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# LEADERSHIP IN CLIMATE CHANGE MITIGATION: CONSEQUENCES AND INCENTIVES

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**Abstract.** Initiatives in favor of unilateral action on climate change are frequently challenged by concerns over free riding. Nevertheless, we observe an increasing number of unilateral efforts at different administrative levels and in different parts of the world. Previous academic literature described various individual mechanisms where emissions abroad may increase or decrease as a reaction to unilateral emission reductions. In this paper, we collect a comprehensive set of both positive and negative reactions and analyze them in stylized models. This allows us to identify the most important characteristics that determine the potential of a leader to boost mitigation efforts abroad. We find that this potential depends on (i) a strong ability to generate knowledge through leadership, (ii) a high degree of credibility in the international community, and (iii) a similar economic structure to the most important emitters. While most effects are difficult to quantify, this comprehensive assessment suggests that leakage effects resulting from unilateral mitigation may well be outweighed by positive reactions.

**Keywords.** Game theory; Leadership; Unilateral climate policy

## 1. Introduction

Despite a continued effort spanning more than two decades, negotiations under the United Nations Framework Convention on Climate Change (UNFCCC) have not produced a sustained decrease in global greenhouse gas emissions. Several local, national, and regional initiatives have, however, emerged independently of internationally coordinated mitigation efforts that pursue unilateral abatement. The emission permits trading schemes of the European Union and California are prominent examples, and the number of such initiatives has been rising steadily (Kossoy *et al.*, 2015). This may come as a surprise, as the standard simultaneous move game of public good provision predicts that ambitious unilateral provision of a global public good never benefits the providing player. Instead, due to the strong free-riding incentives in public good provision, the contributions (abatement in our case) from all other players decrease in response to any unilateral action beyond the purely selfish level. This reduces the effectiveness of the unilateral abatement and generates losses for the leader (Hoel, 1991; Cornes and Sandler, 1996).

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Focusing solely on the *homo economicus*'s urge to free-ride, however, ignores arguably important motivations for environmental policy such as "moralist" (Frey, 1999; Brekke *et al.*, 2003) or "Kantian" (Roemer, 2015) convictions. Irrespective of the motives for unilateral action, however, the possible reaction of followers to unilateral environmental policy extend beyond free-riding. Recent research on climate policy leadership has revealed various channels of interaction with diverse consequences from unilateral emission reductions. Depending on the channel under consideration, countries may raise or lower their emissions in reaction to the leading country's additional abatement. It is *a priori* not clear, whether the aggregate effect of all reaction channels is positive or negative in terms of abatement. Instead of triggering the often presumed free-riding behavior, leadership in ambitious abatement could increase abatement in other countries. A comprehensive assessment of all channels of reaction is thus necessary to understand the net consequence of climate policy leadership.

Our analysis studies "leadership by example" in unilateral emissions abatement. We analyze major channels through which unilateral abatement of a climate policy leader affects other countries. Leading by example or "directional leadership" is only one of four types of leadership identified by Parker and Karlsson (2014). We do not study the other types, structural, idea-based, and instrumental leadership, since their mechanisms differ from the public good setup studied in economics.

We define a common modeling framework to derive functions for the resulting reaction in emissions. We identify nine different channels (Sections 3.1–3.9) and derive comparable expressions for them, specifically the slopes of the reaction functions. For each effect, the slope measures by how many units countries change their emissions when the leading country decreases its emissions by one unit.

Three channels describe a rise in emissions in response to climate leadership, also known as carbon leakage.

- The free-riding effect (Hoel, 1991): Countries increase their emissions because more of the public good is provided. This decreases the demand for the individual production of the public good in all the other countries.
- The energy market effect (Bohm, 1993): The leader decreases the demand for emission-intensive energy carriers, which decreases their global price. This leads to an increased demand in other countries and hence higher emissions.
- The trade effect (Siebert, 1979): Emission-intensive production relocates from the leading country to countries with less stringent policies and hence emissions increase abroad.

The negative carbon leakage effects are counterbalanced by six positive reactions, through which countries decrease their emissions in response to unilateral abatement.

- First, the leading country will develop new technologies and production techniques to decrease its emissions in the face of ambitious abatement targets. Through technological spill-overs to other countries, global emissions decrease even without additional emission policies by other countries (Lovely and Popp, 2011).
- Second, the following country can learn from the leader whether a particular policy implementation works well (Volden *et al.*, 2008).
- Third, a leading country decreases abatement cost uncertainty by performing emission reductions. This will encourage risk-averse countries to increase their emissions reduction targets after learning about the costs of the leader (Elofsson, 2007).
- Fourth, a leading country may signal to other countries that it is implementing the cooperative effort, inducing other countries to adopt an analogous effort (Hermalin, 1998).
- Fifth, countries may have an incentive to reciprocate, that is, respond in kind, to the ambitious actions of a leader (Bolton and Ockenfels, 2000).
- Finally, followers may emulate the leader by imitating his action with the intention of acting "appropriately" (Towns, 2012).

A country will actively engage in leadership only if it finds this to be worthwhile given the costs and benefits. Conditions are thus favorable for leadership if a country values climate change mitigation highly and if it has low costs of abating. In addition, the characteristics of the leading country determine how responsive other countries will be, in positive and negative ways, to the leadership. If other countries are likely to react to the leader's action by increasing their own abatement efforts, leadership becomes more attractive.

We propose to group the relevant country characteristics into ability, credibility, and similarity. A country with a good ability in the design of policy or developing low carbon technology will trigger diffusion processes, which will make abatement more attractive abroad. Countries with strong credibility in the international community will be more successful in establishing climate policy as a new a norm and of signaling its value. A country that is similar in structure to high-emitting economies has the potential to generate relevant information on policy design and policy cost. Behavioral reactions of reciprocity and policy emulation are also more likely to occur in similar countries.

The size of a country is an ambivalent characteristic when it comes to effectiveness as a leader. Large countries have more cheap mitigation options in absolute terms. They will thus find it cheaper to finance large absolute abatement. Smaller countries, however, can serve as a source of information on the effect of stringent climate policy, even if the absolute amount of abatement is small.

By spelling out the mechanisms behind each effect, our analysis can indicate rationales for the observed ambitious abatement of current climate policy leaders and their future abatement policies, and help identify possible future leaders in the abatement of greenhouse gases. We make two contributions to the literature. First, we compile and model a wide range of leadership effects and derive follower reaction functions in a common modeling framework. Second, we determine which country characteristics are likely to trigger a positive reaction to leadership from other countries. Our systematic and comprehensive assessment of leadership mechanisms could serve as a starting point for empirical estimates on the aggregate effect of leadership. This could help shift the focus from possible adverse effects to a more balanced appreciation of both threats and opportunities.

