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Stranded Assets: How Policy Uncertainty affects Capital, Growth, and the Environment

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Abstract

Standard environmental economics prescribes policies which are optimal and implemented immediately. The paper argues that, in reality, environmental policy often deviates from the optimum and implementation is not deterministic but subject to major uncertainty and frequent change. We present a model with a stochastic policy process that affects investors' decisions and the composition of capital. We assume that pollution is reduced by private green services and public abatement. The government subsidizes green services and taxes dirty capital albeit at a rate which may become random, causing unexpected capital write-offs. Tax jumps depend on environmental degradation and the share of green services. We show how policy uncertainty affects capital valuation and how it alters individual portfolios, green services, and economic growth.

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Key Words: Policy uncertainty; stranded assets; private abatement; stochastic growth.

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1 Introduction

1.1 Policy uncertainty

Effective climate policies require significant structural change of the current economies. This involves adjustments in consumption and production patterns - primarily affecting transportation, heating, and manufacturing. Capital invested in more polluting sectors is particularly exposed to policy changes and may become stranded when investments are irreversible. In most countries it is very likely that carbon policy will be implemented or made more stringent in the future. Prominent reasons are an intensification of climate shocks, the Paris Climate Agreement, and a public process of further evolving social norms and of possible stigmatization of fossil fuels. Taken together it creates a political environment in which policy implementation becomes likely but is still highly uncertain. In particular, the exact date and the specific kind of policies are nearly impossible to predict for market participants. Shifts in political priorities may delay political action or even revert past policy decisions. All these uncertainties associated to climate policy affect investment decisions, economic growth, and the state of the natural environment. They pose a special challenge to long-run investments which are dominant in central sectors such as buildings, energy, and infrastructure. As a novel contribution to literature, the present paper aims at exploring these links by developing and using an appropriate theory framework.

As a response to market failures such as environmental externalities economists are used to derive and propose policies restoring the social optimum. In reality, however, governments are usually not willing and/or not able to directly implement such recommendations. Deviating from first-best optimal solutions, political reality is better characterized by a process in which pending issues like climate change are debated for a period of time while the implementation of concrete policy measures happens suddenly and unexpectedly.[1] These measures may include new government regulations that limit the use of fossil fuels,[2] a change in demand for fossil fuels due to a shift towards subsidized renewable energy,[3] or legal action banning certain polluting or harmful activities.[4] If in a sector asset conversion is constrained by irreversibilities or high adjustment costs, some assets lose part of their value or become completely stranded (McKibben 2011). Understanding the dynamic relationship between expectations, portfolio decisions, and policy changes then becomes crucial for understanding capital accumulation and the various effects of environmental policy.

[1] A recent example is the German court which ruled in February 2018 that German cities are allowed to implement a ban of diesel cars and trucks for certain areas, meaning that these restrictions now become politically feasible but are still highly uncertain.

[2] Examples are emission standards for vehicles or heating technologies.

[3] These subsidies are broadly used in different countries because carbon pricing is politically difficult or even not feasible (Kalkuhl et al., 2013); they are only second-best and may give rise to time-inconsistency problems, see Rezai and van der Ploeg (2017).

[4] Like the decisions on a nuclear phaseout in Germany and Switzerland and the possible ban of diesel vehicles in European cities like Copenhagen; Berlin, and Paris to combat air pollution.

Assets become ”stranded” when suffering from unanticipated or premature write-offs, downward revaluations, or conversions to liabilities, see International Energy Agency (IEA 2013, p.134) and Generation Foundation (2013, p.26). Unexpected revaluation may affect all types of capital in the economy. It usually does not involve a complete capital loss but rather a lower capital return for specific investments. It has recently been estimated that a third of oil reserves, half of gas reserves and more than 80% of known coal reserves should remain unused in order to meet global temperature targets under the Paris Agreement (McGlade and Ekins 2015). As these reserves are already known the write-offs are largely disconnected from active investment activities which becomes different when recent or current exploration investment and fossil fuel discoveries of oil, gas and coal companies are involved. These investments are irreversible so that assets are especially prone to value loss with effective climate policy. The risk of stranded assets then affects those who have invested in the extracting company’s stocks or bonds, which may include individuals, firms, or organizations like pensions funds.[5] Risks are often not fully accounted for which has resulted in a high exposure of the portfolios in many economies to carbon-intensive assets. From the perspective of production, all capital which is used jointly with fossil fuels as an input to production is potentially affected by environmental policy. Capital is especially exposed when it is technically difficult to substitute a clean energy for the input of fossils, which holds true for many sectors. Hence, in the non-oil countries, most of the stranded assets belong to companies that use ”dirty” machines, i.e. machinery running with fossils, in production. This is what we will incorporate in our model.

That capital may become stranded in a market economy is related to the effect of ‘creative destruction’ (Schumpeter 1942). However, the Schumpeterian creation and destruction of values is caused by innovations and technical breakthroughs which are, by their nature, not fully predictable yet crucial for development. Conversely, carbon and other environmental policy is uncertain due to the complex conditions of the political process. Policy making includes many simultaneous tasks at different levels and features governments which are very reluctant to commit to policies over a longer time horizon (Ulph and Ulph 2013). Rational agents will take prevention measures to reduce their risk exposure but will be hit unexpectedly at the time of a policy shock. The governments’ limited commitment ability to announce a carbon tax in advance makes it difficult for economic actors to fully anticipate the policy and to avoid stranded assets (Williams 2011, Helm et al. 2003). Problems such as unemployment, lost profits, and reduced tax income may be associated with asset stranding (Caldecott 2015). Policy should aim at finding ways to effectively address these negative consequences when societies transition to more environmentally sustainable economic structures. It should be noted, however, that not only climate policy but also the absence of the policy, i.e. climate change, causes a substantial decrease of asset values (Dietz et al. 2016). In fact, climate change (e.g. in the form of large climate shocks) does not only harm current production (or utility) as assumed in many IAMs but also destroys part of the existing capital stock which has a strong impact on economic growth (Bretschger 2017).

[5] Weyzig et al. (2014) estimate that the exposure of the European financial sector (banks, insurance companies, and pension funds) to high-carbon assets was over 1 trillion Euro.

The impact of uncertain policy on the environment, capital accumulation, and the composition of the capital stock is the topic of the present paper. We analyze rational investment decisions and their macroeconomic consequences when policy is not deterministic and interacts with private green activities. While standard environmental economics assumes that an environmental tax is implemented once and forever and that its value should ideally be close or equal to the optimal level we argue that this pattern is basically nowhere observed in reality. What is more relevant in our view is that private investors are confronted with a randomness in terms of time of introduction of the policy, policy changes, and the duration of the policy. This has been the experience with the existing policies of oil and carbon taxation and is also documented by older examples such as the tobacco tax. Smoking is an especially illuminating case because tax rates have jumped upward many times in the past. Moreover, the size of the jumps has increased with the public awareness of the health problems associated with smoking and has also grown with the share of the non-smokers (who are also voters at the same time) of total population. This may serve to form expectations about the possible shape of future climate policies. Given the empirical evidence on policy implementation and the importance of the topic it is quite surprising that the literature has not covered the issue of uncertain environmental policy so far. The present paper aims to fill this gap.

1.2 Contribution to the literature

The paper topic relates to different strands of literature dealing with environment, uncertainty, finance, and endogenous growth. The effects of isolated uncertain environmental shocks were studied formally by Tsur and Zemel (1996, 1998, 2008) with a special focus on endogenous hazard rates. Deriving optimal carbon policies, de Zeeuw and Zemel (2012) and van der Ploeg and de Zeeuw (2016) apply different hazard functions and various types of environmental risks. Featuring endogenous growth and including different capital stocks, Ikefuji and Horii (2012) assume that climate shocks are idiosyncratic which allows agents to diversify their risk. Soretz (2007) introduces the Wiener process for continuous uncertain environmental events in an endogenous growth model; Bretschger and Vinogradova (2018) add the effects of larger Poisson shocks and the associated optimal response in terms of environmental policy. We will refer to this literature in terms of the methodology but will apply the techniques to a different sector, policy, which opens a completely new perspective on uncertain decisions in a market economy. To study tax rate changes, the Poisson rather than the Wiener process is the appropriate mechanism to represent uncertain shocks.[6]

Political uncertainty has been largely neglected in general and environmental economics literature so far. An early exception is the contribution of Xepapadeas (2001) who studies the effects of uncertainty in environmental policy in combination with uncertainty in prices and technology. That paper applies optimal stopping to determine when firms invest in abatement capital or relocate production.

[6] Steger (2005) formally derives the differences and similarities of economic growth under Wiener and Poisson uncertainty.

