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# Strategic carbon taxation and energy pricing under the threat of climate tipping events

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ABSTRACT

An appropriate design of climate mitigation policies such as carbon taxes may face a lot of challenges in reality, e.g., the strategic behavior of fossil fuel producers, and huge uncertainty surrounding the climate system. This paper investigated the effect of possible climate tipping events on optimal carbon taxation and energy pricing, taking into account the strategic behavior of energy consumers/producers and the uncertainty of tipping points through a stochastic dynamic game. The game was solved numerically to get some insights into the equilibrium carbon taxation and energy pricing strategies under the threat of possible tipping events. The results suggest that the sudden occurrence of tipping events will shift the carbon tax upwards but shift the (wellhead) fuel price downwards, which generates an overall effect of a sudden increase in the consumer price. The irreversibility of the damage caused by a tipping point implies more aggressive carbon taxation. Moreover, the design of climate policy should adjust to tipping probabilities, damage uncertainty, and types of tipping events.

## 1. Introduction

Climate change has been considered as one of the most important environmental issues at our time and the accumulated greenhouse gases (GHGs) in the atmosphere are believed to be the main cause of this. Mitigating climate change needs to address the externalities caused by GHGs emissions from fossil fuel consumption, through policy instruments such as carbon taxes or emission trading systems (see, e.g., Wu et al., 2014; Ouchida and Goto, 2016; Fan et al., 2016). However, the optimal design of climate policy is subject to many issues in reality, e.g., oligopoly in fossil energy markets, strategic behavior of agents, and uncertainties in the climate system.

It is known that there are huge uncertainties surrounding climate system, which implies that it is almost impossible to be sure about the exact effect of greenhouse gas (GHG) emissions on global climate change, and thus the ecological and socio-economic damage in the future. Therefore, the decisions on regulating emissions have to be made before we realize the exact consequences of climate change and the design of climate policy needs to take such uncertainties into consideration. However, there is a great variation in the approaches for modeling climate uncertainty across different studies. Many studies assume that the damage from climate change is a continuous function of atmospheric temperature which is stochastic due to the uncertainty in the effect of $CO_2$ concentration on temperature increase (e.g., Wirl, 2007). However, the scientific evidences show that the mechanism of climate change in reality can be much more complex. For instance, global warming could push the climate and ecosystem toward passing a threshold, where sudden, irreversible events would occur and lead to remarkable and persistent damage. These tipping events can be the melting of the Antarctic ice sheet, the die-back of the Amazon rainforest, and so on. What could be even worse is that we are not sure when these tipping events would occur. The sudden, irreversible damage caused by the tipping events implies a shift in the damage function at some certain levels of temperature, which are so-called tipping points. After the occurrence of tipping events, the damage will still be persistent even if there is no further warming or even there is cooling. That is, the regime after the occurrence of a tipping event will be different from the one before, as shown in Fig. 1.

In addition to the tipping events, another prevailing issue in global warming studies is the strategic behavior of stakeholders occurring around the taxation and pricing of fossil energy resources. Given the unbalanced resource endowment in the world, there are always conflicts of interest between different stakeholders, e.g., fossil energy consumers and producers, during the mitigation of climate change. From a more general perspective of energy production and consumption worldwide, a phenomenon that is high-likely to be observed in climate change mitigation can be described as follows: A possible coalition of energy importing countries coordinating their carbon

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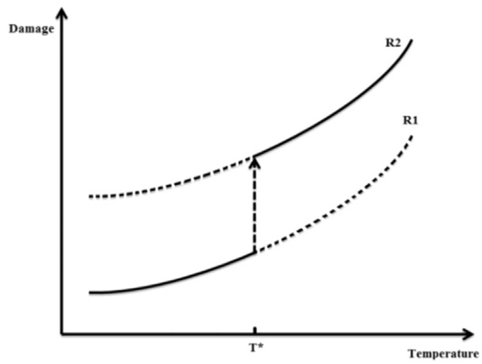


**Fig. 1.** The tipping point and irreversible damage.

taxation can affect the pricing strategy of energy produce/export countries, and meanwhile, the energy producer can react strategically and preempt carbon taxes by raising the producer price (Wirl, 1995).

As two of the most prevailing issues, climate uncertainty and strategic interaction have been shown their importance in the climate policy design. Following Wirl (2007), this paper tries to integrate the strategic interaction issue between carbon taxation and energy pricing with climate uncertainty in a dynamic game framework, which allows us to examine the optimal carbon taxes and energy prices under the threat of climate tipping events. More precisely, within a stochastic dynamic game framework, this stud y models the strategic interactions between energy seller side and buyer side on rent contest with integrating the uncertainty of climate tipping points. Two representative players have been modeled here: the collective consumer's benevolent government (or a consumer coalition/cartel, such as an empowered Organisation for Economic Co-operation and Development (OECD), or Annex I Countries); and the (cartelized) energy producers (such as Organization of the Petroleum Exporting Countries, OPEC). While the strategic interaction issues have been extensively examined in the literature, none of the previous studies (to the best of our knowledge) has incorporated the climate tipping points and its uncertainty issues which are well supported by the climate-economy integrated assessment models, into the investigation of strategic interaction issues. This paper tries to fill this gap in the literature. Based on a similar framework that was employed in Wirl (1994), Tahvonen (1996, 1997), Rubio and Esriche (2001) and Liski and Tahvonen (2004), this paper makes the extension by incorporating the uncertain climate tipping points through introducing a first order Markov chain for the climate state indicating whether a climate tipping event occurs or not. The probability of climate tipping events occurring increases as the temperature rises and the occurrence of tipping event is irreversible. Through theoretical analysis and numerical simulation, we find some interesting results such as how the carbon taxes and energy prices should look like in different cases and how they would differ before and after the occurrence of climate tipping events, and so on.

