DE GRUYTER OLDENBOURG Journal of Economics and Statistics 2025; aop

Under Debate

José Pedro Bastos Neves* and Willi Semmler

A Carbon Wealth Tax: Modelling, Empirics, and Policy

https://doi.org/10.1515/jbnst-2024-0078
Received October 4, 2024; accepted March 25, 2025

Abstract: Although economists widely advocate carbon pricing as an effective solution to reduce carbon emissions, this mechanism has had so far limited effects. This paper proposes a new type of tax to help finance (and accelerate) the green transition. A carbon wealth tax (CWT) is proposed to be levied on carbon-intensive (brown) wealth rather than primarily on carbon-intensive goods. We consider tax implementation issues such as tax base, incidence, and efficiency. Moreover, we analyze the impacts of such a tax scheme by setting up a model of asset pricing and dynamic portfolio decisions. Green and carbon-intensive returns used in the model are calibrated with low-frequency returns on stock prices between 2010 and 2021. We find that such a tax and subsidy scheme is a feasible and effective instrument in speeding up the transition to a greener economy, particularly in protracted periods of economic contraction. Our approach also brings a new perspective to the wealth inequality discussions.

Keywords: climate change; taxation; wealth; portfolio optimization

The views expressed in this article are those of the author and do not necessarily reflect the views or policies of Brazilian Ministry of Finance

Earlier versions of this paper have been presented at the Henry George School of Social Science, June 2022 and the 26th Forum for Macroeconomics and Macroeconomic Policies (FFM) Conference, Berlin, Germany, in October 2022. This work has benefited from insightful comments from Katherine Pratt, David Gamage, and Shi-Ling Hsu made at the Tax Policy Colloquium of the Loyola Law School, October 2022. We would like to express our special thanks to Joao Paulo Braga for assisting us on the harmonic estimations. We are also grateful for helpful discussions with Tom Krebs, Werner Roeger, Claudia Kemfert and Dorothea Schaefer. We also want to thank the reviewers and the editor of the Journal for excellent comments on our paper.

***Corresponding author: José Pedro Bastos Neves**, Brazilian Ministry of Finance, Brasília, Brazil, E-mail: bastj193@newschool.edu. https://orcid.org/0000-0002-0275-9788
Willi Semmler, The New School, New York, USA; Bielefeld University, Bielefeld, Germany; and IIASA, Laxenburg, Austria. https://orcid.org/0000-0002-8384-8159

JEL Classification: G11; H23; Q58

1 Introduction

There is an increasing consensus on the urgency of tackling climate change. However, limiting the temperature increase to 1.5 C implies a CO_2 reduction greater than that achieved in the last decades. As the IPCC 2018 stated, for a 2 degree Celsius threshold the world carbon emissions must fall 25 % from 2010 levels by 2030 and reach net zero emissions by 2070 (Masson-Delmotte et al. 2018). In order to constrain the global warming to 1.5°, the net emissions must be halved by 2030 and decline to net zero by 2050. Most likely, that additional reduction needs to come from fossil fuels, as they are the main contributors to global warming in radical mitigation pathways (Luderer et al. 2018; Masson-Delmotte et al. 2018).

Carbon pricing is currently the most popular economic policy for climate mitigation, both in the literature and in practice. In the 2010s, governments at national and state levels introduced climate-oriented policies at a record pace. The latest data compiled by the World Bank shows that 46 national jurisdictions implemented at least one form of carbon pricing on just over 22 % of global greenhouse gas (GHG) emissions (2021).

Their popularity, however, contrasts with the actual results of carbon-pricing policies implemented so far. Although econometric estimates suggest a significant impact on CO_2 emissions, carbon pricing has yet to reduce global emissions to the required levels. This is because a large portion of emissions is still not priced, and the current carbon price is significantly below what would be necessary to lower emissions to a sustainable path (Stiglitz et al. 2017). On the other hand, higher carbon prices have led in may countries to popular unrest since they were experienced as distributionally regressive.

While mitigation efforts have gained momentum, meeting the climate challenge at this stage will require not only intensifying current solutions but also implementing new and innovative ones.[1] Even if all the national plans (Nationally Determined Contributions, or NDC) for CO_2 reductions submitted to the Paris Agreement are fully implemented, there would be an additional 14Gt CO_2 reduction

1 The climate change policy literature usually considers alternatives, such as energy efficiency standards and subsidies to carbon-free technologies. These practices are better seen as complements of, and not substitutes to, carbon taxation, generally because of their lower social cost (Nordhaus 2013). Also, the Stiglitz-Stern report 2017 indicates that involving other instruments halved the requisite implicit carbon price (Stiglitz et al. 2017). Arguments backing this allegation often include the complexity of government regulation, the discretionary aspect of it, the potential harm of ill-designed policies, and the political interference that vested interests can exert.

required to meet the least-cost path goal (Fawcett et al. 2015; Masson-Delmotte et al. 2018; Rogelj et al. 2016).

To fill this gap, we propose a carbon wealth tax (CWT) to complement current carbon pricing efforts and accelerate the green transition. Our work discusses how a tax scheme such as CWT could be implemented by governments, addressing its tax base, incidence, and efficiency. Moreover, to investigate the effects of the proposed taxation on consumption and asset allocation patterns, we set up a dynamic portfolio model incorporating alternative tax regimes in asset returns, thus impacting the investor's decisions. We use it to compare the wealth, consumption, and allocation trajectories under alternative tax scheme specifications. We expect that the CWT will decelerate the accumulation of carbon-intensive assets in favor of green ones, contributing thus to the green transition. Moreover, we also investigate the case where the revenues raised with the proposed tax can be further recycled into subsidies to green capital.

Empirically, we calibrate our model with low-frequency returns estimated from S&P 500 companies' stock prices. Moreover, the differentiation of green from carbon-intensive companies is a crucial element of our empirical strategy. In this paper, we rely on ESG firm-level data on carbon emissions, and we consider our choice by comparing it to the alternatives in the literature, particularly the carbon disclosure efforts from Central Banks and the private sector. Overall, our results show the feasibility and relevancy of the CWT as a climate policy instrument. In addition, a CWT should be much more preferable, in terms of the distributional perspective and burden sharing of mitigation policies.

Indeed, a fundamental *rationale* for a CWT can be derived from the public finance literature. The proportionality principle in taxation, revived by the work of Richard Musgrave (Musgrave 1973), maintains that those who enjoy a higher proportion of public goods need to pay higher taxes. Viewed in reverse, this means that those who create a higher proportion of "public bads" (Beckerman and Markandya 1974) – meaning negative externalities – need to pay a higher tax. Brown capital stock locks the economy in an unsustainable path from which no individual can exclude themself. In other words, it implies non-excludability, and, in that sense, it can be thought of as a public bad. The idea of "public bads" is also related to the joint production system where there are non-zero disposal costs (Hinrichsen and Krause 1981). In this case, the unwanted products – in our case, carbon emissions – entail a cost that is not acknowledged in the price system, making a case for taxation.

The CWT can accelerate the green transition because it directly tackles the polluting asset, whereas the classic carbon tax targets the flow of emissions associated with the consumption or production of carbon-intensive goods, hence is basically an excise tax affecting everybody. In this respect, recent work has shed light on the relevancy of brown capital (carbon-intensive industries and firms, power plants, transportation infrastructure, etc.) to carbon emission dynamics. First, the emerging economies that are still building up their capital stock are likely to contribute to higher emissions quite soon (Semieniuk et al. 2021). Secondly, those industries with a long life cycle lock the economy into a carbon-intensive path: investments in brown capital today imply emissions for a long time in the future (Luderer et al. 2018; Pfeiffer et al. 2016). Some authors, thus, refer to the committed cumulative emission (CCE), a type of carbon budget associated with energy and transport investment projects (Pfeiffer et al. 2016). In some calculations, these locked-in emissions already fill up most of the carbon budget (Davis and Caldeira 2010). In this context, policies incentivizing disinvestment and rapid depreciation in installed capacity in dirty sectors are pivotal for the green transition.

Furthermore, by explicitly tackling production factors so far missing from climate policy-making, namely, carbon-based wealth and capital return, the CWT echoes a growing public (and academic) concern with low levels of corporate taxation. The recent debate on wealth taxation (Guvenen et al. 2019; Saez and Zucman 2019) suggests that such a tax can have meaningful consequences on the dynamics of capital increase. In economic theory, more recent studies have shown that finite-lived agents (Golosov et al. 2006), heterogeneity in asset's returns (Guvenen et al. 2019), and the introduction of a wealth motive in the utility function (Saez and Stantcheva 2018) undermine the classic capital taxation results from the 1970s and 1980s (Atkinson and Stiglitz 1976; Chamley 1986; Judd 1985). Empirically, Piketty (2013), amog others, demonstrated that wealth is highly concentrated in terms of the Gini coefficient, much more than income, and follow-up works have associated the recent trend in inequality with the decrease in corporate taxation.

Following this introduction, Section 2 is concerned with the literature on carbon emissions, particularly with the carbon taxation schemes that have been discussed and implemented so far, and on the debate of wealth taxation. We aim to highlight how insights from wealth taxation relate to the debate on carbon taxation. In Section 3, we introduce our theoretical model to investigate the dynamics of such a proposal. Section 4 discusses our estimations and results, and finally, Section 5 concludes.

2 Literature Review

This paper brings together strands of the literature that have flourished in recent years but that have not yet had a significant interconnection. The first one is the prolific literature on carbon pricing and its impact on emissions. The second is the debate on the optimum level of capital (and wealth) taxation, brought about by recent theoretical challenges, as well as the empirical relationship between downward corporate taxation and increasing wealth inequality. The third type of literature is the one on public finance and on public "bads", as mentioned above.