It uses the Wiener process for continuous fluctuations in a static framework. Conversely, we model potentially large policy events in a dynamic model with endogenous growth. More recently, referring to rare macroeconomic disasters, Barro (2015) has shown that optimal environmental investments decrease with uncertainty about policy effectiveness, pointing at the importance of risks stemming not only from the environment but also from environmental policy. Pommeret and Schubert (2017) introduce uncertainty about the future cap in an emission permit system, analyse the effects on clean investments, and find conditions where abatement and investment in clean technology grow with uncertainty. We build on these insights by fully developing a model with endogenous economic growth and stochastic tax policies. Our contribution analyzes a dynamic economy in which environmental policy is neither optimal nor predictable but comes with significant shocks. We are particularly interested in the effects on capital returns, investment decisions, policy design, and economic growth.

With the analysis of stranded assets in a growth context the paper is related to Rozenberg et al. (2014) who introduce two types of capital to analyze the transition to clean capital when polluting investment is irreversible, which imposes a transition cost to the economy. Their paper shows that avoiding stranded assets by appropriate policy comes at the cost of lower efficiency in emission reduction and higher transition cost. We differ from their approach by using a model of endogenous growth and by introducing a random process generating policy shocks. Kalkuhl et al. (2018) study how irreversible investments and imperfect commitment by regulators affect climate policy outcomes. Stranded assets result from the government strategically deviating from the previously announced policy. Their paper uses a partial equilibrium approach and assumes that the government maximizes its objective function. We take a different route by analyzing a general equilibrium framework and introducing a government that is driven by pollution and greenness of the economy but not fully predictable for the investors. Van der Ploeg and Rezai (2016) analyze a model with stock-dependent fossil fuel extraction costs and green technical progress to derive the optimal carbon tax and the optimal amount fossil fuel left in the ground, the stranded fossil asset. We add to the literature by studying stranded assets which are associated with capital investments under the conditions of a policy that deviates from first best.

Our topic is also related to the studies looking at the impact of environmental policy on economic growth, following the tradition of Bovenberg and Smulders (1996), Pittel (2002), Smulders et al. (2014), and Xepapadeas (2006). The production structure including capital and services is close to the seminal contribution of Barro (1990). The paper topic has parallels to the financial market analysis of carbon exposure and the possibly destabilizing effects of climate change and uncertain policy on the financial system (Battiston et al. 2017). Similar to policy private divestment campaigns can affect financial markets and investment behavior. But rather than having a direct effect on firms it has been suggested that divestment campaign are indirectly effective by changing market norms and triggering a negative image of fossil fuel companies which could then translate into political action, the topic of our contribution.

Our model includes environmental externalities and endogenous growth depicting the macroeconomic conditions and a broad set of policy choices reflecting the political sector. Tax policy is supplemented by subsidies to green activities and by public and private abatement activities. We believe that private activities may play an important part in mitigation but that, under realistic conditions, agents have suboptimally low incentives to undertake these efforts. We assume that the government is not an autonomous institution acting like a benevolent dictator but rather a decision unit reacting to specific developments yet in a not fully-predictable manner. Environmental tax increases arrive in the form of shocks. We study how this uncertain environmental policy interacts with optimal subsidies and private green services. We also derive the optimal portfolio choices in the presence of policy uncertainty and the effects of the tax jumps on economic growth. After a tax jump, the capital return is reduced which devalues the capital stock. The agents are aware of the uncertainties in the policy process but the single shocks to capital return come unexpectedly which entails the form of stranded assets we consider in our model.

The remainder of the paper is organized as follows. Section 2 develops the model. In Section 3 we derive the solutions for our benchmark economy. Section 4 introduces stochastic capital taxation. In Sections 5 and 6 we analyze short and long-run effects of uncertain taxation. Section 7 concludes.

2 Modelling framework

Our analytical approach encompasses several building blocks. We start from including capital and endogenous capital investments into the production process of the economy. Physical capital investments are crucial for the portfolio composition and for determining economic growth but are, at the same time, harming the environment by raising emissions. We posit that environmental externalities are taxed by the government albeit at a non-deterministic rate. As a consequence, investors aim to anticipate the shocks by a change in investment behavior; however, they may also be subject to unexpected capital losses. Policy does not solely rely on taxes but is broader, including public abatement activities and subsidies to private abatement efforts. In our model, the private sector devotes resources to build a productive input reducing emissions which we label "green services". Given our assumption of non-altruistic behavior, private efforts are strictly positive when they are associated with a private return. We ensure private clean activity by assuming that green services are an input to final goods production which substitutes for dirty capital.

Capital taxation has a deterministic and a stochastic component. To build a reference case we first analyze a benchmark economy where uncertain policies are completely absent i.e. we start by analyzing the deterministic tax component in the next section and add the tax shocks separately in later sections. We use a comprehensive policy approach to study the phenomenon of stranded assets. First, the tax level can vary and even reach, in an extreme case, 100 percent which is equal to a ban of using the specific capital, like in the case of nuclear power plants in certain countries. If the tax level is increased but does not reach 100 percent, profitability of installed capital is reduced instantaneously. Tax policy is complemented by public abatement and subsidies to green services. Finally, public emission mitigation is supplemented by private abatement efforts. Equipped with this framework we analyze portfolio decisions, policy design, and economic growth in the following.

2.1 Production and pollution

Output Y is produced by capital stock K and a flow of green services G

$$Y_t = AK_t^{\alpha} G_t^{1-\alpha} \tag{1}$$

where t is the time index; $A > 0$ and $0 < \alpha < 1$. Machines are dirty i.e. the use of physical capital K causes environmental degradation. Services G are assumed to be green i.e. not to harm but to benefit the environment. They are provided by the private sector and, for simplicity, produced from output at constant marginal costs which we normalize to unity. The public sector reduces emissions by spending on abatement, H. The level of emissions, E, is then increased by physical capital and reduced by abatement expenditures and green services, each term multiplied by the associated intensity, so that

$$E_t = \phi K_t - \theta H_t - \psi G_t \qquad \text{with } \phi, \theta, \psi > 0, \quad \theta > \phi > \psi. \tag{2}$$

2.2 Government

Due to the negative environmental externalities of physical capital accumulation the government imposes a tax on capital. Similar to the existing literature we use a deterministic tax with rate τ but, in addition, thoroughly study the case when the government changes the tax rate in a stochastic manner. Notably, the tax levied on capital follows a Poisson process according to

$$dT_t = K_t(\tau dt + \gamma_t dq). \tag{3}$$

The Poisson process is denoted by γ_t indicating the change in the tax rate at time t driven by the stochastic process q with an increment dq and the arrival rate λ. It reflects the unanticipated changes in taxation due to environmental and/or political reasons. To internalize the positive environmental benefits of green private services the government may apply a deterministic subsidy rate s for service expenditures. Subsidies are financed by the revenues from deterministic capital taxation so that deterministic and stochastic policy effects can clearly be distinguished. Note that, although the production technology is riskless as given in (1), net return from production becomes uncertain as soon as taxation follows a stochastic process, so that

$$Y_t dt - dT_t = (Y_t - \tau K_t)dt - \gamma_t K_t dq. \tag{4}$$

2.3 Households

Instantaneous utility depends on consumption and emissions as given by

$$U(C_t, E_t) = \frac{(C_t E_t^{-\beta})^{1-\sigma}}{1-\sigma} \tag{5}$$

where $0 < \beta < 1$ determines disutility out of pollution and $1/\sigma > 0$ denotes the intertemporal elasticity of substitution. We assume intertemporal utility to be additively separable in time, with $\rho > 0$ denoting the constant rate of time preference. In the presence of uncertainty, we consider expected utility maximizing individuals. Recall that emissions are determined by the aggregate levels of physical capital stock, abatement and green services. With a continuum of households, the impact of individual decisions on these aggregate variables vanishes, hence individuals consider emissions to be exogenous to their decisions.

3 Benchmark economy

3.1 Social optimum

A familiar benchmark case for our economy is provided by the social optimum. To determine the socially optimal time path, the impacts of physical capital accumulation, abatement expenditures, and green services on emissions given in (2) are taken into account for intertemporal welfare maximization. In our model, uncertainty enters the economy only via the stochastic behavior of the government, i.e. random taxation, which forces individuals to deviate from their optimal plans. Hence, the social optimum is determined without stochastic taxation, in a purely deterministic setup with $\gamma_t = 0$ in (3). We state the result in Lemma 1.

Lemma 1: *In social optimum, the growth rate of consumption is given by*

$$g_C = \frac{1}{\tilde{\sigma}} \left(A\alpha \left(\frac{G}{K} \right)^{1-\alpha} - \frac{\phi}{\theta} - \rho \right) \qquad \textit{with } \tilde{\sigma} = \sigma + \beta(1-\sigma) \tag{6}$$

Proof: The program of the social planner is given by the Hamiltonian

$$\mathcal{H} = e^{-\rho t} \frac{(CE^{-\beta})^{1-\sigma}}{1-\sigma} + \nu(AK^{\alpha}G^{1-\alpha} - G - H - C) \tag{7}$$

Maximisation with respect to consumption, C, and abatement expenditures, H, yields

$$E = \beta\theta C \tag{8}$$

Abatement expenditures are higher relative to consumption expenditures, if environmental preferences are stronger (higher β) or abatement is more effective (higher θ). Moreover, emissions will grow with the same rate as consumption on the social optimal time path. This property follows immediately from our assumptions on utility which imply a constant intratemporal elasticity of substitution between emissions and consumption. Maximization of the Hamiltonian with respect to capital, K, allows deriving the growth rate of consumption. ■

The direct marginal return of physical capital in production is reduced by ϕ/θ due to the need of abatement activity. Additionally, the effective intertemporal elasticity of substitution, $1/\tilde{\sigma}$ is modified by environmental preferences. For empirically relevant parameter values, $\sigma > 1$, environmental preferences increase the effective intertemporal elasticity of substitution, which is a familiar result in environmental economics.