This paper is organized as follows. Section 1 gives an introduction on these issues and Section 2 describes the model and some optimality analysis. Section 3 describes the initialization and parameterization for numerical solution of the game. Section 4 presents the numerical results and discussions. Concluding remarks and their policy implications are summarized in the final section.

## 2. The model

### 2.1. Two players

As in Wirl (1994, 2007), Tahvonen (1996, 1997), Rubio and Esriche (2001) and Liski and Tahvonen (2004), there are two players in the dynamic game of strategic interaction: the collective consumers' benevolent government (e.g., an empowered OECD) who maximizes the net present value of consumers' welfare by choosing a carbon tax $\tau_t$; and the (cartelized) energy producers (e.g., OPEC) who maximize the net present value of profits by setting the (wellhead) fossil energy price $p_t$. Consequently the consumer price in period $t$ would be $\pi_t = p_t + \tau_t$, which will determine the demand for fossil energy (measured in emissions). As in Wirl (1994, 2007), and Rubio and Esriche (2001), we use a linear function form $D(\pi) = a + b\pi$, where $D(\pi)$ stands for the demand for fossil energy, and $a$ and $b$ are constants.

The net present value of consumers' welfare, which the collective consumers' government wants to maximize, consists of consumers' surplus plus carbon tax revenues minus the damage cost of climate change. In a discrete time framework, the maximization problem for the consumers can be expressed as:

$$W = \max_{\{\tau_t\}} E\left\{\sum_{t=0}^{\infty} \frac{1}{(1+\rho)^t}[u(p_t+\tau_t) + \tau_t D(p_t+\tau_t) - \Omega(T(S_t), J_t)]\right\} \tag{1}$$

where $u(p_t + \tau_t) = u(\pi_t) = \int_{\pi_t}^{\pi^c} D(x)dx = \frac{1}{2}a\pi^c - \frac{1}{2}b\pi_t^2 - a\pi_t$ is the consumes' surplus and $\pi^c$ is the choke price which makes $D(\pi^c) = 0$. Given the linear demand function, we have $\pi^c = -a/b$. The term $\tau_t D(p_t + \tau_t)$ represents the tax revenues and they are reimbursed to the consumers. Since these tax revenues are not taken into account by the consumers' surplus $u(\pi_t)$, they have to be added explicitly in (1). The external cost of climate change is represented by $\Omega(T(S_t), J_t)$, where $T$ is the atmospheric temperature depending on the carbon concentration (cumulative emissions) in the atmosphere, which is represented by $S$. $J$ is a discrete variable indicating the state of the climate, i.e., whether the climate is in the normal/pre-tipping regime (before the occurrence of a tipping event) or in the post-tipping regime (after the occurrence of a tipping event).

With the producers' surplus being neglected by the consumers' government, the external cost of climate change is ignored by the energy producer and thus the producers' cartel concentrates only on maximizing the present value of its net profits through the pricing strategy $p_t$:

$$V = \max_{\{p_t\}} E\left\{\sum_{t=0}^{\infty} \frac{1}{(1+\rho)^t}[p_t \cdot D(p_t+\tau_t)]\right\} \tag{2}$$

Consistent with Wirl (2007), the discount rate is the same for both the consumers' government and the producers' cartel, and the extraction costs of producer are ignored.

### 2.2. Temperature and $CO_2$ concentration

The temperature (relative to the pre-industrial level) in period $t$ is a function of the atmospheric $CO_2$ concentration:

$$T_t = \lambda\left(\ln \frac{S_t}{\overline{S}} / \ln 2\right) \tag{3}$$

where $\lambda$ is the climate sensitivity, which is often expressed as the temperature change associated with a doubling of $CO_2$ concentration in the atmosphere with respect to the preindustrial level $\overline{S}$). Eq. (3) states that the temperature (relative to the pre-industrial level) will be $\lambda$ when the current $CO_2$ concentration is the double of the pre-industrial level.[1]

The accumulation of $CO_2$ in the atmosphere depends on the consumption of fossil fuels and the natural decay of existing $CO_2$ in the atmosphere:

$$S_{t+1} = (1-\delta)S_t + D_t \tag{4}$$

where $S$ is the carbon dioxide concentration in the atmosphere and $\delta$ is

[1] As can be seen in Eq. (3), the effect of other greenhouse gases is ignored for the sake of simplicity.