2.1 Carbon Pricing Mechanisms

Carbon pricing consists of two alternative policies: carbon taxation and cap-and-trade systems (Metcalf and Stock 2020; Stiglitz et al. 2017). They diverge in that while carbon taxes are levied on the use of fossil fuels, cap-and-trade sets a limit on emissions and allows producers to trade their "right to pollute". In other words, carbon tax sets a price target and lets the quantity float, whereas the cap-and-trade system does the opposite (Stavins 2019).

The preference for one scheme over the other varies in the literature. Prominent names advocating for carbon taxes include Nordhaus (2008). The arguments range from the simplicity of the tax system (Stavins 2019) to avoiding the potential price volatility associated with a quantity constraint that may further deter the investment process. It has also been pointed out that a price-setting policy works better in a scenario with non-linear climate damages caused by carbon emissions and linear mitigation benefits. The opposite vision (Stavins 2019) argues that quantitative goals, such as emission abatements, are better tackled by cap-and-trade, due to their reliance on quantitative emission allowances. However, from the distributional and cost viewpoints, both devices produce equivalent outcomes (Stavins 2019).

Empirical work has found that carbon pricing has a discernible, albeit limited, impact on emissions. Among the multi-country studies, Best, Burke, and Jotzo (2020), using panel data on carbon emissions for 142 countries, found a 2 % decrease in emissions after the adoption of carbon pricing. On the other hand, Haites et al. (2018) investigates all the 55 jurisdictions that had at least one form of carbon policy in 2015. He found that the carbon tax reduced emissions concerning business-as-usual (BAU) scenarios, but not in absolute terms. Emissions Trading Systems (ETS) schemes have fared better, reducing more CO_2 while costing less. Metcalf and Stock (2020), estimating an SVAR model for 31 European countries, found that the scheme led to a CO_2 reduction between 3.8 % and 6.5 % according to the model specifications.

As for scheme-specific evaluations, there is mixed evidence on the European Union ETS effectiveness. One work finds a decrease in emissions between 2 % and 6.3 % during the program's first 2 phases (Narassimhan et al. 2017), although accounting for the economic crisis may reduce this number substantially (Bel and Joseph 2015). Contrarily, Biancalani et al. (2024), using a methodology of matrix completion method, find a more substantial decrease of 15.4 %. Looking at other jurisdictions, Pretis (2019), using a difference-in-difference model for British Columbia, found that despite a 5 % reduction in transportation emissions, carbon taxation failed to impact aggregate pollution. Martin, De Preux, and Wagner (2014) investigating England's Climate Change Levy, determined that it lowered CO_2 emission by 8.4 % and 22.6 % in firms subject to the levy compared to other firms. Lin and Li (2011), analyzing northern European countries, found that in 4 out of 5 of them, reductions remained between 0.5 % and 1.7 %.

It is clear from the above that, although the point estimates vary considerably, they all fall short of the reductions required to mitigate climate change. It has to be taken into account the fact that the EU ETS does not cover all sectors due to, among other reasons, political restrictions. Currently, it covers domestic aviation, heavy industry, such as steel, aluminum and chemistry, and power sectors (International Carbon Action Partnership 2024). The 4th phase of the program, that will set the rule for the system until 2030, will increase the scope to cover also sectors such as maritime transportation and buildings, while also increasing the program's reduction goals (European Commission 2024). Thus, the emission results are driven in an important way by political factors, and are not a shortcoming of the instrument itself.[2]

One of the features of carbon pricing that was developed to lower the political resistance against it was the use of revenues to lower decarbonization costs for firms and reversing the distributional effects. Therefore, the literature also analyzed additional benefits coming from the potential uses of carbon revenues. Indeed, revenues associated with carbon pricing are significant and increasingly so. Earlier literature showed, for example in 2013, that they totaled USD $27 billion, in 2017, USD $32 billion (Haites et al. 2018). For 2013, 70 % of ETS revenue was used for green subsidies, while 9 % was used to lower other taxation. For the carbon tax revenue, these figures were 15 % and 44 %, respectively (Haites et al. 2018).

The so-called second dividend, or revenue recycling, literature stresses that carbon revenues are a vital feature in securing efficiency in the policy choices (Bovenberg and Goulder 1996; Goulder, Parry, and Burtraw 1996). Provided that the second dividend is strong enough, a carbon tax could be adopted with zero net cost for the economy and also avoids the precise calculation of the environmental benefits of the carbon tax (Bovenberg and Goulder 2002). Historically, there were two

2 The same kind of restrictions – in fact, one would expect even greater political restrictions – would apply to a CWT. This point was raised by one anonymous referee. However, it should be noted that the political resistance would be come from different sectors. The CWT, being a form of wealth taxation (and financial regulation), would face more resistance from the financial sector. On the other hand, with less impact on final prices, it could potentially avoid popular resistance that traditional carbon pricing has faced, such as the yellow vest movement in France.

forms of recycling: subsidizing green investments (Nordhaus 2013), or reducing other kinds of inefficient taxes (Bovenberg and Goulder 1996). In this respect, the current taxation mix is crucial, and a carbon tax can improve efficiency provided that it shifts the tax burden from inefficient, high marginal excess burdens to low marginal excess burdens.[3]

So far, the majority of studies have suggested the use of carbon revenue to cut capital taxation (Bovenberg and Goulder 2002). Parry and Williams III (2012) find that the efficiency gain can be higher if the recycling scheme produces a shift of taxation from capital to labor. Some authors have gone even further to claim that the benefits of recycling exist only if this shift away from capital taxation takes place (Bovenberg and Goulder 1996). Alternatively, Metcalf (2007) proposes using carbon tax revenue to decrease income tax by issuing tax credits equal to payroll taxes. According to the authors, this tax mechanism is sufficient to improve the tax's progressiveness. Overall, one main finding is that policy design is instrumental in shaping the distributional effects of carbon taxation.

2.2 Wealth Taxation

The literature has considered the use of carbon revenue to decrease capital taxation partly because economic theory modeling had traditionally maintained that optimality conditions include a zero rate for capital tax. However, there have been recent challenges to this result, which raises the question of using carbon pricing not to lower capital taxation, but to raise it.

A striking conclusion from the classical taxation models is that capital taxation should be zero. For example, Atkinson and Stiglitz (1976) used a life-cycle model to show that taxing only labor is always more efficient than taxing a mix of labor and capital. Moreover, the canonical models of Chamley (1986) and Judd (1985) showed that the steady-state optimal capital taxation is zero when the long-run capital supply is infinitely elastic.

However, recent developments have cast doubts on such results. Saez and Stantcheva (2018) show how incorporating wealth into the utility function produces heterogeneity in wealth (unrelated to heterogeneity in labor earnings), invalidating the zero capital tax result of Atkinson and Stiglitz (1976). Building on the same assumptions of the canonical models, Straub and Werning (2020) proved that intertemporal elasticity below one is already sufficient to produce positive capital taxation. Guvenen et al. (2019), in turn, studied an economy in which agents, because

3 Specifically, that happens if the environmental burden falls on the factor with a low marginal excess burden, or if the revenues are used to reduce taxes on the high marginal-efficiency cost factor.

of their idiosyncratic abilities, can extract different returns from the assets. This heterogeneity is enough to yield a rationale for wealth taxation since it penalizes the idleness of the asset holder.

Yet, empirically, it is a well-documented fact that developed countries have extensively lowered corporate taxation in recent decades. On average, the statutory corporate income tax rate was around 33 % in 2000, dropping to less than 25 % in 2020 (OECD 2021). This downward trend was mirrored by an upward trend in wealth concentration. For the US, China, UK, and France, Alvaredo et al. (2017) found that since 1990 there is a clear upward trend in the share of wealth for the 1 % bracket.

Scheuer and Slemrod (2021) highlight the challenges associated with wealth taxation, noting that currently, only three OECD countries continue to impose such taxes. The decline in wealth taxation is largely attributed to its unintended consequences, including shifts in saving behavior, portfolio adjustments, and significant levels of tax avoidance and evasion. These challenges raise concerns about the effectiveness and enforceability of wealth taxes, particularly in the context of highly mobile capital. However, the carbon wealth tax (CWT), by targeting returns on carbon-intensive assets rather than net wealth in general, circumvents some of these issues by focusing on taxing revenue flows rather than accumulated wealth. Nevertheless, problems related to avoidance and evasion remain, necessitating strong international coordination, as further discussed in Section 5.

Thus, the historically low levels of corporate tax, together with the recent theoretical developments, support our consideration that the increase in carbon pricing required by climate change may assume the form of additional taxation on asset returns.

2.3 Tax Implementation and Incidence

Usually, a wealth tax's base is the net worth of individuals or companies. This is the case in Saez and Zucman (2019) and Jakobsen et al. (2020), whose tax base is the household's net wealth, including all financial and non-financial assets net of liabilities. There is also the proposal of Guvenen et al. (2019), where the tax base consists of all assets in the economy (thus ignoring the liabilities).

In the present work, we consider wealth taxation as an additional tax on (brown) capital returns. Although different in form, actually, the tax on a stock of wealth and on the flow of income from wealth can be equivalent. This is so because a sufficiently high capital income tax has the same effect as a small tax on the entire wealth. To see why, consider the following after-tax wealth equations from Guvenen et al. (2019), where w_i is the individual's wealth, r is the return on wealth, τ_k is a capital revenue tax, and τ_w is a wealth tax. It is possible to write the following:

$$w^{after-tax} = w_i + (1 - \tau_k).r.w_i \tag{1}$$

$$w^{after-tax} = (1 - \tau_w).w_i + (1 - \tau_w).r.w_i \tag{2}$$

Combining Eq. (1) and Eq. (2) gives us a mapping from the capital income tax into wealth tax:

$$\tau_w = \frac{\tau_k.r}{1 + r} \tag{3}$$

Therefore, there is always a (high) level of capital income taxation that corresponds to tax levied directly on wealth (Auerbach 2008).