In Section 2, we detail the game theoretic framework of climate policy leadership. In Section 3, we model each of the leadership effects described in the literature and derive a follower reaction function. In Section 4, we use the results from the previous section in order to identify the characteristics that are most important to make the leader effective. Section 5 concludes.

## 2. The Model Framework

We model a global economy, where one country considers unilateral abatement. This "leader" country has an expectation of the reaction from the rest of the world, and for simplicity, we assume that the leader has perfect information about the followers' reactions. This setting is known as a Stackelberg game in the literature on industrial organization. In the Stackelberg equilibrium, the leader chooses its strategy in full knowledge while the followers take this strategy as given. This is either because the Stackelberg leader has an informational advantage, or because the Stackelberg leader moves first and is able to commit itself to the chosen strategy (Friedman, 1968). This setting allows us to discuss the incentives of a country, which decides to undertake unilateral abatement in a first move considering the prospective response it will elicit.

We choose a game-theoretic model in which sequential decisions are taken in two stages. To keep the analysis tractable, we disaggregate the world into a leading country $A$, and the rest of the world into one follower country $B$. In the first stage country $A$, the Stackelberg leader, chooses its abatement level $q_A$. In the second stage, country $B$ chooses its abatement level $q_B$.

We solve the game using backward induction. In the second stage, the follower country $B$ knows the state of the world that results from leader abatement $q_A$. The follower chooses abatement

$q_B$ by optimizing some payoff function $\Pi_B$, which depends on $q_A$. The reaction function of the follower is

$$q_B = q_B(q_A) \tag{1}$$

This defines how the follower changes its abatement depending on the leader's abatement. $q_B(q_A)$ aggregates each of the nine effects that leadership of country $A$ entails, which we describe in detail below.

In the first stage of the game, the leading country bases its decision to abate on a payoff function, which is typically used to study public good problems (equivalent formulations in Bergstrom *et al.*, 1986; Brandt, 2004; Rivas and Sutter, 2011):

$$\Pi_A = \Pi_A(q_A, Q) \tag{2}$$

where $Q = q_A + q_B$ is total abatement and represents a pure public good. The payoff depends on leader abatement $q_A$ in a two-fold way. The first argument represents abatement costs: when keeping total abatement $Q$ fixed, the payoff function depends negatively on individual abatement, $\frac{\partial \Pi_A}{\partial q_A} < 0$, since individual abatement incurs costs. The payoff depends positively on total abatement $\frac{\partial \Pi_A}{\partial Q} > 0$, since the level of the public good determines environmental quality, and therefore the benefits of abatement.

Country $A$ can choose its own abatement level $q_A$ directly. As a Stackelberg-leader, country $A$ maximizes its payoff anticipating the reaction of the follower countries, $q_B(q_A)$. The maximization procedure of the leader hence leads to the following first-order conditions:

$$\begin{aligned} &\max_{q_A} \Pi_A\left(q_A, q_A + q_B(q_A)\right) \\ &\Rightarrow 0 = \underbrace{\frac{\partial \Pi_A}{\partial q_A}}_{<0} + \underbrace{\frac{\partial \Pi_A}{\partial Q}}_{>0} \cdot \left(1 + \tfrac{\partial q_B(q_A)}{\partial q_A}\right) \end{aligned} \tag{3}$$

The leader will abate until marginal costs of individual abatement, $-\frac{\partial \Pi_A}{\partial q_A}$, are equal to marginal benefits of total abatement, $\frac{\partial \Pi_A}{\partial Q}$, times the increase in total abatement with each additional unit of the leaders abatement, $(1 + \frac{\partial q_B(q_A)}{\partial q_A})$.

Equation (3) gives us an initial idea of what determines a country's incentives to exert leadership. The leader's preference regarding valuation of climate damages is captured by $\frac{\partial \Pi_A}{\partial Q}$. The higher a country values the avoidance climate damages, the greater will be its incentive to increase its ambition in leadership, if it expects positive abatement resulting from its action. With the same logic, the incentive to lead is high when marginal abatement costs $\frac{\partial \Pi_A}{\partial q_A}$ are low as each unit abated leads to little total costs.

The final factor in Equation (3) reflects the anticipation of the follower's reaction. The incentive to abate for the leader is strengthened or diminished depending on the sign of $\frac{\partial q_B(q_A)}{\partial q_A}$, that is, whether the followers react positively to the leader's policy or free-ride on the effort. Whether the slope of the reaction function $q_B(q_A)$ is positive or negative depends in turn on the net effect of the combined channels.

For the sake of tractability, we assume that first order effects dominate the reaction function, specifically, we make two simplifying assumptions. First, while in general there will be interactions between the nine channels that make up the net reaction, we abstract from any interactions in this study. Second, we focus on a linear approximation of the aggregate follower's reaction by considering the first terms of a Taylor-approximation around $q_A = 0$.[1]

$$q_B(q_A) \approx q_B(q_A)\big|_{q_A=0} + \sum_{j=1}^{9} \left.\frac{\partial q_B^j(q_A)}{\partial q_A}\right|_{q_A=0} \cdot q_A \tag{4}$$

$$= q_B^0 + \sum_{j=1}^{9} r_j \cdot q_A \tag{5}$$

The error of this approximation will be small as long as the abatement of the leader is small relative to the emissions of the rest of the world. We refer to $q_B(0)$ as $q_B^0$ and denote the slope of the nine channels of the reaction function as $r_j$. That is, $r_j$ specifies by how many units the follower increases (respectively, decreases) abatement with each unit of abatement $q_A$ of channel $j$.

In the context of Equation (3), large, positive $\sum_j r_j$, that is, an anticipation of a strong in-kind response by the followers, implies a strong incentive to abate for the leader. At the other extreme, the leader has no incentive for unilateral abatement if it anticipates that for each unit of reduced emissions is offset or even overcompensated for by an increase in the follower's emissions, that is, $\sum_j r_j \leq -1$.

In order to get a more precise understanding of the determinants of $\sum_j r_j$, we model the different effects in Section 3. In Section 4, we will identify the most important patterns in the leadership determinants identified in Sections 2 and 3.

## 3. The Reaction Functions

As pointed out in Section 2, we consider leadership in a sequential game with two steps. In this section, we analyze the second step: the reaction of the follower to abatement efforts by the leader.

Unilateral climate mitigation will trigger positive and negative effects in other countries. The negative effects can be grouped into a strategic decision of the government to free ride (Section 3.1) and two market-based effects working through prices in energy market leakage (Section 3.2) and trade leakage (Section 3.3).