The optimal ratio of green services to physical capital results from maximization of the Hamiltonian with respect to G

$$\frac{\psi}{\theta} + A(1-\alpha)\left(\frac{G}{K}\right)^{-\alpha} - 1 = 0 \quad \Rightarrow \quad \frac{G}{K} = \left(\frac{A(1-\alpha)}{1-\frac{\psi}{\theta}}\right)^{\frac{1}{\alpha}} \equiv \omega^* \tag{9}$$

Note that, if green services had no impact on emissions (i.e. $\psi = 0$), the optimal ratio of capital to green services would be identical to the Barro (1990) model. With positive ψ, there is an additional positive effect of green services, hence the optimal greenness of production increases. For the sake of brevity we will label the ratio of green services to physical capital, G/K, as "green service ratio" below. Optimal public abatement, H, is given by the abatement ratio

$$\delta^* = \frac{\phi}{\theta} - \frac{\psi}{\theta}\omega^* - \frac{\beta}{1-\beta}\left(\frac{\rho}{\tilde{\sigma}} + \frac{\tilde{\sigma}-1}{\tilde{\sigma}}\left(A\alpha(\omega^*)^{1-\alpha} - \frac{\phi}{\theta}\right)\right) \tag{10}$$

and emissions consequently evolve according to

$$E^* = (\phi - \theta\delta^* - \psi\omega^*)K = \frac{\beta\theta}{1-\beta}\left(\frac{\rho}{\tilde{\sigma}} + \frac{\tilde{\sigma}-1}{\tilde{\sigma}}\left(A\alpha(\omega^*)^{1-\alpha} - \frac{\phi}{\theta}\right)\right)K. \tag{11}$$

3.2 Competitive deterministic equilibrium

We now show that, due to environmental externalities, the green service ratio is suboptimally low and the growth rate is suboptimally high in the competitive equilibrium. For the government this may give rise to environmental taxation and green services subsidy. To make a first comparison to the social optimum we restrict the analysis in this subsection to linear deterministic capital taxation and add the full analysis of stochastic tax rates in the next section.

We consider household-producers which have access to the production technology and decide on consumption and investment as well as on green services expenditures. Private agents provide green services G to final goods production while the government pays subsidies for green services at a rate s and additionally provides public abatement as given by $H = \delta K$ where δ is a (possibly non-optimal) expenditure rate e.g. resulting from the political process. Individuals maximize lifetime utility subject to physical capital accumulation

$$\max_{C,G,K} \quad \int_0^\infty e^{-\rho t} \frac{(CE^{-\beta})^{1-\sigma}}{1-\sigma} dt \tag{12}$$

$$\text{s.t.} \quad \dot{K} = AK^\alpha G^{1-\alpha} - \tau K - (1-s)G - C. \tag{13}$$

We are now ready to state

Proposition 1: *In decentralized equilibrium, the growth rate of the economy is given by*

$$g_C = \frac{1}{\tilde{\sigma}} \left(A\alpha\omega^{1-\alpha} - \tau - \rho \right). \tag{14}$$

Proof: As long as we neglect stochastic capital taxation, the optimization problem is deterministic and can be solved with the Hamiltonian

$$\mathcal{H} = e^{-\rho t} \frac{(CE^{-\beta})^{1-\sigma}}{1-\sigma} + \nu(AK^\alpha G^{1-\alpha} - \tau K - (1-s)G - C). \tag{15}$$

Since the impact of a single household-producer on emissions is insignificant, emissions are considered exogenous to individual decisions and maximization with respect to green service results in

$$A(1-\alpha)\left(\frac{G}{K}\right)^{-\alpha} - (1-s) = 0 \quad \Rightarrow \quad \frac{G}{K} = \omega = \left(\frac{A(1-\alpha)}{1-s}\right)^{\frac{1}{\alpha}}. \tag{16}$$

With the same argument, the impact of physical capital on emissions is ignored in the optimization of capital accumulation. Emissions grow with the common growth rate of capital and consumption, because the abatement ratio, δ, is constant by assumption and the green service ratio is constant according to (16). The resulting growth rate given in Proposition 1 is determined by net marginal return of physical capital and can be adjusted through the choice of the tax rate level. ■

In the absence of an environmental tax policy ($\tau = s = 0$), individuals choose the green service ratio according to $\omega = (A(1-\alpha))^{\frac{1}{\alpha}}$, as can be derived from equation (16). In this case, green services are suboptimally low (due to the environmental externality). At the same time, without capital taxation, growth becomes suboptimally high. Both results reflect the well-known characteristics of externalities, as green services entail a positive and physical capital a negative externality. It is straightforward to show that, in the optimum, the environmental externalities are internalized with tax and subsidy rates satisfying

$$\tau = \frac{\phi}{\theta} \quad \text{and} \quad s = \frac{\psi}{\theta}. \tag{17}$$

4 Stochastic capital taxation

We now turn to the stochastic policy setting which we believe lies at the heart of the stranded assets problem. We thus add the random term in the tax rate equation (3) i.e. the stochastic tax rate γ is now imposed on capital, additional to deterministic capital taxation at rate τ. We assume that the time of arrival of tax shocks is purely random so that investors are indeed caught by surprise. However, it is plausible to posit that the size of the tax jumps depends on specific conditions. We have two different effects in mind, which have been observed in recent policy development.

First, we assume that the size of the tax increase in case of a policy change, γ_t, depends positively on the green service ratio, G/K. The assumption relates to the recent example of the two countries with the highest market shares of electric cars, Norway and the Netherlands, which were the first to seriously consider a future ban of internal combustion engine cars, which is equivalent to an infinitely high emission tax rate. Also, looking at the history of tobacco taxes, it is revealing that tax rates were raised significantly only after an important part of the population had become non-smokers. We conclude that emission tax increases get more political support with higher importance of green technology relative to dirty capital and that stringent environmental policies become politically feasible when production technology has become sufficiently green. In that case, households rely relatively less on dirty capital and are thus less likely to oppose increasing taxation on emissions.

Second, emission levels, associated catastrophic events, and the awareness of environmental problems are important promoters of (sudden) environmental policy reforms. A prominent example is the decision on a nuclear phaseout in Germany and Switzerland right after the Fukushima nuclear accident. Also, based on the Paris climate agreement, future increases in policy ambitions will be effectuated stepwise, contingent on the degradation of the atmosphere. If production in the market equilibrium is not sufficiently green, environmental degradation guides the economy further away from social optimum so that the necessity of environmental taxes and tax increases tend to get larger. With this effect the size of the tax increase, γ_t, depends on the ratio of environmental degradation which we capture by the ratio of emissions E to green services G. For a more complete characterization of the different stochastic tax effects we add a constant term $\bar{\gamma}$ to the tax jump. Hence, the change in taxation is given by

$$\gamma_t = \bar{\gamma} + \eta \left(\frac{G_t}{K_t}\right)^{\chi} + \varepsilon \left(\frac{E_t}{G_t}\right)^{\xi} \tag{18}$$

where $0 < \chi, \xi < 1$ and $\eta, \varepsilon > 0$.

With respect to the individual impact on stochastic taxation we consider two alternative model variants concerning the green service ratio. First, if we assume that agents act in complete isolation they will consider aggregate green services as well as the aggregate capital stock to be exogenous and independent of their individual decisions. Then, the tax shocks depend on aggregate macroeconomic conditions which cannot be influenced by individual decisions. We will label this case the

”fragmented equilibrium (FE)”. Second, alternatively, we may posit that agents have the power and willingness to cooperate in order to use the green service ratio as a strategic device framing the political process, a case we will label ”activist equilibrium (AE)”. Here we have in mind producer lobbies or consumer activism encouraging and implementing common action. Examples are public campaigns pushing for an increase of the green services which, given (18), raises political support for intensified pollution taxes. Conversely, a movement aiming at a reduced public support of green tax policies may push for a lower green service ratio i.e. a higher capital share because this raises households' exposure to unexpected capital write-offs.