There are important reasons that justify opting for taxing capital returns. First, the implementation is straightforward, since capital taxation is already adopted in a majority of countries, whereas net-worth taxation is much less so. Secondly, it overcomes opacity issues. As pointed out by Kopczuk and Mankiw (2019), net-worth taxation is not based on observable arm's-length transactions, which would hinder the government's oversight and give incentive to under-reporting.[4] Finally, this option has been considered in policy discussions to tax wealth. For example, the 2023 Budget of the U.S. Government includes the introduction of a "tax on billionaires", which relies on a special tax on investment gains for individuals whose net worth is above the $100 million threshold (Office of Management and Budget 2022).

Next, we discuss the crucial issue of tax incidence. The classic model of Harberger (1962) showed that, in a two-sector general equilibrium model, the sector in which the tax is levied is not necessarily the one that ends up paying for it. The result was that the capital taxation would be borne by the two forms of capital in proportion to their relative size (Auerbach 2006). In the case of CWT, this problem is less stringent. First, brown sectors are the greater part of the capital stock, so the incidence would still fall on the targeted sector. Secondly, the low substitutability between brown and green capital hinders tax shifting. Moreover, to the extent that substitutability happens, with brown capital moving to the green, tax-free sector, that is actually what is intended in a green transition context.

A potential shortcoming in our proposal is related to the tax's efficiency. All wealth tax schemes are subject to prompt capital flight to foreign countries, thus increasing tax evasion problems. To the extent that the CWT is adopted by only one or few countries, it would be subject to the same criticism. However, capital flight depends crucially on the elasticity of capital supply. In this respect, there is at least some evidence that the elasticity is not high (Saez and Stantcheva 2018).

4 This is, by the way, is one of the reasons why the only form of wealth taxation that continues to be commonly adopted by governments is the estate taxation: inheritance of property is the one occasion where agents have to disclose and evaluate fairly their assets to the government.

2.4 Identification of Green and Brown Assets at the Firm Level

Finally, the CWT relies fundamentally on the discrimination between green and brown assets. The literature on climate economics provides us with two ways of identifying green and brown activities: one at the sector level and the other at the firm level.

The sector-level identification is relevant for a broad range of climate topics, such as the impact of carbon pricing and green subsidies in technological efforts (Acemoglu et al. 2012) the study of the production function's substitutability between clean and dirty energy (Malikov, Sun, and Kumbhakar 2018; Papageorgiou, Saam, and Schulte 2017), and forecasting the net impact of the green transition in employment levels and patterns (Markandya, Arto, González-Eguino, and Román 2016).

In practice, it is usual to assess the sectors' carbon intensity using the Input-Output framework, which combines information of economic activity with the CO_2 emission per sector. Publicly available databases, such as the World Input-Output Database (Timmer et al. 2015) compile information spanning several years and almost 40 countries. Energy use data are collected from different sources, including the International Energy Agency, OECD, and Eurostat. Additionally, some countries' statistics bureaus publish environmental tables in their national accounts. Notably, Germany has an accurate and detailed table, which has been used, for instance by Kato et al. (2013) and Mittnik and Semmler (2022), to differentiate between dirty and green sectors. Advantages of this approach include its broader scope since it (in principle) covers all the companies' activities in each economic sector. Moreover, input-output methods, such as the Hilferding–Hirschman, allows the calculation of the downstream and upstream emissions associated with a specific economic activity.

However, in the context of taxation, the sectoral classification is not sufficient. For one, taxes are usually levied on firms, not sectors. Moreover, carbon pricing schemes aim at aligning incentives towards the adoption of mitigation and adaptation actions. In that case, the relevant differentiation is not between polluting and non-polluting sectors but firms. Fortunately, there is a second identification approach that assesses directly how much carbon emissions are associated with the activities of each company.

In advanced countries, governments are moving in the direction of mandating firms to disclose data on their environmental actions, in particular carbon emissions. Table 1 summarizes the carbon disclosure efforts in the European Union, the United Kingdom, and the United States. We refer to the Appendix for a fuller discussion of each action. In general, they target publicly listed or large companies,

Table 1: Main disclosure efforts.

Country	Scope	Implementation date	CO_2 metrics
EU	Corporate bonds held by ECB	Early 2023	Sector-specific actions on mitigation/adaptation
UK	Listed/large private companies, financial sector	2025	GHG (Scope 1 and 2)
US	Listed companies (SEC registrants)	2024 (If approved)	GHG (Scope 1, 2, and 3 if material)

mandating the disclosure of climate-relevant information in the next few years. Importantly, in the case of the UK and the US, the carbon metrics underlying this regulation are the 3-scope methodology calculated by the GHG Protocol or the Carbon Disclosure Project. It is the same metrics that we rely on in our empirical strategy to classify green and carbon-intensive capital, which we detail in Section 4.1. As more and more firms use these metrics, it is expected that they will advance in terms of standardization, comparability, and availability of CO_2 emission metrics. Thus, reinforced by the expansion of ESG finance, we expect that carbon emission metrics at the firm level will be widely available information in the near future.

In summary, a CWT on capital returns in the brown sectors and firms is feasible and reasonably efficient, in the sense that it is levied broadly on the targeted factor.

3 The Model

The dynamic portfolio models were first introduced by Merton (1973, 1975) to investigate wealth trajectories according to different asset allocations. In the model's framework, there are two classes of assets available for investors, one risky and the other risk-free. They maximize an expected intertemporal utility derived from consuming a portion of their wealth. Their sole source of income is the asset returns from their portfolio. During each period, the agent faces two choices: how much of their wealth to consume, and how to allocate their portfolio between the available assets.

This class of models resembles the more popular capital asset pricing model (CAPM) introduced by Markowitz (1952), although there are crucial divergences. Most importantly, unlike the CAPM where asset returns are usually static, the dynamic portfolio model features time-varying returns, which in turn are particularly useful for capturing asset-specific externalities and varying investment horizons (Semmler et al. 2021).

Indeed, the dynamic portfolio model was recently used in climate economics by Semmler et al. (2024), who investigate the effects of short-termism on wealth allocation (and green investments) in a green transition context. Braga (2022) also uses the same framework to investigate the investor's behavior (and investment decisions) in a financial market increasingly affected by environmental issues. His model features green and brown bonds whose yields explicitly depend on climate positive (and negative) externalities, see also Lichtenberger, Braga, and Semmler (2022).

Similar to these works, our model shares the view that environmental risks will affect investment decisions in meaningful ways. However, we expand the other dynamic portfolio models by introducing an exogenous, asset-specific tax regime. The government levies taxes either on consumption or on financial assets. There is no public debt, so we assume that the government runs a balanced budget throughout. Tax revenues may be used to subsidize green investments. This framework allows us to address questions relevant to the climate economics literature, such as the effects of taxation in accelerating a green transition, its particular role in funding green investment while also tracking wealth trajectories, and an investor's portfolio allocation decisions.

The problem is not trivial since asset taxation changes substantially the pattern of time-variant returns, hence impacting wealth dynamics. Guvenen et al. (2019) addressed the effects of tax regimes on asset return heterogeneity across households and periods. Returns are not permanent and do not necessarily replicate past performances. But while their focus is on the households – i.e. the ability of, say, gifted entrepreneurs in extracting higher yields from a capital asset, ours is justified by the heterogeneity of capital.

In our model, there are three kinds of assets: brown, green, and safe assets. Whereas the share of investments in the safe asset is exogenous, the share of portfolio allocation in brown and green assets is optimally determined at each period. By Merton's original formulation, the investment's return increases wealth from one period to another. Safe assets are assumed to yield a constant rate of return of 3 %, and the proportion of wealth allocated to safe assets in each period is denoted by $(1 - \pi_{1,t})$.

On the other hand, both green and brown assets are subject to time-varying returns. $\pi_{2,t}$ is the share of risky investments allocated to green assets, and $(1 - \pi_{2,t})$ to brown assets. A representative investor chooses to hold any proportion of them, bounded by 10 % and 90 %, so that they always diversify a small fraction, but are not allowed to go to short-selling.

The investor's problem is to optimally allocate its wealth on each asset at each period in order to maximize utility derived from consumption. In each period, they choose the consumption level c_t together with the portion allocated to green and brown assets $\pi_{2,t}$. The indirect utility function is given by:

$$\max_{c,\pi} \mathbb{E}\left\{ \int_S^N e^{-\delta_0 (t-s)} F(c_t W_t) ds \right\} \tag{4}$$

The asset utility of the owner stems from consumption in current and future periods. We specify the utility's function form as a log utility function:

$$F(c_c W_t) = log(c_t W_t)) \tag{5}$$

The state equation represents the dynamic wealth process. In each period, the time-variant asset returns increase the investor's wealth. In practice, the wealth grows by the weighted average of the three types of return: safe, green, and brown. On the other hand, wealth is subtracted by the amount the investor chooses to consume, as well as by the transaction costs of transforming assets into other assets. Transaction costs have long been considered in the portfolio optimization literature (Cadenillas 2000). In our specification, we follow Duffie and Sun (1990) and Liu and Loewenstein (2002) in setting them proportionally to the assets held (and thus to the investor's wealth). The resulting state equation is:

$$\dot{W}(t) = \pi_{1,t}\pi_{2,t} W_t r_t^g + \pi_{1,t}(1-\pi_{2,t}) W_t r_t^c + (1-\pi_{1,t}) W_t r_t^f - c_t W_t - X(\Pi_t, W_t) \tag{6}$$

The allocation proportion $\pi_{2,t}$ is the key variable as it determines the share of green investment in the economy. A similar approach was used by Bonen et al. (2016), who also investigate the green transition dynamics through the share of capital allocated to growth or adaptation and mitigation purposes. Hence, in our model, the behavior of $\pi_{2,t}$ across time represents the ability of the economy to finance the green transition. We expect that taxation and subsidies to alter the variable's behavior, in particular in early periods when green investment is more crucial to a green transition.