One group of positive effects is information transmission. In technology diffusion (Section 3.4), policy learning (Section 3.5), cost uncertainty (Section 3.6), and signaling (Section 3.7), the followers learn something from the leader. In policy learning, the follower learns how a law can be formulated so that it achieves its objective, while in cost uncertainty, the follower can use the leader's information to reduce the uncertainty on how expensive a given policy is. In signaling, the leader seeks a way to credibly reveal its knowledge to the follower to overcome an information asymmetry.

The second group of positive effects are behavioral effects. Reciprocity (3.8) describes a situation, where a follower understands the leader's abatement as an offer of cooperation and responds in kind with the intention to be fair. Policy emulation (Section 3.9) describes a situation, where the follower copies the abatement of the leader because it is considered appropriate and because it is perceived as the new norm.

Throughout the paper, whenever there is no explicit sign restriction on a parameter, it will be positive, that is, in the interval $[0, \infty)$.

### 3.1 *Free Riding*

Free riding is well-known as a strategic reaction in public good provision. In the context of the "abatement game" (cf. Barrett, 1994) this translates to contributing emissions reductions to provide stable climate conditions (or at least limit the anthropogenic impact on the earth's climate). Since there is a decreasing marginal utility from public good provision, countries react to an increase in public good contributions by other governments by reducing their own contribution, thus free riding on the others' abatement efforts. For the case of climate change mitigation, this effect is described in Hoel (1991).

We specify the payoff function of the follower as

$$\Pi(q_B, Q) = a_B Q - \frac{b_B}{2} Q^2 - \frac{c_B}{2} q_B^2 \tag{6}$$

$$= a_B(q_A + q_B) - \frac{b_B}{2}(q_A + q_B)^2 - \frac{c_B}{2}q_B^2 \tag{7}$$

Country B maximizes its individual payoff by setting $\frac{\partial \Pi(q_B, Q)}{\partial q_B} = 0$, so that

$$q_B = \frac{a_B - b_B q_A}{b_B + c_B} \tag{8}$$

This is the reaction function faced by the Stackelberg leader. The parameter $r$ in Equation (4) thus corresponds to

$$r_1 = \frac{-b_B}{b_B + c_B} \tag{9}$$

which is clearly less than zero.

For the effectiveness of leadership, it is the level of abatement that matters, not the properties of the leader. The properties of the follower also influence the effectiveness:

- Free riding increases in $b_B$, the slope of marginal benefits of abatement of the follower. If the benefit of environmental quality is high, there is a strong reaction of the follower to emission reductions of the leader.
- A high abatement cost parameter increases free riding, since the gains of country $B$, from cutting back its own contribution, would be high.

### 3.2 *Energy Market Leakage*

The mechanism of energy market leakage works through the price of fossil resources on international markets. When climate policy takes effect in one country, it reduces its utilization of fossil fuels and hence drives down the global aggregate demand for fossil fuels and along with demand, its price. In turn, this raises demand for fossil fuels in countries without regulation, which will then produce additional emissions (cf. Bohm, 1993). Sinn (2008) takes this argument to the extreme, when assuming a very elastic reaction of the supply side.

To illustrate leakage through energy–market interaction, we use the model of Gerlagh and Kuik (2014). Let $E_i$ be the carbon energy consumption of country $i \in \{A, B\}$ and $\theta = \frac{E_A}{E_A + E_B}$ be the share of country $A$ in total emissions. Countries buy the carbon energy in a competitive international market at price $p_E$. We can write the price elasticity of energy supply as $\psi = \frac{d(E_A + E_B)}{dp_E}\frac{p_E}{E_A + E_B} = \frac{1}{\hat{p}_E}(\theta \hat{E}_A + (1 - \theta)\hat{E}_B)$, where a hat denotes the relative change in a variable, $\hat{p}_E = \frac{dp_E}{p_E}$. We can thus write

$$\psi \hat{p}_E = \theta \hat{E}_A + (1 - \theta)\hat{E}_B \tag{10}$$

Output in the energy-intensive sector is $Y_i$ and it uses carbon energy $E_i$ as one of several inputs. The price $p_i$ for the energy-intensive good is country specific. Carbon energy demand depends on output in the energy-intensive sector and on the relative price of energy to the energy-intensive good. Country $A$ applies carbon taxes to the carbon energy, so that its gross price for energy is $p_E \tau$. Assuming that the carbon-intensive good is produced with a constant elasticity of substitution (CES) production function with elasticity of substitution $\rho$, demand for energy is given by

$$\hat{E}_A = \hat{Y}_A + \rho(\hat{p}_A - \hat{p}_E - \hat{\tau}) \tag{11}$$

$$\hat{E}_B = \hat{Y}_B + \rho(\hat{p}_B - \hat{p}_E) \tag{12}$$

This system of supply (Equation (10)) and demand (Equations (11) and (12)) allows us to understand leakage. When country $A$ increases tax $\tau$ with the objective of changing energy use $E_A$, it also affects the world market price for carbon energy $p_E$ and thus carbon energy consumption in country $B$, $E_B$. As a first step, we determine the endogenous variables $Y_i$ and $p_i$. The price elasticity of demand for the energy-intensive good is $\varepsilon$, so that demand can be written as

$$\hat{Y}_A = -\varepsilon \hat{p}_A \tag{13}$$

$$\hat{Y}_B = -\varepsilon \hat{p}_B \tag{14}$$

Let the share of carbon energy in value added be $\alpha$ and assume that all other input prices remain constant. Then the price of the energy-intensive good only depends on the (gross) carbon energy price,

$$\hat{p}_A = \alpha(\hat{p}_E + \hat{\tau}) \tag{15}$$

$$\hat{p}_B = \alpha \hat{p}_E \tag{16}$$

We can use these seven equations in the seven variables $\hat{Y}_A$, $\hat{Y}_B$, $\hat{p}_E$, $\hat{p}_A$, $\hat{p}_B$, $\hat{E}_A$, $\hat{E}_B$ to write carbon energy consumption in country $B$ as a function of consumption in country $A$,

$$\hat{E}_B = -\frac{\theta(\alpha\varepsilon + \rho(1-\alpha))}{\psi + (1-\theta)(\alpha\varepsilon + \rho(1-\alpha))}\hat{E}_A \tag{17}$$

Defining abatement as $q_i = dE_i$, we have $q_B = E_B \hat{E}_B = \frac{1-\theta}{\theta} E_A \hat{E}_B = \frac{1-\theta}{\theta} \frac{q_A}{\hat{E}_A} \hat{E}_B$. Inserting (17) we obtain

$$q_B = -\frac{(1-\theta)(\alpha\varepsilon + \rho(1-\alpha))}{\psi + (1-\theta)(\alpha\varepsilon + \rho(1-\alpha))} q_A \tag{18}$$

The parameter $r$ in Equation (4) thus corresponds to

$$r_2 = -\frac{(1-\theta)(\alpha\varepsilon + \rho(1-\alpha))}{\psi + (1-\theta)(\alpha\varepsilon + \rho(1-\alpha))} \tag{19}$$

which is clearly less than zero.