4.1 Wealth development

Each household has access to the production technology (1) which now gives an uncertain net return due to stochastic taxation. As we focus on investment decisions in the presence of uncertain environmental policy, we follow the finance literature and additionally include a safe asset with riskless interest rate r. This asset has no interrelation with the production sector of the economy and thus offers the possibility to avoid or reduce uncertain investments revealing important insights in the effects of environmental policy on portfolio composition. Individual wealth W is composed of physical capital, K, and the safe asset, B, where n denotes the portfolio share of physical capital. Wealth accumulation is given by

$$\begin{aligned} dW =& Y dt - \tau K dt - \gamma K dq + rB dt - C dt - (1-s)G dt \\ =& [Y(nW,G) - \tau nW + r(1-n)W - C - (1-s)G]dt - nW\gamma dq \end{aligned} \tag{19}$$

The household-producers maximize expected lifetime utility subject to the evolution of wealth

$$\max_{C,n,W} \quad E_0 \int_0^{\infty} \frac{(C_t E_t^{-\beta})^{1-\sigma}}{1-\sigma} e^{-\rho t} dt \tag{20}$$

$$\text{s.t.} \quad dW = [Y(nW,G) - \tau nW + r(1-n)W - C - (1-s)G]dt - nW\gamma dq \tag{21}$$

The Hamilton-Jacobi-Bellman equation with $V(W)$ denoting the value function, results in

$$\begin{aligned} \rho V(W) = \max_{C,n} \Bigg\{ & \frac{(CE^{-\beta})^{1-\sigma}}{1-\sigma} + V_W[A(nW)^{\alpha}G^{1-\alpha} - \tau nW + r(1-n)W - C - (1-s)G] \\ & + \lambda(V(\tilde{W}) - V(W)) \Bigg\} \end{aligned} \tag{22}$$

where $\tilde{W} = (1-\gamma n)W$ denotes the level of wealth after the tax increase occurred. The first-order condition with respect to consumption

$$C^{-\sigma}E^{-\beta(1-\sigma)} - V_W = 0 \tag{23}$$

allows for the conjecture that consumption and physical capital will grow at the same rate in dynamic equilibrium. Definition of $C = \mu nW$ and again $\tilde{\sigma} = \sigma + \beta(1-\sigma)$ results directly in

$$\begin{aligned} V_W &= (\mu nW)^{-\sigma} E^{-\beta(1-\sigma)} \\ &= \mu^{-\sigma} \left(\phi - \theta\delta - \psi \frac{G}{K} \right)^{-\beta(1-\sigma)} (nW)^{-\tilde{\sigma}} \end{aligned} \tag{24}$$

4.2 Portfolio

Individuals optimally adjust their portfolios to policy risks. Again, we distinguish between the fragmented equilibrium (FE) and the activist equilibrium (AE). In the FE, individuals neglect their impact on macroeconomic variables, hence they perceive the tax jumps as purely exogenous. Contrarily, the AE describes the case where agents collude and expect the others to behave similar to themselves. Then, individuals have an impact on the green service ratio. Optimal portfolio composition for the two equilibria is expressed in Proposition 2.

Proposition 2: *Given uncertain environmental taxation, the portfolio of investors in the fragmented equilibrium (FE) and the activist equilibrium (AE) is characterized by the two arbitrage conditions:*

$$A\alpha \left(\frac{G}{K} \right)^{1-\alpha} - \tau = r + \underbrace{\lambda(1-\gamma\bar{n})^{-\tilde{\sigma}}\gamma}_{\text{risk premium FE}} \tag{25}$$

$$A\alpha \left(\frac{G}{K} \right)^{1-\alpha} - \tau = r + \underbrace{\lambda(1-\gamma\check{n})^{-\tilde{\sigma}} \left(\gamma - \eta\chi \left(\frac{G}{K} \right)^{\chi} \right)}_{\text{risk premium AE}}. \tag{26}$$

Proof: We obtain the portfolio composition directly by the derivative of the Hamilton-Jacobi-Bellman equation with respect to n; in the fragmented equilibrium agents do not optimize γ over the portfolio share of capital, n, irrespective of the impact of capital accumulation on stochastic taxation because without coordination their individual action has no impact. ■

The proposition shows that the deterministic part of capital return must equal the riskless interest rate plus a risk premium.[7] With an increase in risk (rising probability λ or rising loss γ) or in risk aversion σ, the risk premium becomes larger. It can be increased (or reduced, respectively) by an increase (or reduction) of the portfolio share of physical capital, the risky asset in the portfolio.

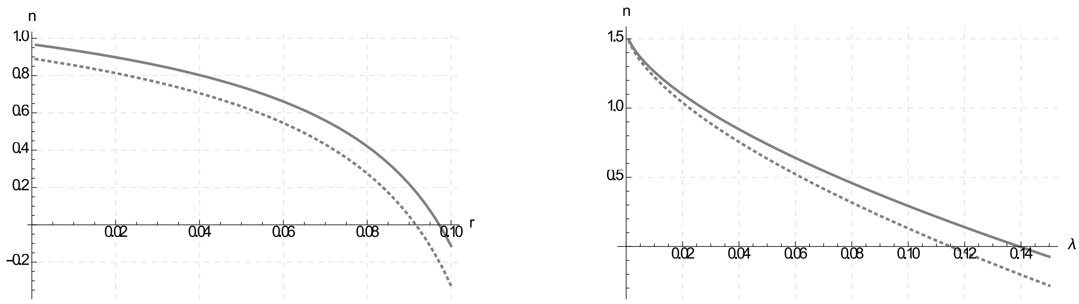
The interest rate of the safe asset, r, is given exogenously, and households compose their portfolio such that the necessary condition (25) or (26) is met. Rearranging terms gives the respective equilib-

[7] In order to ensure feasible solutions we will assume a riskless rate which induces a positive portfolio share of capital. Therefore, the riskless rate has to be small enough, precisely $r < A\alpha(G/K)^{1-\alpha} - \tau$.

rium portfolio composition $\bar{n}$ for the fragmented equilibrium and $\check{n}$ for the activist equilibrium

$$\bar{n} = \frac{1}{\gamma}\left(1 - \left(\frac{\lambda\gamma}{A\alpha\left(\frac{G}{K}\right)^{1-\alpha} - \tau - r}\right)^{\frac{1}{\sigma}}\right), \qquad \check{n} = \frac{1}{\gamma}\left(1 - \left(\frac{\lambda\left(\gamma - \eta\chi\left(\frac{G}{K}\right)^{\chi}\right)}{A\alpha\left(\frac{G}{K}\right)^{1-\alpha} - \tau - r}\right)^{\frac{1}{\sigma}}\right). \quad (27)$$

The individuals choose a higher portfolio share n of risky physical capital when the safe interest rate, r, becomes lower or when uncertainty decreases (decreasing λ). The implications of the equilibrium type (FE or AE) and of the specific design of stochastic environmental taxation can be seen in the numerators in equation (27). Since in the FE the size of the tax shock, γ, is perceived to be exogenous to the portfolio decision, only γ itself is relevant for the portfolio composition and appears in the numerator.



(a) *impact of riskless rate r* (b) *impact of uncertainty λ*

Figure 1: *Portfolio share of capital, n; dotted lines: FE, solid lines: AE*

Contrarily, in the AE, the risk-increasing impact of the greenness of production (due to $\eta, \chi > 0$) increases the portfolio share of capital, n. The reason is that, with increasing physical capital, the green service ratio decreases and a sudden depreciation of physical capital due to taxation gets less probable. Put differently, investors know that the increase of tax rate in case of a tax shock grows with the green service ratio which raises the revaluation of capital i.e. intensifies the stranded capital-effect. As a consequence, investments in polluting capital act as a political "insurance" against major tax increases; capital portfolio shares rise compared to the FE, as can be seen in figure[8] 1. This increase in physical capital investment is strategic behavior: it is due to the investors' knowledge that tax increases get less politically feasible with larger capital accumulation.

It is worth noting that the impact of increasing pollution level on tax shocks does not influence the portfolio decision in either equilibrium setting, at least not directly. Recall that the second term in γ as assumed in (18) reflects increasing tax jump as a consequence of environmental degradation.

[8]For numerical calculations, we choose standard parameters from the literature. If not otherwise stated the parameters are set as follows: preference parameters $\sigma = 3$, $\beta = 0.7$, $\rho = 0.03$, production parameters $A = 1$, $\alpha = 0.5$, $\omega = 0.2$, pollution parameters $\phi = 0.3$, $\theta = 2$, $\psi = 0.1$, $\delta = 0.1$.

Hence, this uncertainty increase seems independent from the capital stock and hence from portfolio choice. Just as the exogenous tax jump, $\bar{\gamma}$, this type of uncertain taxation only affects portfolio composition indirectly through the resulting size of the tax jump γ.

4.3 Green services

In our setup, household-producers decide on the level of green service provision. Green services are productive and — in the stochastic context — affect the size of the tax jumps. Again, we distinguish between the fragmented equilibrium (FE) and the activist equilibrium (AE).

In both types of equilibria individuals are fully informed about productivity as well as costs of green services. But only in the AE they can affect the change in the size of the tax jump γ by an increase in green services. In the FE, however, the stochastic tax rate is perceived to be independent of the individual choice of green services; consequently, individuals will not optimize their tax burden over the green service ratio.