The central variable determining portfolio allocation is the time-varying return on assets. We model the green and brown returns using harmonic estimation in the same way as Chiarella et al. (2016). The process uses the Fast Fourier Transform to obtain the low-frequency oscillations, that we later incorporate into the dynamic portfolio model. The resulting equations follow the form:

$$r_{brown} = \sum_{k=1}^{k} \alpha_{1,i} sin\left(\frac{1}{\omega_{1,i}} 2\pi\right) + \beta_{1,i} cos\left(\frac{1}{\omega_{1,i}} 2\pi\right) \tag{7}$$

$$r_{green} = \sum_{k=1}^{k} \alpha_{2,i} sin\left(\frac{1}{\omega_{2,i}} 2\pi\right) + \beta_{2,i} cos\left(\frac{1}{\omega_{2,i}} 2\pi\right) \tag{8}$$

We add to these two equations the different types of tax – excise tax, capital (wealth) tax, and green subsidies – to evaluate the impact they may have on the transition to a green economy. Returns are modified by wealth taxation, understood as a high level of τ_k. Brown returns decrease proportionally to the incidence rate, whereas green returns increase in case the tax revenue is spent as subsidies. The latter has an additional corrector term $\frac{1-\pi_{2,t}}{\pi_{2,t}}$ that factors in the relative size of the brown assets in the portfolio. It captures the fact that as allocation shifts between brown and green sectors, so does the CWT tax base.

$$r_{brown}^{after-tax} = r_{brown}.\,(1-\tau_k) \tag{9}$$

$$r_{green}^{subsidies} = r_{green}.\,(1+\tau_k).\frac{(1-\pi_{2,t})}{\pi_{2,t}} \tag{10}$$

We consider two cases for the CWT. First, the additional capital gains taxation τ_k is levied on the carbon-intensive assets only, but no use is made of the revenue thus generated. This allows us to assess the effect of pure taxation and is relevant for fiscal adjustment scenarios where the government uses revenues to repay debt. In this case, the green returns are unaffected by the tax regime. Conversely, in the second case, the revenue is converted into a subsidy for investment in green assets, effectively raising its return.

Finally, to allow comparison to the classical carbon tax, we consider an ad-valorem excise tax τ_c that falls on the consumption goods (Barrage 2020). In principle, to consume the same basket the investor would have to dedicate a higher proportion of their wealth, impacting its dynamic negatively. The result, shown in Equation (6), is a modified state equation, as it is done in Bovenberg and Goulder (2002) and Bovenberg and Goulder (1996).

$$\dot{W}(t) = \pi_{1,t}\pi_{2,t}W_t r_t^g + \pi_{1,t}(1-\pi_{2,t})W_t r_t^c + (1-\pi_{1,t})W_t r_t^f - (c_t+\tau_c)W_t - X(\Pi_t, W_t) \tag{6'}$$

4 Data, Results, and Discussion

4.1 Data

We estimated the returns on equity in the following way. First, we obtained daily equity prices from the S&P 500, the market index that tracks the 500 largest companies listed in the United States. We transformed it into a monthly series by selecting the last day of each month. The period covered is from January 2010 until

September 2021, totaling 141 observations. Next, the individual company prices were aggregated into portfolios using the respective S&P 500 weights. Specifically, we computed the portfolio value as:

$$P_t = \sum_{i=1}^{n} \omega_i \epsilon_{i,t} \tag{11}$$

where P_t is the total portfolio value, ω_i is the individual S&P 500 weights, and $\epsilon_{i,t}$ are the individual stock prices. Finally, the resulting portfolio prices were used to obtain monthly logarithmic returns.

We classified firms as clean or dirty based on two metrics of the MSCI ESG index, which evaluates the environmental performance of over 8,000 companies and bonds. In this, we follow other works that have used ESG criteria to assess a portfolio's carbon footprint (Bolton and Kacperczyk 2021; Jondeau, Mojon, and Pereira da Silva 2021; Schoenmaker 2021). The first metric is the "Carbon Emissions Weight," which captures the importance of the company's sector to environmental issues. The second metric is the "Carbon Emissions Score", which grades from 0 to 10 the companies individually by their carbon emissions and climate mitigation efforts. This criterion relies on self-reported and Carbon Disclosure Project data.

First, we used the weighting index to keep only the 25 % highest weights in the dataset. Our use of sectoral emission data as thresholds to determine portfolios follows the strategy in Jondeau, Mojon, and Pereira da Silva (2021). In practice, this narrowed our sample to companies operating in the most crucial sectors of climate efforts. Next, we further subset the companies based on their performance grades. We classified the 30 % lowest-ranked firms as dirty, and symmetrically, the 30 % higher rates were classified as green.

Finally, we matched the two groups (dirty and green companies) with the S&P 500 to obtain equity prices. In the end, we were left with 38 green companies and 40 dirty companies. The list is reported in Tables 2 and 3 below. Although cumbersome, this process prevents us from considering a company as green if it emits a smaller amount of CO_2 just because it operates in a low-emitting sector. Instead, we categorize a green company as one with low emissions in high-polluting sectors. Finally, we performed a robustness check comparing the firms selected through our process to an alternative approach based on input-output data (see Appendix A) (Table 4).[5]

5 A potential refinement to the CWT design could involve a tiered taxation system, where firms are taxed at different rates based on their specific carbon intensity rather than a uniform rate for all classified as 'brown.' This approach would acknowledge the varying levels of pollution across firms and provide stronger incentives for incremental emission reductions. However, implementing such a system would require a more granular classification framework, potentially relying on firm-level emissions data which still needs further development in terms of standardization, availability and

Table 2: List of green and brown companies.

	Brown companies	Green companies
1	Exxon Mobil Corporation	NextEra Energy Inc.
2	Chevron Corporation	United Parcel Service Inc. Class B
3	Linde plc	Duke Energy Corporation
4	Union Pacific Corporation	Southern Company
5	ConocoPhillips	FedEx Corporation
6	CSX Corporation	Dominion Energy Inc
7	Norfolk Southern Corporation	Ecolab Inc.
8	Air Products and Chemicals Inc.	Johnson Controls International plc
9	EOG Resources Inc.	Exelon Corporation
10	Dow Inc.	Carrier Global Corp.
11	Marathon Petroleum Corporation	Sempra Energy
12	Pioneer Natural Resources Company	American Electric Power Company Inc.
13	Kinder Morgan Inc Class P	Schlumberger NV
14	Nucor Corporation	DuPont de Nemours Inc.
15	Williams Companies Inc.	PPG Industries Inc.
16	Phillips 66	Xcel Energy Inc.
17	Southwest Airlines Co.	International Flavors & Fragrances Inc.
18	WEC Energy Group Inc	Public Service Enterprise Group Inc
19	Old Dominion Freight Line Inc.	Ball Corporation
20	Valero Energy Corporation	Charles River Laboratories International Inc.

Table 3: List of green and brown companies (cont.).

	Brown companies	Green companies
21	Delta Air Lines Inc.	International Paper Company
22	Kansas City Southern	DTE Energy Company
23	Occidental Petroleum Corporation	Ameren Corporation
24	LyondellBasell Industries NV	Expeditors International of Washington Inc.
25	PPL Corporation	Baker Hughes Company Class A
26	FirstEnergy Corp.	Amcor PLC
27	KeyCorp	Halliburton Company
28	Devon Energy Corporation	CMS Energy Corporation
29	AmerisourceBergen Corporation	Avery Dennison Corporation
30	United Airlines Holdings Inc.	AES Corporation
31	Diamondback Energy Inc.	Evergy Inc.
32	American Airlines Group Inc.	Alliant Energy Corp
33	Atmos Energy Corporation	Allegion PLC
34	CF Industries Holdings Inc.	FMC Corporation
35	NRG Energy Inc.	C.H. Robinson Worldwide Inc.
36	Comerica Incorporated	A. O. Smith Corporation
37	Marathon Oil Corporation	Sealed Air Corporation
38	Cabot Oil & Gas Corporation	Pinnacle West Capital Corporation
39	APA Corp.	
40	Alaska Air Group Inc.	

Table 4: 15 most polluting sectors according to the company and sector-level methods.

	Company-level	Sector-level
1	Oil and Gas Exploration and Production	Electricity, Gas and Water Supply
2	Airlines	Public Admin and Defence; Compulsory Social Security
3	Oil and Gas Refining, Marketing, Transportation and Storage	Inland Transport
4	Marine Transport	Coke, Refined Petroleum and Nuclear Fuel
5	Construction Materials	Air Transport
6	Steel	Chemicals and Chemical Products
7	Energy Equipment and Services	Mining and Quarrying
8	Paper and Forest Products	Other Non-Metallic Mineral
9	Road and Rail Transport	Renting of M&Eq and Other Business Activities
10	Containers and Packaging	Basic Metals and Fabricated Metal
11	Commodity Chemicals	Health and Social Work
12	Metals and Mining - Non-Precious Metals	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods
13	Specialty Chemicals	Hotels and Restaurants
14	Integrated Oil and Gas	Pulp, Paper, Paper, Printing and Publishing
15	Air Freight and Logistics	Food, Beverages and Tobacco

As discussed in the previous section, asset returns are a central variable in the dynamic portfolio model. Therefore, we obtained harmonic estimations of returns on green and brown assets following the methodology in Semmler and Hsiao (2011), which relies on the fast Fourier transform (FFT) of the time series (see also Chiarella et al. (2016)). The advantage of FFT is that it captures low-frequency movements on the returns, subtracting the effect of short-term noises that are often irrelevant in portfolio allocation decisions. Appendix B reports the sine-cosine coefficient and the sum of squared errors related to the harmonic estimations. Figure 1 plots both estimations of the low-frequency behavior of green and brown assets. Consistent with other findings, brown assets are more volatile. Notably, green returns are more resilient to economic downturns.

