries like Brazil (Burlamaqui, insert).

Given that innovation will be central to solving big societal challenges the world faces – climate change, the demographic transition, and secular stagnation (Bowen & Hepburn, 2015; European Commission, 2015; World Health Organization, 2013), policy on how to finance such transitions must go beyond the traditional questions on overcoming financing constraints' and move towards the more qualitative question of what type of finance—its characteristics— will lead the way. The high uncertainty and long cycles of renewable energy innovation mean that the kind of finance that is needed is that which is patient and not too risk-averse (Gallagher, Grubler, Kuhl, Nemet, & Wilson, 2012).

A recent report by Bloomberg New Energy Finance finds that in 2013 state investment banks were the largest funders of the deployment and diffusion phase of renewable energy, outpacing

[6] M.Mazzucato, 2013 op. cit.

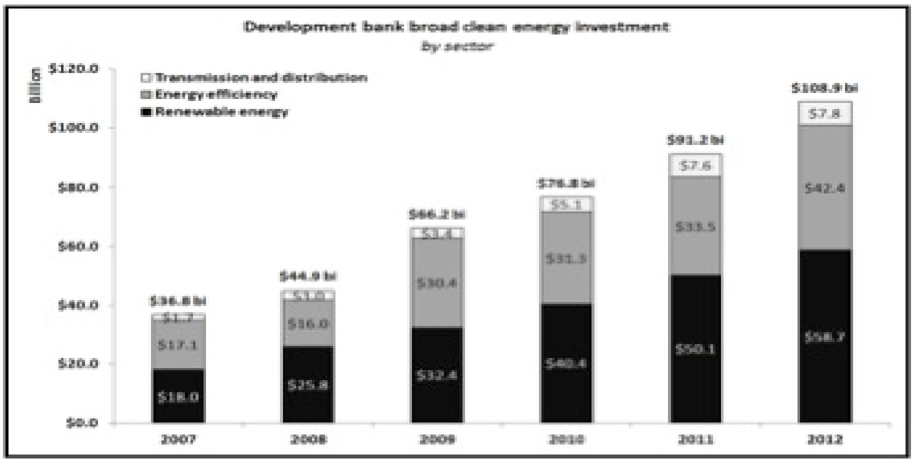

Figure 9: Renewable energy investments financed by SIBs, by sector
Source: Mazzucato and Penna (2014), based on data from FS-UNEP (2013)

investment from the private sector.[7] The four most active banks are (in order) the Chinese Development Bank, the German KfW, the European Investment Bank (EIB), and the Brazilian BNDES. Examples of 'mission-oriented' investments include the European Investment Bank's ď14.7 billion commitment to sustainable city projects in Europe[8], the efforts of KfW to support Germany's Energiewende policies through the greening and modernisation of German industries and infrastructures[9], China Development Bank's investments in renewable energies[10], and the technology fund put in place by BNDES to channel resources toward selected technologies in Brazil (FUNTEC)[11]. Figure 10 below, for example, illustrates the way in which KfW has not only played a classical Keynesian counter-cyclical role, but also directed that funding towards 'climate financing'.

But when state investment banks actively finance innovation and promote transformational objectives, are they just correcting market failures? The lesson from recent 'mission-oriented' programs of SIBs is that in practice they are actively creating and shaping markets, not only fixing them.[12] When successful, they have the capacity to make things happen that otherwise would not, as Keynes called for the state to do.[13] But more importantly, they are paving the way for the kind of 'Great Transformation' that Polanyi referred to when arguing that market-based mechanisms cannot be expected to provide the solution to societal and environmental challenges.[14]

[7]Louw (2012)
[8]Griffith-Jones and Tyson (2012)
[9]Duve (2007); Schroeder et al. (2011)
[10]Sanderson and Forsythe (2013)
[11]BNDES 2012. 'Apoio Inovao', 2012, Rio de Janeiro: BNDES.
[12]Mazzucato and Penna (2015)
[13]J.M.Keynes, op. cit.
[14]K.Polanyi, op. cit.

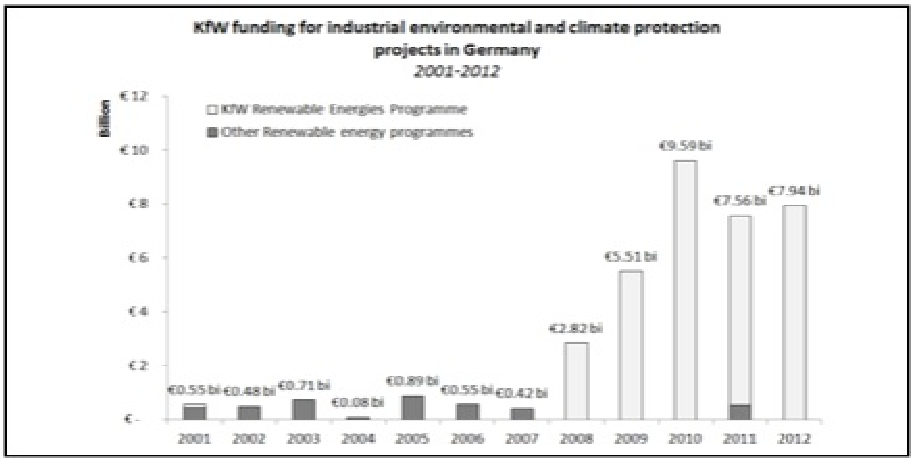

Figure 10: Kfw funding for 'green' projects
Source: Mazzucato and Penna (2014), based on data from KfW's annual reports

At a time in which countries need not only to promote growth but also to address key challenges of this kind, SIBs seem well positioned to effectively promote the much needed capital development of the economy in a smart, inclusive and sustainable direction. Analysing, theorising and constructively criticising what is being done is a new agenda for economists. This agenda would improve our understanding of the degree to which the activities of a state investment bank can open up new technological landscapes and economic opportunities – making new 'Great Transformations' happen.