In the FE setting, maximization of the Hamilton-Jacobi-Bellman equation results in

$$V_W\left(A(1-\alpha)\left(\frac{G}{K}\right)^{-\alpha}-(1-s)\right)=0 \tag{28}$$

hence the choice of the green service ratio is unaffected by stochastic taxation and the same as described in the competitive deterministic equilibrium, see (16).

In the AE case, maximization of the Hamilton-Jacobi-Bellman equation with respect to G includes the change in uncertainty due to the adjustment of the stochastic tax rate

$$V_W\left(A(1-\alpha)\left(\frac{G}{K}\right)^{-\alpha}-(1-s)\right)-\lambda V_W(\tilde{W})\left(\eta\chi\left(\frac{G}{K}\right)^{\chi}-\varepsilon\xi\left(\frac{E}{G}\right)^{\xi}\right)\left(\frac{G}{K}\right)^{-1}=0. \tag{29}$$

It is straightforward that in the AE steady state green services and physical capital will grow with the same rate, hence we can set $G=\omega K$ again, where we will use the notation $\bar{\omega}$ for the fragmented equilibrium and $\breve{\omega}$ for the activist equilibrium. This gives the condition for the individually optimal green service ratio in the AE setting

$$A(1-\alpha)\breve{\omega}^{-\alpha}-(1-s)-\lambda(1-\gamma n)^{-\tilde{\sigma}}(\eta\chi\breve{\omega}^{\chi-1}-\varepsilon\xi(\phi-\theta\delta-\psi\breve{\omega})\breve{\omega}^{\xi-1})=0 \tag{30}$$

which will be analysed further in section 5.

4.4 Capital accumulation

Individually optimal wealth accumulation is given by the derivative of the Hamilton-Jacobi-Bellman equation with respect to wealth. Again it differs with respect to the equilibrium setting

$$\begin{aligned}\text{FE:}\quad \rho V_W =& V_{WW}\left(A\omega^{1-\alpha}nW - \tau nW + r(1-n)W - C - (1-s)\omega nW\right)\\ &+ V_W\left(A\alpha\omega^{1-\alpha}n - \tau n + r(1-n)\right) + \lambda\left(V_{\tilde{W}}(\tilde{W})(1-\gamma n) - V_W\right) \qquad (31)\\ \text{AE:}\quad \rho V_W =& V_{WW}\left(A\omega^{1-\alpha}nW - \tau nW + r(1-n)W - C - (1-s)\omega nW\right)\\ &+ V_W\left(A\alpha\omega^{1-\alpha}n - \tau n + r(1-n)\right) + \lambda\left(V_{\tilde{W}}(\tilde{W})(1-\gamma n + n\eta\chi\omega^{\chi}) - V_W\right) \qquad (32)\end{aligned}$$

Together with the conjecture of the value function this first-order condition allows for the derivation of the consumption ratio in the respective equilibrium setting

$$\begin{aligned}\text{FE:}\quad \tilde{\sigma}\bar{\mu}\bar{n} =& \rho + (\tilde{\sigma}-1)(A\alpha\bar{\omega}^{1-\alpha} - \tau) + \tilde{\sigma}A\bar{\omega}^{1-\alpha}\bar{n}(1-\alpha) - \tilde{\sigma}(1-s)\bar{\omega}\bar{n}\\ &- \lambda\left((1-\gamma\bar{n})^{1-\tilde{\sigma}} - 1 - (1-\gamma\bar{n})^{-\tilde{\sigma}}(1-\tilde{\sigma})(1-\bar{n})(\gamma - \eta\chi\bar{\omega}^{\chi})\right) \qquad (33)\\ \text{AE:}\quad \tilde{\sigma}\check{\mu}\check{n} =& \rho + (\tilde{\sigma}-1)(A\alpha\check{\omega}^{1-\alpha} - \tau) + \tilde{\sigma}A\check{\omega}^{1-\alpha}\check{n}(1-\alpha) - \tilde{\sigma}(1-s)\check{\omega}\check{n}\\ &- \lambda\left((1-\gamma\check{n})^{1-\tilde{\sigma}} - 1 + (1-\gamma\check{n})^{-\tilde{\sigma}}\check{n}\eta\chi\check{\omega}^{\chi} - (1-\gamma\check{n})^{-\tilde{\sigma}}(1-\tilde{\sigma})(1-\check{n})(\gamma - \eta\chi\check{\omega}^{\chi})\right) \qquad (34)\end{aligned}$$

which verifies that consumption and wealth grow with a common rate and therefore confirms the existence of the steady state growth path. The impact of stochastic environmental taxation on capital growth will be discussed in section 6.

5 Environmental policy design

In a market equilibrium, agents do not consider the impact of their individual investments on aggregate emissions and their effects on intertemporal utility. Therefore, green services tend to be suboptimally low and, consequently, emissions become suboptimally high

$$E = (\phi - \theta\delta - \psi\omega)K \gtreqless E^* \quad \Longleftrightarrow \quad \omega \lesseqgtr \omega^*. \qquad (35)$$

As shown in the deterministic model variant above the environmental externalities can be internalized to achieve social optimum. Then, the green service ratio, ω, is on the optimal level. In the non-deterministic case, tax and subsidy rates could, in principle, be adjusted to accommodate the underlying economic risks. Moreover, in an activist equilibrium agents use green service provision as a strategic device. However, in the fragmented equilibrium, agents will not adjust the green service ratio because of stochastic taxation. The green service ratio is given by

$$\bar{\omega} = \left(\frac{A(1-\alpha)}{1-s}\right)^{\frac{1}{\alpha}} \qquad (36)$$

which coincides with the green service ratio without stochastic taxation. The consequence of this outcome is quite serious: Taxation of dirty capital will only lead to an increase in green services if individuals perceive the possibility to affect taxation by means of greener production. A political process generating unanticipated environmental tax jumps will solely affect capital accumulation — and thereby lead to stranded assets (as will be shown in the next section) — but does not have any impact on the greenness of production when individuals are not actively shaping the political process via common action.

In the activist equilibrium, the green service ratio is used by agents to have an impact on tax development. Hence, this effect on the stochastic tax is included in the optimization of the green service ratio as shown in equation (30). With the deterministic subsidy and — additionally — the stochastic tax rate, the optimal green service ratio determined in equation (9) can be realized by any combination fulfilling

$$s - \frac{\psi}{\theta} = \lambda(1-\gamma\check{n})^{-\tilde{\sigma}}(\eta\chi\check{\omega}^{\chi-1} - \varepsilon\xi(\phi-\theta\delta-\psi\check{\omega})\check{\omega}^{\xi-1}) \tag{37}$$

and hence

$$s^* \gtrless \frac{\psi}{\theta} \quad \Longleftrightarrow \quad \eta\chi\check{\omega}^{\chi-1} - \varepsilon\xi(\phi-\theta\delta-\psi\check{\omega})\check{\omega}^{\xi-1} \gtrless 0. \tag{38}$$

However, to impose a planner solution on a deficient government does not appear to be consistent. In fact, we do not see the government as an autonomous decision unit but rather as a body that depends on political support inducing uncertain policy implementation. Hence, our focus is different: We aim at analyzing the effects of uncertain policy on the green service ratio in decentralized equilibrium.

Rearranging terms from equation (30)

$$A(1-\alpha)\check{\omega}^{-\alpha} - (1-s) = \lambda(1-\gamma\check{n})^{-\tilde{\sigma}}(\eta\chi\check{\omega}^{\chi-1} - \varepsilon\xi(\phi-\theta\delta-\psi\check{\omega})\check{\omega}^{\xi-1}) \tag{39}$$

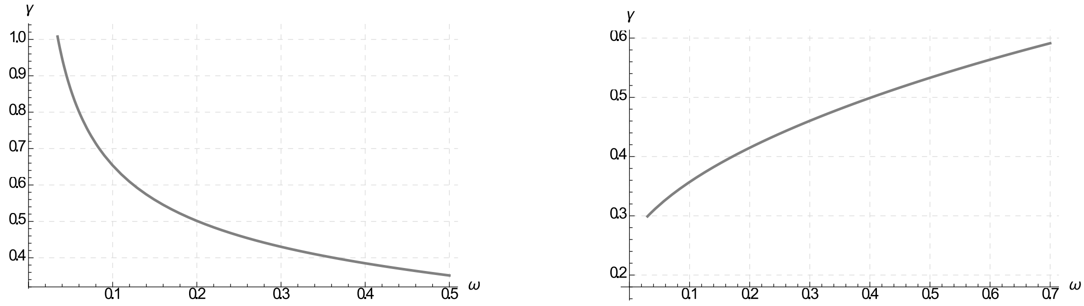
shows the impact of tax uncertainty on green service provision when looking at the right hand side of (39). Its direction depends on whether the risk increasing impact ($\eta\chi$) of green services or the risk reducing impact ($\varepsilon\xi$) dominates. In both settings, the safe asset lowers the impact of tax uncertainty on the individually optimal green service ratio (since $(1-\gamma\check{n})^{-\tilde{\sigma}} < (1-\gamma)^{-\tilde{\sigma}}$). As individuals have access to safe return, only part of individual wealth is exposed to taxation uncertainty. Hence the effect of taxation uncertainty on individual decisions is smaller.