The dynamic portfolio optimization problem is solved numerically using the nonlinear model predictive control (NMPC) algorithm introduced by Grüne and Pannek (2012) and Grüne, Semmler, and Stieler (2015). We run the simulation for 40 periods for different tax regimes. In the business-as-usual (BAU) scenario, no tax is imposed. To assess the CWT's impact, we run the model for after-tax brown returns

reliability, as noted previously. While this idea is promising, it is beyond the scope of the present study and is left for future research.

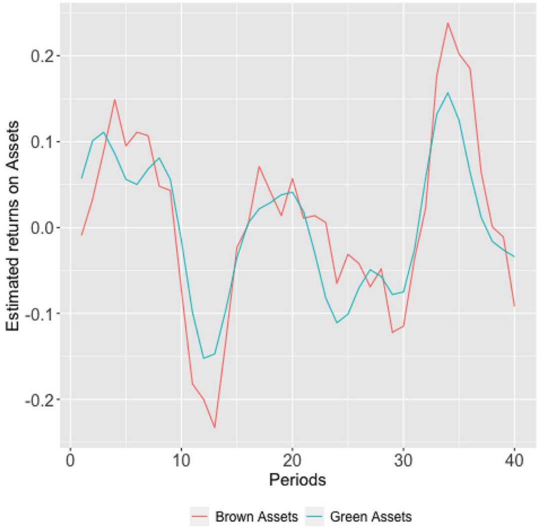


Figure 1: Harmonic estimations for asset returns. Note: This figure appeared first in Neves and Semmler (2024).

(Equation (9)) and after-subsidies green returns (Equation (10)). We investigated scenarios with a rate of 20 % and 40 % to capture the influence of the magnitude. Finally, to assess the effects of the classic excise carbon tax, we run the model for each state equation (Equations (6) and (6')) with rates of 30 % and 50 %. We present the main findings in the next section.

4.2 Results and Discussion

Our first finding is that, in a dynamic portfolio model, the excise tax that aims at penalizing emission-intensive consumption plays a limited role in changing the wealth dynamics. The underlying reason is that within a classic carbon tax environment, the investor lowers their consumption level so that the saved share of wealth remains the same. This adaptation behavior can be seen in Figure 2, where we plotted how much of the wealth the investor opts to consume over the periods in three different tax rates: 0 %, 30 %, and 50 %. The reduction in consumption virtually matches the hike in the rates so that the share of wealth not consumed stays the same. Importantly, given that asset returns are unchanged, the allocation decisions remain the same.

A lower disposable income following a hike in tax rates is a familiar feature as provided by the classic taxation models Barro (1974); Ljungqvist and Sargent (2018). However, whereas in the canonical settings households can counterbalance this by

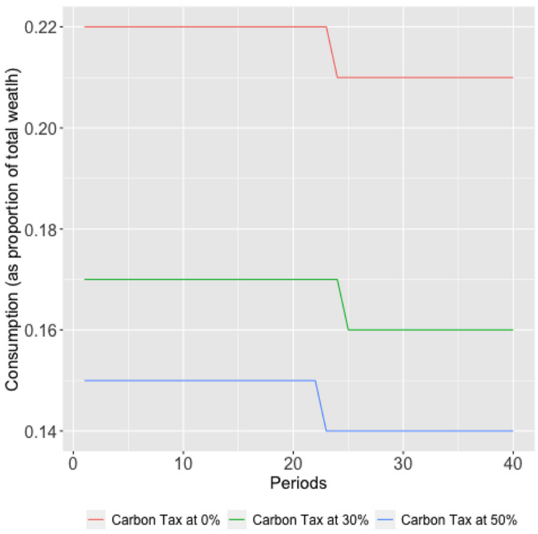


Figure 2: Consumption decision in the classic carbon tax.

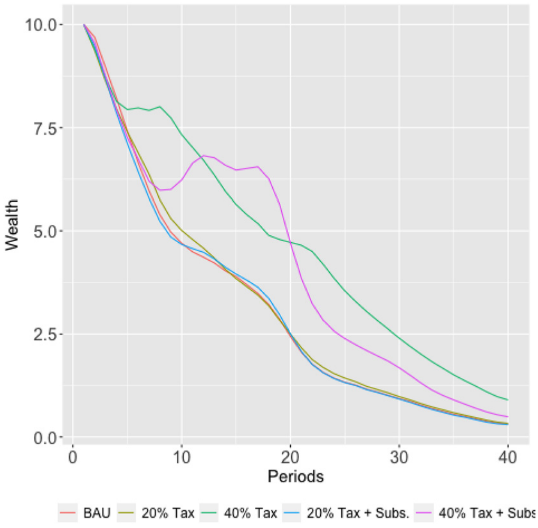


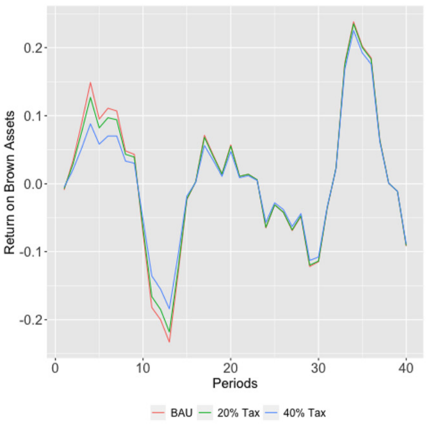
Figure 3: Wealth dynamics under different tax schemes. Note: As observable from the above figure we have chosen a parameterization of the model such that wealth will be depleted in finite time.

smoothing consumption intertemporally through government bonds, in our model, this channel is shut down by the balanced-budget assumption. Empirically, there is robust evidence of a low smoothing behavior by households, or what is labeled "excess sensitivity of consumption," which further reinforces our finding

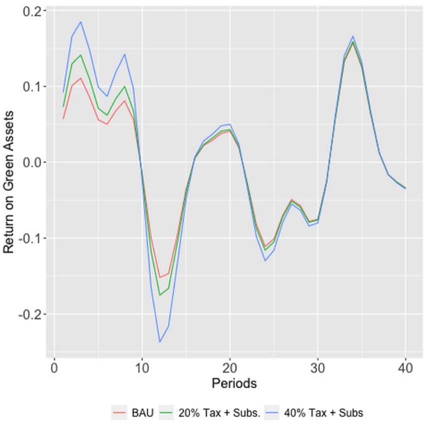
(Flavin 1981; Jappelli and Pistaferri 2010; Mankiw 2000; Mankiw 2000, Flavin 1981, Jappelli and Pistaferri 2010). The same seems to happen in carbon pricing. Kanzig (2021) studied the European carbon market and showed that households lower their consumption level in the face of a carbon tax shock.

Thus, precisely because of the pass-on effect, the excise carbon taxation has a (very) limited impact on wealth dynamics and investment patterns. On the other hand, that is precisely what is achieved by taxing brown capital directly. In that sense, the CWT is an innovative policy instrument since it addresses a variable – equity returns – that has so far remained untouched by climate policies. Figure 3 evaluates how the investor's total wealth behaves over 40 periods under different tax regimes. In the business-as-usual scenario, wealth decreases more or less steadily as consumption outpaces the investment's returns. Between periods 10 and 15, the decline is less pronounced as returns on both assets increase substantially (see Figure 4 below).

A CWT is capable of altering the wealth dynamic through its direct impact on capital returns, but the level of taxation matters. At 20 %, there are only slight changes in the wealth trajectory. By lowering brown returns, CWT makes investors shift to green investments early on, and the lower volatility of the latter contributes to a slightly lesser decline. On the other hand, at 40 %, the taxation is stronger and meaningful alterations happen. As expected, taxing asset returns impacts the trajectory negatively in the first few periods. Around period 5, the trajectories diverge, with taxation decreasing more smoothly. Such early movements, moreover, have long-lasting effects on wealth. Until the end, wealth under the more aggressive tax



(a)



(b)

Figure 4: Dynamics of returns on assets. (a) Carbon-Intensive Assets. (b) Green Assets.

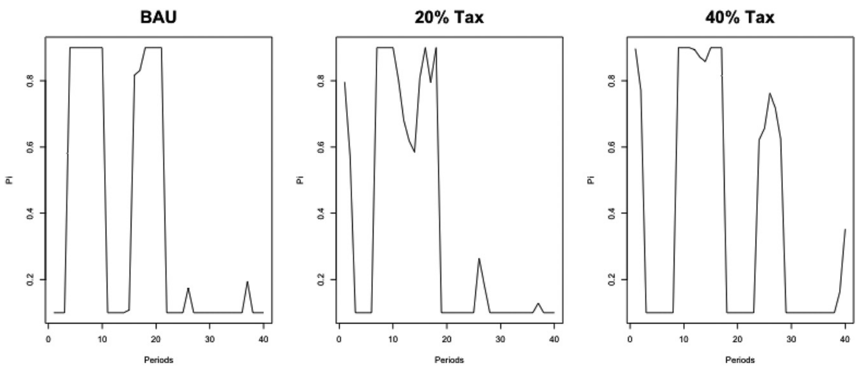


Figure 5: Portfolio allocation under three levels of taxation.

regimes remains higher, indicating a lasting improvement in the wealth path. On the other hand, we also note that subsidies for green technology have transitory effects. Its strongest influence is felt in the middle periods, where the share of green investments is greater.

Indeed, a CWT alters wealth paths precisely because of its ability to change asset returns. Figure 4 plot the total calibrated behavior of brown and green yields, respectively. Common to both assets, we see that the BAU scenario is changed substantially in the early periods. This is a consequence of the fact that the CWT's tax base – wealth – is larger in the beginning, and diminishes as wealth is consumed away in the later periods. As expected, CWT decreases brown asset returns proportionally to its taxation levels, with subsidies having the opposite effect on green returns.