Equation (18) allows us to decompose the effect of abatement in region $A$ on abatement in region $B$:

- $\alpha\varepsilon$ reflects that a higher carbon energy price reduces output. $\rho(1-\alpha)$ reflects that the economy substitutes away from carbon energy as an input. Leakage increases in both of these elasticities.
- $\theta$ and $1-\theta$ are the shares of the regions in the world. They reflect that the ability of a country to affect the world equilibrium depends on its size. Large countries cause a smaller leakage effect, since the remainder of the world, which can increase emissions, is smaller.
- $\psi$ is the carbon energy price elasticity. It reflects that prices decrease when country $A$ engages in abatement. This provides the incentive for country $B$ to increase carbon energy consumption as a reaction to a decrease in country $A$.

### 3.3 *Trade Leakage*

Trade leakage follows directly from international trade theory, where the international division of labor is determined by relative competitive advantages of countries. When climate policy unilaterally imposes a price on emissions in one country, the competitive advantage to produce emission-intensive goods shifts to unregulated countries (Siebert, 1979; Felder and Rutherford, 1993; Copeland and Taylor, 2004), which leads to an output-related increase in emissions.

In order to isolate the specialization effect, we adopt the model of Elliott *et al.* (2010) in which labor decisions alone determine output and emissions. The economy consists of two countries $i = \{A, B\}$, each of which produce a dirty good $D$ and a clean good $C$:

$$C_i = \theta_i L_i^C \tag{20}$$

$$D_i = \gamma_i \left(L_i^D\right)^{\beta_i} (F_i)^{1-\beta_i}, \qquad 0 < \beta_i < 1 \tag{21}$$

The clean good is produced using labor $L$ as the sole input factor. The dirty good uses labor and fossil energy $F$ whose demand and supply are inelastic. Labor is perfectly mobile between sectors but immobile between countries:

$$L_i^D + L_i^C = L_i, i = \{A, B\} \tag{22}$$

Emissions are proportional to production in the dirty sector:

$$E_i = e_i D_i, i = \{A, B\} \tag{23}$$

Representative households consume each good:

$$u_i = (\widetilde{D}_i)^{\omega}(\widetilde{C}_i)^{1-\omega}, \qquad i = \{A, B\}, 0 < \omega < 1 \tag{24}$$

Countries are interlinked via trade on the commodity good level:

$$\widetilde{D}_A + \widetilde{D}_B = D_A + D_B \tag{25}$$

$$\widetilde{C}_A + \widetilde{C}_B = C_A + C_B \tag{26}$$

Country $A$ introduces a limit on its emissions: $\bar{E} = e_A D_A$. We solve for the competitive equilibrium by maximizing the Negishi-weighted social welfare function:

$$\max\ w_A u_A + w_B u_B \tag{27}$$

$$\text{s.t. } \bar{E} = e_A D_A, \text{(20)–(26)} \tag{28}$$

An implicit function for the reaction function can be derived from the first-order conditions,[2] while an explicit expression for $E^B(\bar{E})$ cannot be derived. The first-order conditions, however, allow us to show that emissions in country $B$ increase with the stringency of the emissions target in country $A$:

$$\frac{dE_B}{d\bar{E}} = -\frac{e_B}{e_A} \cdot \frac{1 + e_A \frac{\omega}{1-\omega} \frac{\theta_A}{\theta_B} \frac{L_A^D}{\beta_A \bar{E}} \frac{\partial D_B}{\partial L_B^D}}{1 + \frac{\omega}{1-\omega} + \frac{1-\beta_B}{\beta_B} \frac{D_A + D_B}{D_B}} < 0 \tag{29}$$

This results in positive leakage. The linear approximation of the reaction function in Equation (4) can be derived by solving the market equilibrium in the absence of regulation by the leader[3]:

$$q_B(q_A) = E_B^{BAU} - E_B \approx \frac{\partial E_B}{\partial \bar{E}}|_{E_A=E_A^{BAU}} \cdot q_A = -\frac{e_B}{e_A} \cdot \frac{1+\frac{\omega}{1-\omega}}{1+\frac{\omega}{1-\omega}+\frac{1-\beta_B}{\beta_B}\frac{D_A+D_B}{D_B}} q_A \tag{30}$$

A larger slope determined in Equation (30) results in larger trade leakage. The parameter $r$ in Equation (4) thus corresponds to

$$r_3 = -\frac{e_B}{e_A} \cdot \frac{1+\frac{\omega}{1-\omega}}{1+\frac{\omega}{1-\omega}+\frac{1-\beta_B}{\beta_B}\frac{D_A+D_B}{D_B}} \tag{31}$$

The properties of the leader and follower shape the reaction in the following ways:

- A higher emission intensity of the follower, $e_B$, compared to the leader, $e_A$, increases leakage. For each unit of emissions that the leader abates due to less labor in dirty production, a certain share of production shifts to the follower countries. If their production is emission-intensive, the leaders emission reduction efforts are less effective.
- A larger share of dirty production $\frac{D_A+D_B}{D_B}$ in the leading country decreases leakage. If the follower countries have a lower capacity of dirty production, they are less able to fulfill the new demand for the dirty good through increasing production and less of the dirty good is produced overall.
- If the production in the dirty sector of country $B$ increases little with increasing labor, that is, low $\beta_B$, then less leakage results. In the extreme case, where the follower countries cannot produce more of the emission-intensive good ($\beta_B = 0$), there would be no leakage due to trade.

### 3.4 *Technology Diffusion*

There are two stages of leadership in climate mitigation through technology diffusion. In the first step, domestic climate policy generates technological progress, which saves on domestic carbon dioxide emissions. In the second step, this technology spills over to foreign countries, where mitigation becomes cheaper.

Jaffe *et al.* (2003) and Gillingham *et al.* (2008) provide reviews for the first step, technological change induced for environmental objectives. The empirical importance of the second step, technology diffusion, has been shown in Eaton and Kortum (1999) and Keller (2004), among others. Dechezleprêtre *et al.* (2011) and Steinbacher and Pahle (2016) describe how it applies to environmental technology. That environmental policy can cause first domestic and then foreign technological improvement has been shown theoretically in Di Maria and Van der Werf (2008). Empirically, Popp *et al.* (2010) use U.S. patent citations from outside the United States to show the influence of policy in one country on the technology in another. Going one step further Lovely and Popp (2011) show the positive effect of policy in one country on policy in other countries, through the channel of easier access to environmentally friendly technology. Bosetti and De Cian (2013) find that this effect is stronger than free riding and energy market leakage (after an initial phase where leakage increases slightly).