Implicit differentiation of equation (30) demonstrates the influence of uncertainty in taxation on the individual choice of the green service ratio

$$\frac{d\check{\omega}}{d\lambda} = -\frac{-(1-\gamma\check{n})^{-\tilde{\sigma}}(\eta\chi\check{\omega}^{\chi-1} - \varepsilon\xi(\phi-\theta\delta-\psi\check{\omega})\check{\omega}^{\xi-1})}{\mathcal{N}} \gtrless 0 \tag{40}$$
$$\Longleftrightarrow (\eta\chi\check{\omega}^{\chi-1} - \varepsilon\xi(\phi-\theta\delta-\psi\check{\omega})\check{\omega}^{\xi-1}) \lesseqgtr 0$$

$$\text{with } \mathcal{N} = -\alpha(1-\alpha)A\omega^{-\alpha-1} - \lambda\tilde{\sigma}n(1-\gamma n)^{-\tilde{\sigma}-1}(\eta\chi\omega^{\chi-1} - \varepsilon\xi(\phi-\theta\delta-\psi\omega)\omega^{\xi-1})^2$$
$$-\lambda(1-\gamma n)^{-\tilde{\sigma}}(\eta\chi(\chi-1)\omega^{\chi-2} - \varepsilon\xi\psi\omega^{\xi-1} + \varepsilon\xi(\phi-\theta\delta-\psi\omega)(\xi-1)\omega^{\xi-2}) < 0.$$

Increasing the arrival frequency of the tax shock, λ, implies rising uncertainty. The sign of equation (40) depends on the sign of the term in parenthesis in the numerator,[9] $(\eta\chi\breve{\omega}^{\chi-1} - \varepsilon\xi(\phi-\theta\delta-\psi\breve{\omega})\breve{\omega}^{\xi-1})$. We find that rising uncertainty has two opposing effects on the green service ratio.



(a) *dominant impact of emissions;* $\varepsilon = 0.5$, $\xi = 0.5$, $\eta = 0.1$ $\chi = 0.1$

(b) *dominant impact of greenness;* $\varepsilon = 0.1$, $\xi = 0.1$, $\eta = 0.5$ $\chi = 0.5$

Figure 2: *Structure of the stochastic tax*

First, if the importance of $\varepsilon\xi$ — representing the impact of emissions in the determination of tax changes — dominates, risk will be reduced in a greener economy as displayed in figure 2(a). An economy with a higher ratio of green services, ω, will experience a reduction in environmental emissions, e.g. through effective climate mitigation or reduction of environmentally harmful technologies, which curbs the size of environmentally motivated tax increases. The reduction of political risk is an additional benefit of green service provision which raises the green service ratio. In this respect the stochastic tax has the same effect as the subsidy to green services. If the government is constrained to pay substantial subsidies it can obtain the same effect by simply ”threatening” the private economy by a highly stochastic tax setting. This effect is even present when no deterministic tax is implemented as it is effective through the individual aversion against (tax) shocks.

Second, if the importance of $\eta\chi$ — representing the impact of greenness in the determination of tax changes — dominates, larger tax increases get more likely in a greener economy as illustrated in figure 2(b). The increase in green services induces an additional effect on policy uncertainty due to stronger political support. At the same time, it induces more stringent environmental policy in the end. Current examples are countries with a high market shares of green technologies and renewable energies considering even stricter emission abatement policies, e.g. in traffic and for heating. A government which values environmental policy highly can increase its subsidies to green services in order to obtain more political support in tax policy. In this sense, the time sequence first subsidies

[9] The denominator, $\mathcal{N}$, must be negative because it is equivalent to the second derivative of the Hamilton-Jacobi-Bellman equation with respect to green services.

and then taxes becomes a very rational strategy for public policy.

In an activist equilibrium and if $\eta\chi$ dominates, firms anticipate the increasing stochastic taxation and know that this is an additional cost of green services. Hence, they use the amount of green services as strategic variable and agree upon reducing the green service ratio in order to decline the size of tax shocks and thereby diminish uncertainty. Firms in this case decide to reduce the greenness of production to prevent more severe environmental policy measures. Put differently, firms present themselves less green in order to reduce the political feasibility of large tax cuts.

Hence, whether the green service ratio will decrease or increase as a response to tax risks depends on two well defined effects which have an opposite impact. The impact of uncertainty on the optimal green services subsidy, s^*, depends on whether green services increase or decrease uncertainty in the economy. If tax risks become lower in a green economy (if $\varepsilon\xi$ dominates), this additional incentive to use green service reduces the need for internalization through the subsidy rate. This kind of stochastic taxation is a substitute for the deterministic subsidy rate. The individually optimal green service ratio increases due to tax uncertainty and the optimal level of the subsidy rate decreases. If the tax risk becomes higher in a greener economy (if $\eta\chi$ dominates), the stochastic taxation reduces the incentive to use green services. This kind of stochastic taxation impedes the internalization through the subsidy rate. Individually optimal green services expenditures decrease due to this stochastic taxation and the subsidy rate would have to be increased in order to ensure the optimal green service ratio.

The following proposition summarizes our findings in three parts a) - c).

Proposition 3: *With uncertain taxation, environmental policy is characterised as follows:*
a) There exists an optimal policy design with subsidies and purely deterministic taxes; if political restrictions prevent adopting such a design, the optimum can also be achieved in an activist equilibrium through the use of stochastic tax policies.
b) With lower (higher) tax risks in a green economy, firms will increase (decrease) the greenness of production strategically in order to reduce uncertainty.
c) Stochastic taxation serves as a substitute (complement) to deterministic green services subsidy, if uncertainty decreases (increases) in the green service ratio.

With an increase in the constant term $\bar{\gamma}$, the size of the tax jumps increases and the green service ratio is adjusted accordingly. Implicit differentiation of (30) results in

$$\begin{aligned}\frac{d\breve{\omega}}{d\bar{\gamma}} &= -\frac{-\lambda\sigma\breve{n}(1-\gamma\breve{n})^{-\tilde{\sigma}-1}(\eta\chi\breve{\omega}^{\chi-1}-\varepsilon\xi(\phi-\theta\delta-\psi\breve{\omega})\breve{\omega}^{\xi-1})}{\mathcal{N}} \gtrless 0 \\ &\iff (\eta\chi\breve{\omega}^{\chi-1}-\varepsilon\xi(\phi-\theta\delta-\psi\breve{\omega})\breve{\omega}^{\xi-1}) \lessgtr 0.\end{aligned} \tag{41}$$

In an activist equilibrium, an increased level of tax jumps $\bar{\gamma}$ has opposing effects which depend on the specific structure of the stochastic tax system. An increase in $\bar{\gamma}$ causes a positive level effect of tax jumps, immediately increasing uncertainty. Hence there is an incentive to change the green service ratio in order to reduce uncertainty. The remaining argument is the same as given above. Individuals will increase the green service ratio as response to increasing general uncertainty of stochastic taxation, if $\varepsilon\xi$ are high and stochastic taxation will be less uncertain in a greener economy. On the contrary, they will decrease the green service ratio, if $\eta\chi$ are high and stochastic taxation involves higher risks in a greener economy.

6 Growth effects of stochastic taxation

The growth rate of wealth between the tax shocks, which we label the "trend growth rate," is characterized by the following proposition.