The ultimate impact of taxation regimes on the green transition can be seen in Figure 5, which plots the behavior of π_2, the share of the risky portfolio allocated to green assets. We note that as the CWT increases, π_2 is higher in a greater number of periods. Again, the effect is stronger for earlier periods because of the aforementioned tax-base effect. However, we stress that in a green transition context, this is a very meaningful result, given the importance of a fast action on green investment in spurring technological innovations.

5 Conclusions

Recent environmental reports have shown that the world continues to follow a rapid warming path, despite the increase in the adoption of carbon pricing mechanisms in recent years. This suggests the need for additional and innovative measures to curb

CO_2 emitting activities. Our proposal for a carbon wealth tax fills this gap at the same time that it echoes recent theoretical research that shows the desirability of a specific wealth tax. Our CWT, in the form of a tax on carbon-intensive assets, aims to reduce capital flows to carbon-intensive companies in favor of investment in green companies.

Our results indicate that a CWT is likely to generate such a result. In a dynamic portfolio model, we show that a 20–40 % tax rate is effective enough to keep asset accumulation unharmed or even to alter portfolio allocation choices in favor of green capital in the medium run. This is of particular relevance for a green transition, where carbon de-investment is crucial to attaining the Paris Agreement goals. Moreover, as a nascent industry, green energy technology and assets should be allowed to benefit from subsidies now.

Secondly, we find that brown asset taxation and green subsidies alter wealth trajectories because of their capacity to change asset return dynamics. Their most substantial effects happen in the medium run period when the taxation ensures a greater allocation to green assets. Nonetheless, one of the consequences of the dynamic setup of our model is that this transitory feature carries on also for the long run, improving, in particular for the higher tax rates, the wealth path respectively to the BAU scenario.[6]

Thirdly, we find that our CWT is expected to generate results in stark contrast to the classic excise taxation argument. Such mechanisms that increase product prices are negligible in a portfolio optimization context because investors would simply adjust their consumption level according to the higher prices. Wealth allocation, particularly investment patterns, remains unchanged, and that suggests that a carbon wealth tax could indeed be an innovative instrument in addressing climate change.

Finally, our approach also addresses the wealth inequality issue from a different perspective. Wealth taxes in general have a long history and are often criticized for not having – as sometimes argued – a good welfare foundation and not being very practical in terms of the measurement of the stock of wealth. We refer to another dimension of a welfare and fairness perspective, namely the greater burden-sharing of the cost of public "bads" by holders of carbon-intensive wealth that causes the public "bads".

As to the CWT as a policy tool, there are of course still numerous issues to be discussed, presumably related to the different countries' tax systems and to the

6 We want to note at this point that of course a product-oriented tax might be still useful in the case companies assets or wealth income is not traded publicly, for example if asset income comes from private companies or from "Mittelstandsfirmen", as in Germany.

extent to which an international minimum capital tax can be achieved. Many of those issues pose important challenges for further model-guided and empirical studies.

Conflict of interest: All authors declare that they have no conflicts of interest.

Appendix A: Disclosure Initiatives

This appendix provides a more thorough description of how official authorities in Europe and the United States are approaching disclosure mandates on carbon emissions. Several companies have started disclosing information on the carbon emissions associated with their economic activities in recent years. Emissions are often calculated by the GHG Protocol or the Carbon Disclosure Project, which have advanced the standardization, comparability, and availability of CO_2 emission metrics. On the one side, the demand for assets compliant with environmental, social, and governance (ESG) standards is surging. This is related to investors' increasing awareness of the environmental risk to which publicly traded bonds and stocks are exposed. On the other side, governments are implementing disclosure mandates to accelerate and coordinate the green transition. Disclosure is part of the government's climate policies for two reasons: first, to ensure that climate-related financial risks are accounted for and to improve the financial system's resilience. Secondly, to allow targeted policies to ease borrowing conditions and increase support for bond placement for firms that contribute to emission reduction.

The Bank of England has introduced legislation requiring an overall assessment of carbon emissions associated with sovereign and corporate bonds. First, through its Corporate Bond Purchase Scheme, the Monetary Policy Committee will assess the climate impact of issuers of the corporate bonds it holds. Second, the Prudential Regulation Committee will consider climate risks when establishing Basel's Capital Requirements Regulation. Moreover, regarding CO_2 emissions, they rely on GHG Protocol 3 Scope standard, and disclosure of such information is planned to be mandatory by 2025 for both financial and non-financial sectors.

In parallel, the European Commission has established directives to create and implement a comprehensive green taxonomy. The EU Taxonomy is a classification system that identifies the actions required in the most climate-sensitive economic activities for mitigation and adaptation to environmental change. The aim is to channel finance to the crucial investments needed for the green transition. A special Technical Expert Group established 70 mitigation and 68 adaptation actions across several economic activities, along with specific, measurable goals that firms should achieve (Slevin et al. 2020). With this information, it is possible to tell which company is taking the necessary action towards reducing emissions and which is not.

The system currently includes the most carbon-intensive sectors (energy, transport, and buildings), totaling 40 % of listed companies and 80 % of total CO_2 emissions. In addition, the current legislation already mandates that asset managers and larger financial and non-financial companies disclose information on the alignment of the company's activities, or the bonds and equities in their portfolio, to the Taxonomy. Recently, the European Central Bank announced that it would use its policy instruments, such as corporate bond purchases and collateral requirements, to tilt the credit system away from high-polluting initiatives (European Central Bank 2022). Significantly, this measure will require that corporations disclose emission information based on the taxonomy.

In the United States, the Securities and Exchange Commission (SEC), the regulatory agency responsible for financial markets oversight, has proposed requiring companies to assess their activities' climate risks and the economic impact on their business (Securities & Comission 2022). As for carbon emissions, the proposal requires companies to disclose their Scope 1 and Scope 2 emissions and, in some cases, Scope 3. Notably, the reported numbers will be audited by third-party attesting firms.

The international business community has also proposed multilateral initiatives toward information requirements on corporate emissions. The Task Force on Climate-related Financial Disclosures (TCFD) is a framework developed by a diverse group of financial institutions affiliated with the Financial Stability Board. By recommending the publication of standardized information on climate-related risks and actions, their objective is to improve asset pricing and capital allocation and avoid financial stability issues related to an abrupt information shock. Their 2017 report (Financial Stability 2017) established broad guidelines for climate-related financial disclosures that comprise risks associated with the transition to a green economy (policy, legal, technology, market, and reputation risks), and physical risks (event-based and long-term risks). One of the recommendations is that firms disclose the GHG Protocol 3 Scope emissions and the emission reduction targets according to regulatory requirements.

Adoption of the TCFD recommendations by firms and financial institutions is still low but increasing (Financial Stability 2020). Financial institutions supporting the guidelines are over 1,000, with a total market capitalization of almost U$ 200 trillion. Regarding publicly traded companies, in 2020, emissions were reported by 44 % of them, up from 27 % in 2018. Portfolio's carbon content is disclosed by around 11 % of asset managers.

In sum, the main disclosure initiatives currently in place or planned show that information on the company's actions in the face of climate change is likely to become widespread quite soon. In all cases, they explicitly require companies to assess the carbon emissions related to their activities. However, in this respect, the

EU taxonomy is more comprehensive, as it also provides information on which actions each company, based on its economic activities, should be taking. It would be a step forward when enacted concerning both coordination of the green transition and incentives. Regarding disclosure, an evident contrast exists between the initiatives mandating them (The UK, the EU and the US) and recommending it (TCFD). However, the growing numbers of voluntary adoption of TCFD directives show that the contrast is likely to be temporary.

Appendix B: Robustness Check

This appendix shows that the two methods for identifying green and brown assets – the sector-level and the firm-level – are equivalent, in the sense that both select the same brown sectors. Table 1 reports the 15 most emitting sectors by each measure. For the sector-level column, we used WIOD data for the US emissions in 2009 emissions (the last year available). The company-level column displays the MSCI data on ESG companies aggregated to the sector level using the GICS industry classification code. Discrepancies in the sector names exist because of the differences in each classification system, but there is a consistent picture. Activities related to oil and gas production, transportation, chemicals, metals, and paper stand out as common sources of CO_2 emissions regardless of the methodology.

Appendix C: Harmonic Estimations of the Equity Returns

This appendix reports the harmonic estimations for returns on green and brown equity. The estimation is based on the fast Fourier transformation of the original time series, as shown in Equations (7) and (8). Following Semmler and Hsiao (2011), we first de-trended the series. The estimated coefficients are reported in Tables 5 and 6. Coefficient i indicates the frequency, α_i and β_i are the coefficients for the sine and cosine arguments, respectively, whereas ω_i is the period adjustment factor.

Furthermore, for each curve, we selected the number of sine-cosine arguments k in the harmonic estimation based on the sum of squared errors (SSE) statistics up to 6 periods. As usual, it is preferable to use k which yields a lower value of SSE. In Figure 6, sub-figure a) reports the SSE for the brown returns, whose lowest value is achieved when $k = 6$. For the green returns (sub-figure b), the SSE stops reducing substantially after $k = 4$, so we use this value in the harmonic estimation. Finally, the fitted curve is plotted along with the original series in Figure 7.