A model of induced technological change and international spillover needs technology to be factor-specific and endogenous and requires separate geographical jurisdictions. We thus develop a second variant of the model of Gerlagh and Kuik (2014). It contains all these features and can still be solved analytically.

Our model assumes that there are two countries $A$ and $B$. They each produce an energy-intensive good $Y_i$ at price $p_i$. The energy-intensive sector uses carbon emissions $E_i$ as one of several inputs and pays carbon taxes $\tau_i$ for them. $\tau_i$ is thus the input price paid paid by the sector for the input $E_i$. Abatement $q_i$ is defined as the reduction in these carbon emissions.

The price elasticity of demand for the energy intensive good is $\varepsilon$, so that demand can be written as

$$Y_i = p_i^{-\varepsilon_i} \tag{32}$$

Let the input share of carbon emissions be $\alpha_i$ and assume (for tractability) that all other input prices remain constant. Then the price of the energy-intensive good only depends on the carbon tax,

$$p_i = \tau_i^{\alpha_i} \tag{33}$$

Emission reductions in country $A$ are achieved by increasing carbon taxes $\tau_A$, while country $B$ leaves taxes $\tau_B$ unchanged, so that any change in emissions of country $B$ works only through the availability of better technology.

We now drop the country index for simplicity and write the production of the energy intensive good as

$$Y = \left( \sum_k \zeta_k (X_k)^{\frac{\rho-1}{\rho}} \right)^{\frac{\rho}{\rho-1}} \tag{34}$$

$k$ is the index for production factors $X_k$, one of which is carbon emissions $E$. $\zeta$ is the technology vector. $\rho$ is the elasticity of substitution.

Carbon policy induces a new technology vector $A$. For this technology, the elasticity of substitution is reduced to $\mu = (1-\gamma)\rho$. $\gamma$ denotes the share of substitution possibilities due to technological change. For a detailed explanation on this way of modeling-induced technology in a static model, see section 3.1 in Gerlagh and Kuik (2014). Production with the induced technology vector is

$$Y = \left( \sum_k (A_k X_k)^{\frac{\mu-1}{\mu}} \right)^{\frac{\mu}{\mu-1}} \tag{35}$$

The first-order conditions for the two cases are

$$\frac{p_k}{p} = \zeta_k \left( \frac{X_k}{Y} \right)^{-\frac{1}{\rho}} \tag{36}$$

$$\frac{p_k}{p} = A_k^{\frac{\mu-1}{\mu}} \left( \frac{X_k}{Y} \right)^{-\frac{1}{\mu}} \tag{37}$$

$p_k$ is the price of input factor $k$ in the production of the energy-intensive good and $p$ is, as above, the price for the energy-intensive good itself. The two equations have to be consistent so that

$$A_k = \zeta_k \left( \frac{X_k}{Y} \right)^{\frac{\gamma}{\mu-1}} \tag{38}$$

Demand for input factor $X_k$ can be obtained from Equation (37):

$$X_k = A_k^{\mu-1} Y \left( \frac{p_k}{p} \right)^{-\mu} \tag{39}$$

Again, we follow Gerlagh and Kuik (2014) in modeling international technology spillover. In our model, there is full technology spill-over, resulting in a global technology $A$. This is given as a weighted average of the technology inductions in the two countries,

$$A = \left(\zeta_A \left(\frac{E_A}{Y_A}\right)^{\frac{\gamma}{\mu-1}}\right)^{\theta} \left(\zeta_B \left(\frac{E_B}{Y_B}\right)^{\frac{\gamma}{\mu-1}}\right)^{(1-\theta)} \tag{40}$$

where $\theta = \frac{E_A}{E_A+E_B}$ is the share of country $A$ in total emissions.

As we show in Appendix A.1, emissions of the follower can be written as a function of the leader's emissions as

$$\hat{E}_B = \frac{\theta m_A}{\theta m_A + n_A} \hat{E}_A \tag{41}$$

where $m_i = -(1-\alpha_i)\rho\gamma$, $n_i = (1-\alpha_i)(-\mu) - \alpha_i \varepsilon_i$. As before a hat denotes the relative change in a variable, $\hat{E}_B = \frac{dE_B}{E_B}$.

Using $q_B = \frac{1-\theta}{\theta} \frac{q_A}{\hat{E}_A} \hat{E}_B$ we obtain

$$q_B = \frac{(1-\theta) m_A}{\theta m_A + n_A} q_A \tag{42}$$

For a detailed discussion of this reaction function, see Appendix A.1. The parameter $r$ in Equation (4) thus corresponds to

$$r_4 = \frac{(1-\theta) m_A}{\theta m_A + n_A} \tag{43}$$

which is clearly greater than zero.

Two properties of the leader determine its effectiveness. The first is the country size $\theta$. For one unit of abatement in the domestic country, the abatement achieved abroad depends negatively on the country size, since the rest of the world, which could benefit from the technology, is smaller. The second property, summarizing the various elasticities and factor shares, could be labeled the "elasticity of technology development with respect to changes in carbon taxation." Both of these are properties of the leader.

### 3.5 *Policy Learning*

Policy learning occurs when one jurisdiction observes policies and their success in other jurisdictions. This learning process can lead to a reaction ranging from direct copying to abstract inspiration and can occur between the same or different levels of jurisdictions (Dolowitz and Marsh, 2000). In any case, the following jurisdiction benefits from the leader since it can reduce the uncertainty on how the policy should be designed.

The theoretical literature assumes that policy outcomes are uncertain and thus require experimentation (Aghion *et al.*, 1991; Callander, 2011). Learning from neighbors eventually leads to policy convergence (Bala and Goyal, 1998), but also causes a free-rider problem in experimentation (Bolton and Harris, 1999). The empirical literature finds evidence of learning from neighbors. Volden (2006) works at the level of U.S. states and observes that the probability of a policy being copied depends on its success. U.S. cities learn from early adopters and it emerges that the big cities are the innovators and the smaller ones follow (Shipan and Volden, 2008). An illustrative example for this kind of process is given by Ostrom (2012): "Los Angeles took decades to implement pollution controls, but other cities, like Beijing, converted rapidly when they saw the benefits."