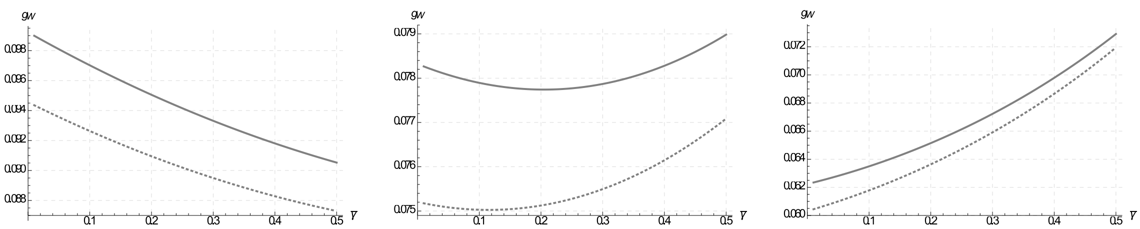
Proposition 4: *The trend growth rate of the economy is given by*

$$g_W = A\omega^{1-\alpha}n - \tau n + r(1-n) - \mu n - (1-s)\omega n$$

$$\text{FE:} \quad \bar{g}_W = \frac{1}{\tilde{\sigma}}\left(A\alpha\bar{\omega}^{1-\alpha} - \tau - \rho\right) + \frac{\lambda}{\tilde{\sigma}}\Big(\underbrace{((1-\gamma\bar{n})^{1-\tilde{\sigma}} - 1}_{(i)} \underbrace{-(1-\gamma\bar{n})^{-\tilde{\sigma}}\gamma(1-\bar{n})}_{(ii)}\Big) \tag{42}$$

$$\text{AE:} \quad \breve{g}_W = \frac{1}{\tilde{\sigma}}\left(A\alpha\breve{\omega}^{1-\alpha} - \tau - \rho\right) + \frac{\lambda}{\tilde{\sigma}}\Big(\underbrace{((1-\gamma\breve{n})^{1-\tilde{\sigma}} - 1}_{(i)} \underbrace{-(1-\gamma\breve{n})^{-\tilde{\sigma}}\gamma(1-\breve{n})}_{(ii)} + \underbrace{(1-\gamma\breve{n})^{-\tilde{\sigma}}\eta\chi\breve{\omega}^{\chi}}_{(iii)}\Big) \tag{43}$$

Proof: The trend growth rate of wealth is directly derived from the equation of motion of capital (19), the portfolio decision (25) and the consumption ratio (33) for FE, and (26) with (34) for AE respectively, and taking into account that $dq = 0$. ■

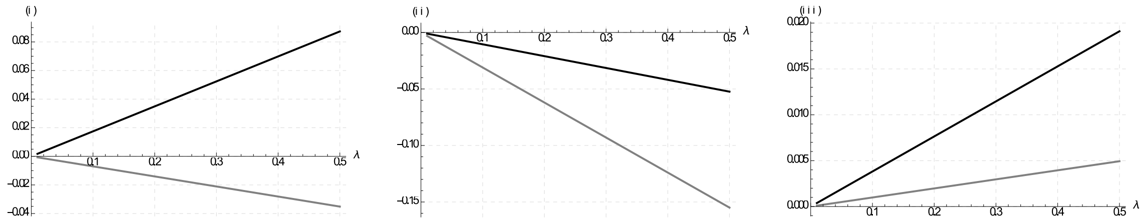


(a) *low risk aversion* $\sigma = 0.5$ (b) *intermediate risk av.* $\sigma = 1.5$ (c) *high risk aversion* $\sigma = 3$

Figure 3: *Impact of exogenous uncertainty* $\bar{\gamma}$ *on trend growth; dotted lines: FE, solid lines: AE*

Direct tax uncertainty, given by the exogenous tax jump, $\bar{\gamma}$, is equivalent to an unforeseeable and exogenous depreciation of physical capital. The impact on the resulting trend growth rate is ambiguous due to the precautionary savings motive and displayed in figure 3. If relative risk aversion, σ, is sufficiently low, the growth decreasing impact of uncertainty dominates. Tax uncertainty decreases the incentive to accumulate capital and thereby supports environmental policy. However, if relative risk aversion, σ, is sufficiently large, the growth increasing impact of uncertainty dominates and tax uncertainty ends up in even larger physical capital taxation and environmental deterioration.

The entire impact of stochastic taxation on the trend growth rate is more complex and displayed in the second parenthesis in equations (42) and (43) respectively; the three impact channels can be discussed by inspection of the terms $(i)-(iii)$. The precautionary savings motive is captured with term (i), the reduction in capital accumulation due to the existence of a safe asset is given in term (ii) and term (iii) describes the additional capital accumulation in order to reduce tax uncertainty. Figure 4 displays the three effects.



(a) *precautionary savings* (i), *black line* $\sigma = 3$, *gray line* $\sigma = 0.5$

(b) *impact of safe asset* (ii), *black line* $n = 0.5$, *gray line* $n = 0.1$

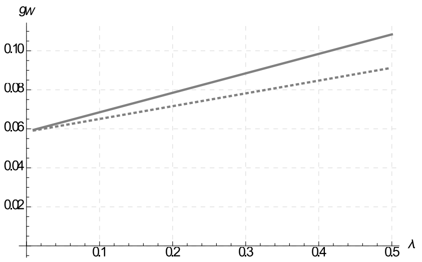
(c) *uncertainty adjustment* (iii), *black line* $\eta = 0.5$, *gray line* $\eta = 0.1$

Figure 4: *Impact of uncertainty on trend growth, terms,* (i)–(iii)

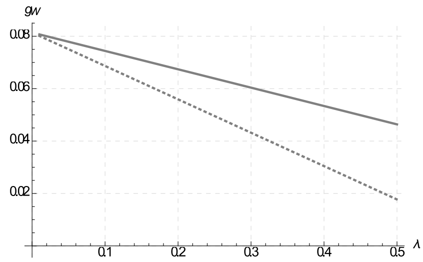
First, as can be seen in term (i), policy uncertainty causes a precautionary savings motive; the agents adjust capital accumulation with the aim to decrease uncertainty. In this respect, the model outcome is in full accordance with the results of stochastic growth theory. If relative risk aversion is sufficiently high such that $\tilde{\sigma} > 1$, term (i) is positive. As a response to uncertainty, savings are increased in order to increase future consumption possibilities and compensate for the utility loss induced by uncertainty. If instead relative risk aversion is low ($\tilde{\sigma} < 1$), term (i) is negative and individuals decrease savings in order to substitute away from uncertainty. Precautionary behavior is a specific aspect of the stranded assets problem: Given the probability of a future capital devaluation or even capital loss, investors deviate from their optimal plans to accommodate uncertainty in an optimal way. Put differently, investors try to alleviate the consequences of sudden capital depreciation and react correspondingly.

In term (ii) we see that individuals will adjust portfolio composition in order to evade tax uncertainty. This is a key feature of the stranded assets problem, harming the growth rate of the economy, whenever $n < 1$ i.e. not all wealth is invested in physical capital. In our model, the availability of a safe asset allows the agents to reduce the tax risk by investing part of the wealth in a way to have a safe return. Individuals substitute away from uncertain capital accumulation and shift wealth into the safe asset which is not subject to stochastic environmental taxes.

Term (iii) shows the effect that capital accumulation alters the green service ratio G/K and with it policy uncertainty. If more capital is accumulated the risk of a sizeable tax increase is reduced, because there is less political support. Capital accumulation reacts positively on the decrease in uncertainty which fosters the growth process. Both effects work in the same direction, i.e. this effect is unambiguously growth enhancing. We interpret this as a further stranded assets effect: capital investments reduce the threat of large tax jumps via the political support channel which in turn incentivizes capital accumulation. Of course, this effect only applies in the activist equilibrium. In the fragmented equilibrium setting, individuals perceive stochastic taxation as purely exogenous to their decisions, hence there is no attempt to reduce the risk of taxation by means of individual capital accumulation.



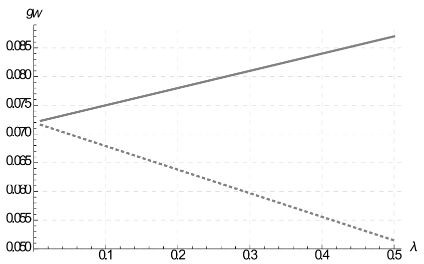
(a) *high risk aversion* $\sigma = 3$



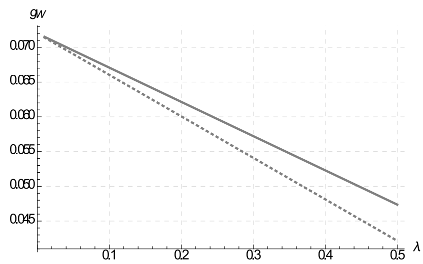
(b) *low risk aversion* $\sigma = 1.5$

Figure 5: *Trend growth rate and relative risk aversion; dotted lines: FE, solid lines: AE*

Figures 5 and 6 show that the overall impact of uncertainty in taxation on the trend growth rate is ambiguous. The stranded assets which arise from unforeseeable capital taxation may lead to a growth decreasing impact of uncertainty. But depending on the specific structure of stochastic environmental taxation, the accumulation increasing incentives may dominate. For sufficiently high relative risk aversion, the precautionary savings argument dominates and the trend growth rate increases with rising uncertainty. Stochastic environmental taxation leads to decreasing growth, if relative risk aversion is small enough. Figure 5 shows that even for relative risk aversions above unity the growth decreasing impact of stochastic taxation may dominate. Individuals then substitute away from risky capital and increase the share of the safe asset in their portfolio.



(a) *political support important* $\eta = 0.5$



(b) *political support unimportant* $\eta = 0.1$

Figure 6: *Trend growth rate and importance of political support; dotted lines: FE, solid lines: AE*

Additionally, figures 5 and 6 reveal that growth rates in the fragmented equilibrium are always lower than in the activist equilibrium. The reason is that firms in the activist equilibrium have an additional incentive to accumulate capital: Capital accumulation can be used as a strategic variable to reduce the greenness of the economy and to undermine political support for sudden environmental tax increases.