Table 5: Estimated harmonic coefficients for brown assets.

i=	1	2	3	4	5	6
$\omega_{1,i}$	43	25.8	32.25	8.0625	18.4286	129
$\alpha_{1,i}$	−0.0873	−0.0385	+0.0140	+0.0073	−0.0246	+0.0112
$\beta_{1,i}$	+0.0902	+0.0121	+0.0365	+0.0252	−0.0189	+0.0398

Table 6: Estimated harmonic coefficients for green assets.

i=	1	2	3	4
$\omega_{2,i}$	43	129	25.8	18.4286
$\alpha_{2,i}$	−0.07245	+0.0355	−0.0281	−0.0144
$\beta_{2,i}$	+0.0428	+0.0289	+0.0213	−0.0288

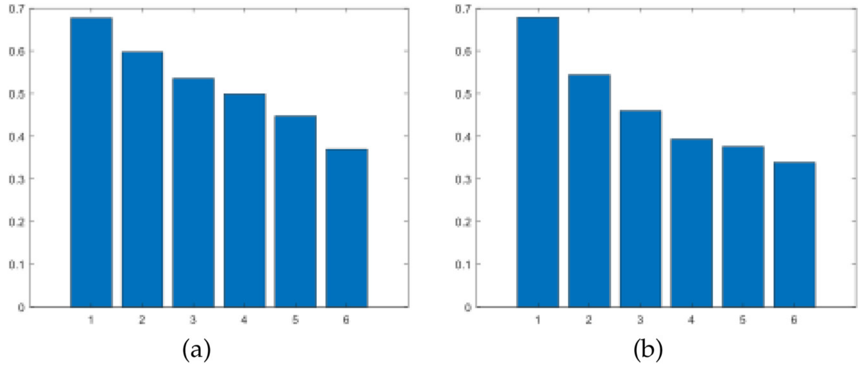


Figure 6: SSE for the harmonic estimations of carbon and green returns. (a) SSE of Carbon Returns. (b) SSE of Green Returns.

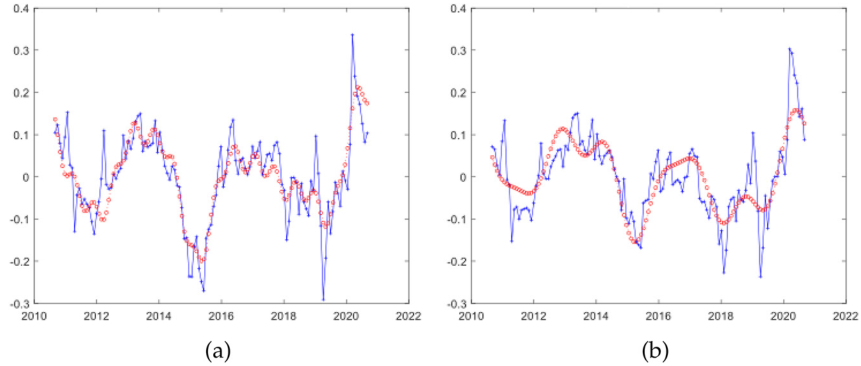


Figure 7: Harmonic estimations and original series of brown and green returns. (a) Harmonic estimation for Brown Returns. (b) Harmonic estimation for Green Returns.

References

Acemoglu, D., P. Aghion, L. Bursztyn, and D. Hemous. 2012. “The Environment and Directed Technical Change.” *American Economic Review* 102 (1): 131–66.

Alvaredo, F., L. Chancel, T. Piketty, E. Saez, and G. Zucman. 2017. “Global Inequality Dynamics: New Findings from WID. World.” *American Economic Review* 107 (5): 404–9.

Atkinson, A. B., and J. E. Stiglitz. 1976. “The Design of Tax Structure: Direct versus Indirect Taxation.” *Journal of Public Economics* 6 (1–2): 55–75.

Auerbach, A. J. 2006. “The Future of Capital Income Taxation.” *Fiscal Studies* 27 (4): 399–420.

Auerbach, A. J. 2008. *Taxation of Wealth. The New Palgrave Dictionary of Economics*, 2nd ed. London: Palgrave Macmillan.

Barrage, L. 2020. “The Fiscal Costs of Climate Change.” In *Aea papers and proceedings*, Vol. 110, 107–12.

Barro, R. J. 1974. “Are Government Bonds Net Wealth?” *Journal of Political Economy* 82 (6): 1095–117.

Beckerman, W., and A. Markandya. 1974. “Pollution Control and Optimal Taxation: A Static Analysis.” *Journal of Environmental Economics and Management* 1 (1): 43–52.

Bel, G., and S. Joseph. 2015. “Emission Abatement: Untangling the Impacts of the EU ETS and the Economic Crisis.” *Energy Economics* 49: 531–9.

Best, R., P. J. Burke, and F. Jotzo. 2020. “Carbon Pricing Efficacy: Cross-Country Evidence.” *Environmental and Resource Economics* 77 (1): 69–94.

Biancalani, F., G. Gnecco, R. Metulini, and M. Riccaboni. 2024. “The Impact of the european union Emissions Trading System on Carbon Dioxide Emissions: a Matrix Completion Analysis.” *Scientific Reports* 14 (1): 19676.

Bolton, P., and M. Kacperczyk. 2021. “Do Investors Care about Carbon Risk?” *Journal of Financial Economics* 142 (1): 517–49.

Bonen, A., M. P. Loungani, W. Semmler, and S. Koch. 2016. *Investing to Mitigate and Adapt to Climate Change: A Framework Model (Tech. Rep. No. WP/16/164)*. Washington DC: International Monetary Fund.

Bovenberg, A. L., and L. H. Goulder. 1996. “Optimal Environmental Taxation in the Presence of Other Taxes: General-Equilibrium Analyses.” *American Economic Review* 86 (4): 985–1000.

Bovenberg, A. L., and L. H. Goulder. 2002. “Environmental Taxation and Regulation.” In *Handbook of public economics*, 3, 1471–545. Amsterdam: Elsevier.

Braga, J. P. 2022. *Three Essays on Climate Finance and Green Economic Policy. PhD dissertation*. New York: The New School for Social Research.

Cadenillas, A. 2000. “Consumption-investment Problems with Transaction Costs: Survey and Open Problems.” *Mathematical Methods of Operations Research* 51 (1): 43–68.

Chamley, C. 1986. “Optimal Taxation of Capital Income in General Equilibrium with Infinite Lives.” *Econometrica* (3): 607–22, https://doi.org/10.2307/1911310.

Chiarella, C., W. Semmler, C.-Y. Hsiao, and L. Mateane. 2016. *Sustainable Asset Accumulation and Dynamic Portfolio Decisions*. Berlin, Heidelberg: Springer.

Davis, S. J., and K. Caldeira. 2010. “Consumption-based Accounting of CO_2 Emissions.” *Proceedings of the National Academy of Sciences* 107 (12): 5687–92.

Duffie, D., and T.-s. Sun. 1990. “Transactions Costs and Portfolio Choice in a Discrete-Continuous-Time Setting.” *Journal of Economic Dynamics and Control* 14 (1): 35–51.

European Central Bank. 2022. *ECB Takes Further Steps to Incorporate Climate Change into its Monetary Policy Operations [press release]*. https://www.ecb.europa.eu/press/pr/date/2022/html/ecb.pr2207044f48a72462.en.html (accessed January 11, 2023).

European Commission. 2024. *About the Eu Emissions Trading System (eu ets)*. https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/about-eu-ets_en (accessed January 27, 2025).
Fawcett, A. A., G. C. Iyer, L. E. Clarke, J. A. Edmonds, N. E. Hultman, H. C. McJeon, J. Rogelj, et al. 2015. “Can Paris pledges Avert Severe Climate Change?” *Science* 350 (6265): 1168–9.
Financial Stability Board. 2017. Recommendations of the Task Force on Climate–Related Financial Disclosures. https://www.fsb-tcfd.org/publications (accessed January 11, 2023).
Financial Stability Board. 2020. Task Force on Climate-Related Financial Disclosures: 2021 Status Report. https://www.fsb-tcfd.org/publications/ (accessed January 11, 2023).
Flavin, M. A. 1981. “The Adjustment of Consumption to Changing Expectations about Future Income.” *Journal of Political Economy* 89 (5): 974–1009.
Golosov, M., A. Tsyvinski, I. Werning, P. Diamond, and K. L. Judd. 2006. “New Dynamic Public Finance: A User’s Guide [with Comments and Discussion].” *NBER Macroeconomics Annual* 21 (1): 317–87.
Goulder, L. H., I. W. Parry, and D. Burtraw. 1996. *Revenue-raising vs. Other Approaches to Environmental Protection: The Critical Significance of Pre-existing Tax Distortions (Tech. Rep.)*. Cambridge, Massachussets: National Bureau of Economic Research.
Grüne, L., and J. Pannek. 2012. “Nonlinear Model Predictive Control.” In *Nonlinear Model Predictive Control*, 45–69. Berlin: Springer.
Grüne, L., W. Semmler, and M. Stieler. 2015. “Using Nonlinear Model Predictive Control for Dynamic Decision Problems in Economics.” *Journal of Economic Dynamics and Control* 60: 112–33.
Guvenen, F., G. Kambourov, B. Kuruscu, S. Ocampo-Diaz, and D. Chen. 2019. *Use it or Lose it: Efficiency Gains from Wealth Taxation (Tech. Rep.)*. Cambridge, Massachussets: National Bureau of Economic Research.
Haites, E., D. Maosheng, K. S. Gallagher, S. Mascher, E. Narassimhan, K. R. Richards, and M. Wakabayashi. 2018. “Experience with Carbon Taxes and Greenhouse Gas Emissions Trading Systems.” *Duke Envtl. L. & Pol’y F.* 29: 109.
Harberger, A. C. 1962. “The Incidence of the Corporation Income Tax.” *Journal of Political Economy* 70 (3): 215–40.
Hinrichsen, D., and U. Krause. 1981. “A Substitution Theorem for Joint Production Models with Disposal Processes.” In *Operations Research Verfahren*, 41, 287–91. Berlin: Springer.
International Carbon Action Partnership. 2024. Eu Emissions Trading System (Eu Ets) Factsheet. https://icapcarbonaction.com/en/ets-system/43/ets-prices (accessed February 12, 2025).
Jakobsen, K., K. Jakobsen, H. Kleven, and G. Zucman. 2020. “Wealth Taxation and Wealth Accumulation: Theory and Evidence from Denmark.” *The Quarterly Journal of Economics* 135 (1): 329–88.
Jappelli, T., and L. Pistaferri. 2010. “The Consumption Response to Income Changes.” *Annual Review of Economics* 2 (1): 479–506.
Jondeau, E., B. Mojon, and L. A. Pereira da Silva. 2021. *Building Benchmarks Portfolios with Decreasing Carbon Footprints*, 21–91. Geneva: Swiss Finance Institute Research Paper.
Judd, K. L. 1985. “Redistributive Taxation in a Simple Perfect Foresight Model.” *Journal of Public Economics* 28 (1): 59–83.
Kanzig, D. 2021. The Unequal Economic Consequences of Carbon Pricing. NBER Working Paper no. 31221. Cambridge, Massachussets: National Bureau of Economic Research. https://doi.org/10.2139/ssrn.3786030.
Kato, M., S. Mittnik, D. Samaan, and W. Semmler. 2013. “Employment and Output Effects of Climate Policies.” In *The Oxford Handbook of the Macroeconomics of Global Warming*, edited by L. Bernard. Oxford: Oxford University Press.
Kopczuk, W., and N. G. Mankiw. 2019. “Comments and Discussion.” *Brookings Papers on Economic Activity* (spring): 512–33.