We illustrate the mechanism with a simplified version of the model in Volden *et al.* (2008). We assume that there are two countries, $A$ and $B$, which have mitigation policies in place, for which costs are sunk. A policy is given as $p_i, i \in \{A, B\}$. Cost of a policy, $c_i$, are certain, but the abatement level, $q_i$, may be uncertain. In this section, cost and abatement are defined relative to the country's size. Expected payoffs are $E[\Pi_i(p_A, p_B)] = -c_i(p_i) + aE[q_A(p_A) + q_B(p_B)])$ with $a > 0$. The status quo is policy $p^0$ with $c_i(p^0) = q_i(p^0) = 0$. A new policy $p^1$ is proposed with cost $c_i(p^1) = c_i$. With probability $\xi$, it is a success and causes further abatement of $\bar{q}_i$, with probability $1 - \xi$ it fails and causes abatement of $\underline{q}_i$ with $0 \leq \underline{q}_i < \bar{q}_i$.

We assume that the probability of success in the two countries is perfectly correlated and that $a((1 - \xi)\underline{q}_B + \xi\bar{q}_B) < c_B < a\bar{q}_B$. Then country $B$ implements policy $p^1$ if and only if it turns out to be a success in country $A$. The expected follower reaction function of country $B$ is

$$q_B(q_A) = \begin{cases} 0, & \text{if } q_A \in \{0, \underline{q}_A\} \\ \bar{q}_B, & \text{if } q_A = \bar{q}_A \end{cases} \tag{44}$$

The parameter $r_5$ in Equation (4) in this case is a step-wise function, depending on whether abatement in country $A$ reaches the threshold level of $\bar{q}_A$. The reaction of the follower thus depends on the probability of policy success in country $A$, that is, the ability of country $A$ to implement the policy.

The strength of the reaction function is limited by the model to all-or-nothing. The results of Shipan and Volden (2008) show that large cities are more innovative with policy. If the reason for this is that the cost of policy implementation are smaller relative to the benefits for large jurisdictions, then large countries or regions might also be best suited for climate policy innovation. The leadership effect thus depends on the characteristics of the leader.

### 3.6 *Cost Uncertainty*

The empirical evidence cited in Section 3.5 shows that designing a good policy is challenging. Even for a well-designed policy, there can be significant uncertainty over the cost it incurs. This uncertainty is a cause of low individual abatement targets. A risk-averse regulator will decrease the level of abatement if the associated costs are uncertain in order to avoid high costs. By changing the level of uncertainty, a leader can influence the abatement choices of followers; after implementing abatement, the leader and the follower are likely to learn about the level of abatement costs. If these costs are correlated between a leader and a follower country, the leader partially reduces cost-uncertainty for the following countries. The following countries will respond by increasing their abatement efforts, inducing a positive reaction function for the leader.

Harrington *et al.* (2000) find that the *ex ante* cost estimates of environmental regulations frequently differ from the realized *ex post* costs based on empirical data, and often have a bias to being overestimated. Uncertainty is common in estimating the costs of abating greenhouse gas emissions, resulting both from parameter and model uncertainty (Edenhofer *et al.*, 2006; Tavoni and Tol, 2010). Elofsson (2007) shows conceptually that leadership in emission reductions induces a learning effect under cost-correlation. Risk-averse following countries increase their abatement efforts. The reaction function can be positive in expectation. The magnitude of the effect depends on the nature of uncertainty, the learning process, and the risk-aversion of individual countries. Examples of empirical estimates of the potential increase in abatement are sparse in the literature.

Our model builds on Elofsson (2007). We extend the model by assuming that the extent of learning depends on the amount of abatement performed by the leading country. We assume that the payoff to a follower country is given by

$$\Pi_B(q_B, Q) = a_B Q - \frac{c_B}{2} q_B^2 \tag{45}$$

in which the slope of marginal abatement costs $c_B$ is uncertain. To introduce risk aversion, we adopt the mean-standard deviation approach, which was introduced by Markowitz (1952) and Tobin (1958). The follower's valuation under risk-aversion $\tilde{\alpha}$ is given by

$$V_B = E_B[\Pi_B] - \tilde{\alpha} \underbrace{\sqrt{E_B[(\Pi_B - E_B[\Pi_B])^2]}}_{\text{standard deviation of payoff}} \tag{46}$$

The follower will take the expected value with respect to its uncertainty regarding abatement costs $c_B$, denoted by $E_B[\cdot]$. We now assume that the follower observes the abatement costs of the leader and updates its probability distribution of cost-uncertainty if abatement costs are correlated. The first-order condition of the follower for valuation $V_B$ becomes

$$q_B = \frac{a_B}{E_B[c_B|c_A] + \tilde{\alpha}\sigma_B(c_B|c_A)} \tag{47}$$

The expected operator $E_B[c_B|c_A]$ denotes the expected value of $c_B$ depending on learning about costs of the leader, denoted $c_A$. Uncertainty about abatement costs, given by $\sigma_B(c_B|c_A)$, decreases the level of abatement of the follower: risk-aversion leads to less abatement. The leader decides on the level of abatement anticipating that the follower will learn its abatement costs. The leading country expects an abatement level of the follower, $E_A[q_B]$, which represents the reaction function. It can be derived from (47):

$$E_A[q_B] = E_A\left[\frac{a_B}{E_B[c_B|c_A] + \tilde{\alpha}\sigma_B(c_B|c_A)}\right] \tag{48}$$

The expectation operator $E_A[\cdot]$ of the leader represents its uncertainty regarding abatement costs $c_A$, the value of which is not known prior to deciding on the abatement level. The leader therefore changes the expected marginal abatement costs and the level of uncertainty of the follower and hence its abatement choice. The follower's reaction function $E_A[q_B]$ can be further determined by modeling uncertainty and learning explicitly. The direction of influence of leader abatement on the follower's abatement can be assessed directly by determining the sign of the derivative $\frac{\partial}{\partial q_A} E_A[q_B]$. An approximate calculation is easily possible by expanding the reaction function $E_A[q_B]$ around the expected value of the denominator in zeroth order

$$E_A[q_B] \approx \frac{a_B}{E_A[E_B[c_B|c_A]] + \tilde{\alpha} E_A[\sigma_B(c_B|c_A)]} \tag{49}$$

The two terms of the denominator determine how learning influences the expectation of follower abatement for the leader. To gain further insight, we (i) apply the law of total expectation for the first term: the leader does not expect that the follower's slope of abatement costs changes in a particular direction after learning, meaning that $E_A[E_B[c_B|c_A]] = E_B[c_B]$, (ii) make the assumption that the standard deviation of the follower about its costs after learning, $\sigma_B(c_B|c_A)$, does not depend on the actual values that have been learned from the leader—the follower is only more certain about her abatement costs than before, $\frac{\partial}{\partial q_A} E_A[\sigma_B(c_B|c_A)] \leq 0$. This can be understood as the leader generating more information about the abatement cost curve when increasing its abatement, which Appendix A.2 illustrates within a simplified model. The derivative of the reaction function becomes:

$$\frac{\partial}{\partial q_A} E_A[q_B] = -\tilde{\alpha} \frac{a_B}{(E_B[c_B] + \tilde{\alpha}\sigma_B(c_B|c_A))^2} \frac{\partial}{\partial q_A} E_A[\sigma_B(c_B|c_A)] \tag{50}$$

Hence, $\frac{\partial}{\partial q_A} E_A[q_B] \geq 0$ in a zeroth-order approximation, and an increase in abatement by the leader triggers higher expected abatement by the follower because uncertainty about the costs of abatement is reduced.