The impact of the specific structure of the stochastic tax system is illustrated in figure 6. η represents the degree to which environmental policy is dependent from political support. For low values of η and in the fragmented equilibria increasing uncertainty in environmental taxation leads to decreasing growth. But if η is large (figure 6(a)) and if we consider an activist equilibrium, the incentive to increase capital accumulation is sufficiently large to reverse the result. Increasing uncertainty in taxation then even has a growth accelerating impact which is due to the strategic reduction of political support for tightening environmental taxation.

7 Conclusions

The paper has analyzed investment decisions and their macroeconomic consequences when environmental policy is not deterministic but uncertain, following the Poisson process. This is a different perspective compared to standard environmental economics models where proposed policies are welfare-maximizing and implemented immediately. As a consequence, we have not derived an optimal policy design when assets tend to become stranded but have rather focused on the impacts of uncertain environmental policies on asset values and the adjustments of individual investment behavior.

We have shown how policy shocks affect capital accumulation, composition of the capital stock, green services, and economic growth and have obtained some major results. First, if political restrictions prevent adopting an optimal policy design with subsidies and deterministic taxes, the same effects may be achieved using stochastic tax policies in an activist equilibrium. Stochastic taxation serves as a substitute for a green service subsidy if uncertainty decreases in the green service ratio; in the opposite case it is a complement. Second, we have found that capital accumulation alters the level of green service provision and with it policy uncertainty. When agents cooperate strategically, capital investments may act as a political "insurance" against future tax increases. Third, policy uncertainty causes precautionary savings. Given the probability of stranded assets i.e. of a future capital devaluation or capital loss, investors deviate from their optimal plans to accommodate the uncertainty in an optimal way. If relative risk aversion is sufficiently high, savings are increased in order to compensate for the utility loss induced by uncertainty. Fourth, individuals adjust portfolio composition in order to reduce tax uncertainty, harming the growth rate of the economy. A diversified portfolio allows the agents to reduce uncertain tax risk and a stranding of assets by investing part of the wealth in a safe asset.

Our analysis highlights that most effects of uncertain policies decrease the welfare in the economy as would be expected. Agents have to adjust their optimal savings and portfolio plans or to cooperate strategically in order to optimally cope with uncertain policy conditions and to reduce the risk of stranded assets. These induced adjustments of individual behavior have adverse effects on income level and income growth. One aspect of policy uncertainty turned out to be less negative, however: the use of unpredictable emission tax policies to discourage polluting investments. We have shown that — under certain conditions — this may restore the optimal green service ratio and thus act like a deterministic environmental policy. To threaten the markets with possible taxes is indeed efficient and may even be seen as relatively "cheap", because agents change their plans "voluntarily". However, if the threat principle in policy is transferred to a general context the conclusion loses much of its attractiveness. In a holistic policy framework, unpredictable behavior of the government is not generally desirable because it not only discourages polluting investments but all kind of investments in the economy. Moreover, the threat principle may also be used for a less favorable purpose than environmental protection, which is likely to harm overall welfare.

The present framework can be extended in several ways. While we have already introduced green services in our model as an alternative input to polluting capital we have sidestepped the option of green capital stock as an investment alternative. We expect that such an extension of the model would strengthen our results on green services. In the same way, the introduction of different production sectors with different degrees of green service or green capital ratios would be a rewarding object to study. This is left for future research.

References

[1] Barro, R.J. (2015): Environmental Protection, Rare Disasters and Discount Rates, Economica (2015) 82, 1–23.

[2] Barro, R.J. (1990): Government spending in a simple model of endogeneous growth, Journal of Political Economy 98: 103-125.

[3] Battiston, S., A. Mandel, F. Schuetze, and G. Visentin (2017): A Climate stress-test of the financial system, Nature Climate Change 7: 283-288.

[4] Bovenberg, A., S. Smulders (1996): Transitional impacts of environmental policy in an endogenous growth model, International Economic Review, 37 (4): 861-893.

[5] Bretschger, L. (2017): Climate Policy and Economic Growth, Resource and Energy Economics, 49: 1-15.

[6] Bretschger, L. and A. Vinogradova (2018): Best Policy Response to Environmental Shocks: Building a Stochastic Framework, Journal of Environmental Economics and Management, in Press.

[7] Caldecott, B. (2015): Stranded Assets and Multilateral Development Banks. Inter-American Development Bank.

[8] Dietz, S., A. Bowen, C. Dixon and P. Gradwell: (2016): Climate value at risk' of global financial assets. Nature Climate Change http://dx.doi.org/10.1038/nclimate2972

[9] Generation Foundation (2013): Stranded Carbon Assets.

[10] Helm, D., Hepburn, C., Mash, R. (2003): Credible carbon policy, Oxford Review of Economic Policy 19 (3): 438-450.

[11] IEA (2013): Redrawing The Energy Climate Map. World Energy Outlook Special Report.

[12] Ikefuji, M. and R. Horii, (2012): Natural disasters in a two-sector model of endogenous growth, Journal of Public Economics 96, 784-796.

[13] Kalkuhl, M., O. Edenhofer, and K. Lessmann (2013). Renewable energy subsidies: Second-best policy or fatal aberration for mitigation? Resource and Energy Economics 35 (3): 217-234.

[14] Kalkuhl, M., J. C. Steckel, and O. Edenhofer (2018): All or nothing: Climate policy under stranded assets, Working Paper.

[15] McGlade, C. and P. Ekins (2015): The geographical distribution of fossil fuels unused when limiting global warming to 2°C, Nature 517: 187–190.

[16] McKibben, B. (2011): Global Warming's Terrifying New Math, Rolling Stone.

[17] Pittel, K. (2002): Sustainability and Endogenous Growth, Cheltenham UK: Edward Elgar.

[18] Pommeret, A. and K. Schubert (2017): Intertemporal Emission Permits Trading Under Uncertainty and Irreversibility, Environmental and Resource Economics, in Press.

[19] Rezai, A. and F. Van der Ploeg (2017). Second-best renewable subsidies to decarbonize the economy: commitment and the green paradox. Environmental and Resource Economics 66 (3): 409-434.

[20] Rozenberg, J., A. Vogt-Schilb, and S. Hallegatte (2014): Transition to Clean Capital, Irreversible Investment and Stranded Assets, World Bank Policy Research Working Paper No. 6859, Available at SSRN: https://ssrn.com/abstract=2433812

[21] Schumpeter, J.A. (1942): Capitalism, Socialism and Democracy. Routledge.

[22] Smulders, S., M. Toman, and C. Withagen (2014): Growth theory and 'green growth', Oxford Review of Economic Policy 30 (3): 423–446.

[23] Steger, T.M. (2005): Stochastic growth under Wiener and Poisson uncertainty, Economics Letters 86 (3): 311-316

[24] Soretz, S. (2007): Efficient dynamic pollution taxation in an uncertain environment, Environmental and Resource Economics: 57-84.

[25] Tsur, Y. and A. Zemel (2008): Regulating environmental threats, Environmental and Resource Economics 39: 297-310.

[26] Tsur, Y. and A. Zemel (1998): Pollution control in an uncertain environment Journal of Economic Dynamics and Control 22: 967-975.

[27] Tsur, Y. and A. Zemel (1996): Accounting for global warming risks: resource management under event uncertainty Journal of Economic Dynamics and Control 20: 1289-1305.

[28] Ulph, A. and D. Ulph (2013). Optimal climate change policies when governments cannot commit. Environmental and Resource Economics 56 (2): 161-176.

[29] Van der Ploeg, F., and A. de Zeeuw (2016): Climate Tipping and Economic Growth: Precautionary Capital and the Price of Carbon, OxCarre Research Paper 118.

[30] Van der Ploeg, F. and A. Rezai (2016): Stranded Assets, the Social Cost of Carbon, and Directed Technical Change: Macroeconomic Dynamics of Optimal Climate Policy, CESifo Working Paper Series 5787, CESifo Group Munich.

[31] Weyzig, F., B. Kuepper, J-W. van Gelder and R. van Tilburg (2014): The Price of Doing Too Little Too Late, The impact of the carbon bubble on the EU financial system, Green European Foundation, Brussels.

[32] Williams, R. C., 2011. Setting the initial time-profile of climate policy: The economics of environmental policy phase-ins. NBER, 245-254.

[33] Xepapadeas, A. (2001): Environmental Policy and Firm Behavior: Abatement Investment and Location Decisions under Uncertainty and Irreversibility, in: C. Carraro and G. Metcalf (Eds): Behavioral and Distributional Effects of Environmental Policy, NBER.

[34] Xepapadeas, A. (2006): Economic Growth and the Environment, in: K.-G. Mäler and J. Vincent (Eds.), Handbook of Environmental Economics, Elsevier Science, Amsterdam.

[35] de Zeeuw, A. and A. Zemel (2012): Regime Shifts and Uncertainty in Pollution Control, Journal of Economic Dynamics and Control 36, 939-950.

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