Lichtenberger, A., J. Braga, and W. Semmler. 2022. "Green Bonds for the Transition to a Low-Carbon Economy." *Econometrics* 10 (1): 11.
Lin, B., and X. Li. 2011. "The Effect of Carbon Tax on Per Capita CO_2 Emissions." *Energy Policy* 39 (9): 5137–46.
Liu, H., and M. Loewenstein. 2002. "Optimal Portfolio Selection with Transaction Costs and Finite Horizons." *The Review of Financial Studies* 15 (3): 805–35.
Ljungqvist, L., and T. J. Sargent. 2018. *Recursive Macroeconomic Theory*. Cambridge, Massachussets: MIT press.
Luderer, G., Z. Vrontisi, C. Bertram, O. Y. Edelenbosch, R. C. Pietzcker, J. Rogelj, H. S. De Boer, et al. 2018. "Residual Fossil CO_2 Emissions in 1.5–2 C Pathways." *Nature: Climate Change* 8 (7): 626–33.
Malikov, E., K. Sun, and S. C. Kumbhakar. 2018. "Nonparametric Estimates of the Clean and Dirty Energy Substitutability." *Economics Letters* 168: 118–22.
Mankiw, N. G. 2000. "The Savers-Spenders Theory of Fiscal Policy." *American Economic Review* 90 (2): 120–5.
Markandya, A., I. Arto, M. González-Eguino, and M. V. Román. 2016. "Towards a Green Energy Economy? Tracking the Employment Effects of Low-Carbon Technologies in the european union." *Applied Energy* 179: 1342–50.
Markowitz, H. 1952. "Portfolio Selection." *The Journal of Finance* 7 (1), https://doi.org/10.2307/2975974.
Martin, R., L. B. De Preux, and U. J. Wagner. 2014. "The Impact of a Carbon Tax on Manufacturing: Evidence from Microdata." *Journal of Public Economics* 117: 1–14.
Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, and P. R. Shukla. 2018. "Global Warming of 1.5 C." *An IPCC Special Report on the Impacts of Global Warming of* 1: 1–9.
Merton, R. C. 1973. "An Intertemporal Capital Asset Pricing Model." *Econometrica* 41 (5): 867–87.
Merton, R. C. 1975. "Optimum Consumption and Portfolio Rules in a Continuous-Time Model." In *Stochastic Optimization Models in Finance*, 621–61. New York: Academic Press.
Metcalf, G. 2007. *An Equitable Tax Reform to Address Global Climate Change (Tech. Rep.)*. Discussion Paper 2007–12. The Hamilton Project. Cambridge, Massachussets: The Brookings Institution.
Metcalf, G., and J. H. Stock. 2020. *The Macroeconomic Impact of Europe's Carbon Taxes (Tech. Rep.)*. National Bureau of Economic Research.
Mittnik, S., and W. Semmler. 2022. "Die substitution fossiler energieträger – die analyse wirtschaftlicher kurz- und langfristwirkungen." *Vierteljahrshefte zur Wirtschaftsforschung/Quarterly Journal of Economic Research* 91 (3): 11–44.
Musgrave, R. A. 1973. *Public Finance in Theory and Practice*. New York: McGraw-Hill Kogakusa.
Narassimhan, E., K. S. Gallagher, S. Koester, and J. R. Alejo. 2017. *Carbon Pricing in Practice: A Review of the Evidence*. Medford, MA, USA: Climate Policy Lab.
Neves, J. P. B., and W. Semmler. 2024. "Financing the Green Transformation with a Carbon-Based Wealth Tax for Climate Protection – a Proposal." *Vierteljahreshefte zur Arbeits- und Wirtschaftsforschung* 1 (3/4): 1–14.
Nordhaus, W. 2008. *A Question of Balance*. New Haven: Yale University Press.
Nordhaus, W. 2013. *The Climate Casino: Risk, Uncertainty, and Economics for a Warming World*. New Haven: Yale University Press.
OECD. 2021. *Corporate Tax Statistics*. 3rd ed. https://www.oecd.org/tax/beps/corporate-tax-statistics-database.htm (accessed January 11, 2023).
Office of Management and Budget. 2022. *Budget of the U.S. Government: Fiscal Year 2023*. The White House. https://www.whitehouse.gov/wp-content/uploads/2022/03/budget_fy2023.pdf (accessed January 11, 2023).
Papageorgiou, C., M. Saam, and P. Schulte. 2017. "Substitution between Clean and Dirty Energy Inputs: A Macroeconomic Perspective." *Review of Economics and Statistics* 99 (2): 281–90.

Parry, I., and I. I. I Williams, R. C. 2012. *Moving Us Climate Policy Forward: Are Carbon Taxes the Only Good Alternative?*, 1. Oxford University Press. http://www.oxfordscholarship.com (accessed January 11, 2023).

Pfeiffer, A., R. Millar, C. Hepburn, and E. Beinhocker. 2016. "The 2C Capital Stock for Electricity Generation: Committed Cumulative Carbon Emissions from the Electricity Generation Sector and the Transition to a Green Economy." *Applied Energy* 179: 1395–408.

Piketty, T. 2013. *Capital in the 21st Century*. Cambridge, MA: President and Fellows, Harvard College.

Pretis, F. 2019. Does a Carbon Tax Reduce CO_2 Emissions? Evidence from British Columbia. *Evidence From British Columbia (February 8, 2019)*.

Rogelj, J., M. Den Elzen, N. Höhne, T. Fransen, H. Fekete, H. Winkler, R. Schaeffer, F. Sha, K. Riahi, and M. Meinshausen. 2016. "Paris Agreement Climate Proposals Need a Boost to Keep Warming Well below 2 C." *Nature* 534 (7609): 631–9.

Saez, E., and S. Stantcheva. 2018. "A Simpler Theory of Optimal Capital Taxation." *Journal of Public Economics* 162: 120–42.

Saez, E., and G. Zucman. 2019. "Progressive Wealth Taxation." *Brookings Papers on Economic Activity* 2019 (2): 437–533.

Scheuer, F., and J. Slemrod. 2021. "Taxing Our Wealth." *Journal of Economic Perspectives* 35 (1): 207–30.

Schoenmaker, D. 2021. "Greening Monetary Policy." *Climate Policy* 21 (4): 1–12.

Securities, & Comission, E. 2022. "The Enhancement and Standardization of Climate-Related Disclosures for Investors." The White House. https://www.sec.gov/rules/proposed/2022/33-11042.pdf (accessed January 11, 2023).

Semieniuk, G., L. Taylor, A. Rezai, and D. K. Foley. 2021. "Plausible Energy Demand Patterns in a Growing Global Economy with Climate Policy." *Nature: Climate Change* 11 (8): 1–6.

Semmler, W., J. Braga, A. Lichtenberger, M. Toure, and E. Hayde. 2021. Fiscal Policies for a Low-Carbon Economy. http://hdl.handle.net/10986/35795 (accessed January 11, 2023).

Semmler, W., and C.-Y. Hsiao. 2011. "Dynamic Consumption and Portfolio Decisions with Estimated Low Frequency Movements of Asset Returns." *The Journal of Wealth Management* 14 (2): 101–11.

Semmler, W., K. Lessmann, I. Tahri, and J. Braga. 2024. "Green Transition, Investment Horizon, and Dynamic Portfolio Decisions." *Annals of Operations Research* 334 (1): 265–86.

Slevin, D., S. Hoerter, N. Humphreys, H. Viñes Fiestas, S. Lovisolo, and J. Wilmotte. 2020. *Taxonomy: Final Report of the Technical Expert Group on Sustainable Finance*. Brussels: European Commission.

Stavins, R. N. 2019. *Carbon Taxes vs. Cap and Trade: Theory and Practice*. Cambridge, Mass: Harvard Project on Climate Agreements.

Stiglitz, J. E., N. Stern, M. Duan, O. Edenhofer, G. Giraud, and G. M. Heal. 2017. *Report of the High-Level Commission on Carbon Prices*. Washington DC: World Bank Group.

Straub, L., and I. Werning. 2020. "Positive Long-Run Capital Taxation: Chamley-Judd Revisited." *American Economic Review* 110 (1): 86–119.

Timmer, M. P., E. Dietzenbacher, B. Los, R. Stehrer, and G. J. De Vries. 2015. "An Illustrated User Guide to the World Input–Output Database: the Case of Global Automotive Production." *Review of International Economics* 23 (3): 575–605.

World Bank. 2021. State and Trends of Carbon Pricing 2021. http://hdl.handle.net/10986/35620 (accessed January 11, 2023).