In summary, the reaction function of the follower is in first-order approximation:

$$q_B(q_A) = q_0 + \left\{ \frac{\partial}{\partial q_A} E_A[q_B] \right\} \cdot q_A \tag{51}$$

The properties of the leader and follower shape the slope

$$r_6 = \frac{\partial}{\partial q_A} E_A[q_B] \tag{52}$$

in the following manner:

- If learning the costs of the leader reduces cost-uncertainty of the follower to a larger extent (a higher magnitude of $\frac{\partial}{\partial q_A} E_A[\sigma_B(c_B|c_A)]$), a follower increases its abatement level also to a larger extent. Hence, if there is higher symmetry in abatement options between a leading and a following country and a higher correlation between cost-uncertainties, a leader country expects a larger increase in abatement in reaction to its abatement. In turn, if the costs of abatement are not correlated between countries, a leader does not induce lower cost-uncertainty for other countries and does not expect any reaction in global abatement from learning its abatement costs.
- The absolute abatement level of the leader only indirectly influences the expected abatement of the follower through reducing uncertainty by providing information. Whether a leading country needs to perform large relative or absolute abatement to generate a given amount of information to the follower depends on the characteristics of both countries.
- A smaller expected slope of marginal costs of the follower $E_B[c_B]$ increases abatement of the follower as costs are lower.
- A larger valuation of the public good of the follower $a_B$ increases the reaction because the following country has a larger unilateral incentive to abate.

Hence, cost uncertainty and learning both contribute to an increase in the expectation of the followers reaction $\sum_j r_j$ in Equation (4).

### 3.7 *Signaling*

As in the previous section, this section explores a setting of incomplete information. Whereas in Section 3.6, however, leader and follower initially face the same uncertainty in abatement costs, this section investigates signaling as a means to overcome distortions due to information asymmetry. In particular, signaling opens the opportunity for the leader to strategically mislead the follower, and hence care must be taken to ensure the signal conveyed is perceived as credible.

The starting point is a situation where the preferred outcome is not achieved due to a lack of information on the part of at least one player (here, we will consider the case where only one player, the prospective leader, knows the true abatement costs). Then, signaling means for the leader to act in a way that communicates the necessary information thus resolving the informational distortion and steering the game toward the preferred outcome.

Asymmetric information is discussed by Konrad and Thum (2014) as one of the main obstacles to successfully negotiating climate policy but their focus is on unilateral commitment without the consideration of signaling. Signaling games for public goods are investigated by Hermalin (1998, 2007).

In the context of international environmental agreements Caparrós *et al.* (2004) and Espinola-Arredondo and Munoz-Garcia (2010) explore signals transmitted by signing an agreement. Similarly, Jakob and Lessmann (2012) discuss a leader's early or delayed action as a signal of high or low costs. In an extension of their earlier work, signaling in Espinola-Arredondo and Munoz-Garcia (2011) entails the announcement of a (nonbinding) commitment level.

We assume that the game structure is either a prisoners' dilemma or a no-conflict game. We also assume that one player knows which of the two cases applies, while the other player does not.

We stay within the setting of a symmetric abatement game with the following payoff function

$$\Pi_i = aQ - cq_i \tag{53}$$

We assume incomplete information about the costs of abatement $c$ which can be either high, $c = c^h$, or low ($c = c^l$). While the follower believes the costs to be low with a probability of $p$ (and conversely, the probability of high costs is $(1 - p)$), the leader knows the true value of $c$. Asymmetric knowledge about the regional costs of implementing climate policy may arise from a large capacity to research the implications of such policy, or could be founded in superior knowledge about regional specifics. Alternatively, when costs include the costs of implementing climate policy, it is plausible that positions of interest groups, implications for political careers etc. represent private information of the political actors of each country.

In this section, we will assume discrete strategies in abatement relative to the size of the country, that is, $q_i \in \{0, 1\}$, which simplifies the analysis from marginal calculus to comparisons within the game's payoff matrix. Then strategy profiles $(q_A, q_B)$ yield the following payoffs: $\Pi_i(q_A = 1, q_B = 1) = 2a - c$, $\Pi_i(0, 1) = a$, $\Pi_i(1, 0) = a - c$, $\Pi_i(0, 0) = 0$.

For this game to be a prisoners' dilemma, we need

$$a < c \tag{54}$$

That is, individual abatement does not pay, and there is an incentive to free-ride on cooperative efforts.

High and low costs of abatement, $c^h$ and $c^l$, respectively, are assumed to fall on either side of $a$ in (54), and thus for high abatement costs $c^h$, we have the well-known dilemma with no easy solution. Even when we assume low costs, the fact that the follower is uncertain about the game structure may impede cooperation. Uncertainty about costs of the leader, will cause no problem, if the follower's expected payoff of abatement is higher than otherwise. From this, it follows that for successful cooperation the follower needs to be sufficiently optimistic that costs are low[4]:

$$p > \frac{c^h - a}{c^h - c^l} \tag{55}$$

The communication of the signal happens in an additional stage of the game prior to the abatement stage. For this signaling stage, we allow the leader to split its abatement into two parts that add up to a regular contribution of 1 unit:

$$q_A = \kappa + (1 - \kappa) = 1. \tag{56}$$

By unilaterally abating $\kappa$ during the signaling stage, the leader can signal its goodwill and commitment to cooperation to the follower. If the follower interprets this unilateral action as a credible signal, it will update its belief about costs of abatement.

Prior to observing A's unilateral abatement effort, the follower's belief system, $\tilde{p}$ (the probability distribution of the possible values for $c$) is the same as the probability given by $p$, $\tilde{p} = p$. The follower, however, will only update its belief if the leader's signal is credible. Put differently, does the leader have an incentive to falsely suggest that its costs are low?

To see this, suppose that costs are high for the leader, $c = c^h$. For the leader, tricking the follower into playing "1" when $c = c^h$ and then defecting itself pays if the payoff is superior to no cooperation, that is, $\Pi_A(\kappa, 1) > \Pi_A(0, 0)$. Hence we have

$$(1 + \kappa)a - \kappa c^h > 0 \tag{57}$$

$$\kappa > \frac{-a}{c^h - a} \tag{58}$$

Thus, the follower will only update its belief system to $\tilde{p} = 1$ if $\kappa$ is sufficiently large. This threshold for $\kappa$ depends on the ratio of the marginal benefit of enticing the follower into acting (the numerator) and the net marginal costs for doing so (the denominator). The larger the gains of tricking the follower and the smaller the costs of doing so, the greater $\kappa$ needs to be to establish credibility.

According to Equation (58), the credible signal rises with $a$, and tends to infinity for $a \to c^h$. $\kappa \leq 1$ is an upper bound to $\kappa$, hence credible signals in terms of $\kappa$ only exist if $c^h > 2a$. Otherwise, the follower is unable to distinguish whether player A is earnest or not.

In this simple model, signaling has no costs. Hence, it is always worthwhile for the leader to send this signal. If signaling bore a cost, for example, because most of the abatement is postponed, the gains of cooperation would need to exceed these costs, and due to these costs, the cooperative equilibrium of the signaling game would be inferior to the equilibrium of the game without information asymmetry. Conversely, if the leader sends no signal, the follower can conclude $c = c^h$.

The signaling game gives rise to the following reaction function:

$$q_B(q_A) = \begin{cases} 1 & \text{if } \kappa \geq a/(c^h - a) \\ 0 & \text{otherwise} \end{cases}$$

Hence, given a credible signal $\kappa$, the follower responds to the anticipated abatement with equal abatement. In this sense,

$$r_7 = 1 \tag{59}$$

in the reaction function Equation (4). Note, however, that this is mostly determined by the assumption of discrete strategies. Still, the simple example holds a number of lessons on when and how the ability to resolve an information asymmetry by establishing a signal may motivate a party to take the lead in climate policy. To begin with, the potential leader needs to find itself in a specific informational setting:

- The other players' lack of information needs to block the better outcome (cf. Equation (55)).
- The leader needs to have superior information which, if communicated credibly, induces others to follow the lead.
- The leader needs to have a signaling action that credibly communicates low costs ($c^h$ need to be large enough).
- Finally, the leader needs to commit itself strong enough to action, that is, to engage in enough up-front mitigation, to entice the other player to follow ($\kappa$).

Lack of information, that is, uncertainty, is certainly common when it comes to taking decisions about climate policy. The uncertainty spans from the climate science to climate change impacts, to the costs of implementing climate policy, and it is a common argument to delay action until better information becomes available.

Arguably, the need for an informational advantage means that leaders are more likely to be countries that are strong in academic and/or industrial research. However, much of the relevant information is publicly available, for example the reports of the IPCC, so it is not easy to make out an informational asymmetry regarding the technical costs of climate policy. When information asymmetry is founded in the policy costs, there is no clear characteristic that would identify a likely leader.

### 3.8 *Reciprocity*

As in other situations which can be described as a public good game, countries would be better off if they would cooperate. The main approach to ensure cooperation has so far been to negotiate a global climate agreement. A second approach is to form climate clubs and apply some form of punishment on nonmembers (Lessmann *et al.*, 2015; Nordhaus, 2015). Reciprocity offers a third option: there is sound evidence that humans react to cooperative behavior by increasing their own level of cooperation (Ostrom *et al.*, 1999; Ostrom, 2010). Buchholz and Sandler (2016) provide a theoretical model of how behavioral effects change the results of leadership in global public good provision.

Moxnes and Van der Heijden (2003) designed an experiment whereby participants could choose a level of pollution in a framing of climate change. They showed that in a situation where one of the participants could move first and thus act as a leader, the level of cooperation was higher. Coats *et al.* (2009) refined the experiment and found that the decisive aspect of leadership is that it functions as a coordination device in a situation where people are willing to cooperate, but only under the condition that others will also cooperate. Rivas and Sutter (2011) further refine the analysis and find that voluntary leadership is more effective than the leadership of a randomly determined leader. That fairness considerations influence decision making by governments has been assumed in papers such as Lange and Vogt (2003) and Johansson-Stenman and Konow (2010).

Reciprocity can be modeled by a “motivation function,” which consists of two components. The first is a standard preference of the player for his payoff. The second is a term that penalizes deviations in payoff between players. Bolton and Ockenfels (2000) develop a theory of reciprocity, which is able to explain results from a wide range of experiments. They give a general description of how preferences with reciprocity should look like, and give a specific example. Let $x$ be the total payoff of all players, $v_i$ be the motivation function of player $i$, and $\sigma_i$ be the share of the total payoff received by player $i$. Then the motivation function proposed on p. 173 of Bolton and Ockenfels (2000) is given by

$$v_i(c\sigma_i, \sigma_i) = y_i x \sigma_i - \frac{z_i}{2}\left(\sigma_i - \frac{1}{2}\right)^2 \tag{60}$$

where $y_i$ and $z_i$ are the parameters indicating the preference of country $i$ for payoff and inequality aversion, respectively.

As a simplification, we define the second component of the preference function not as the relative difference, but as the absolute difference,

$$\bar{v}_i = y_i \Pi(q_i, Q) - \frac{z_i}{2}\left(\Pi(q_i, Q) - \Pi(q_j, Q)\right)^2, \quad i, j \in \{A, B\},\ i \neq j \tag{61}$$

where $\Pi(q_i, Q) = aQ - \frac{c}{2}q_i^2$.

The first order condition of country $B$ yields

$$\frac{d\bar{v}_B}{dq_B} = y_B(a - cq_B) + z_B\frac{c^2}{2}\left(q_A^2 q_B - q_B^3\right) = 0 \tag{62}$$

Let $F(q_A, q_B) = \frac{d\bar{v}_B}{dq_A}$. By the implicit function theorem we have

$$\frac{dq_B}{dq_A} = \frac{z_B c q_A q_B}{y_B - z_B\frac{c}{2}\left(q_A^2 - 3q_B^2\right)} \tag{63}$$

Let $q_B(q_A)$ be the reaction function of country $B$. We have $F(q_A, q_B(q_A)) = 0$ so that $z_B \frac{c^2}{2}(q_A^2 - (q_B(q_A))^2) = \frac{y_B(cq_B(q_A)-a)}{q_B(q_A)}$. Inserting this into (63) yields for the parameter $r$ in Equation (4)

$$r_8 = \frac{dq_B}{dq_A} = \frac{z_B c q_A q_B(q_A)}{\frac{y_B a}{q_B(q_A)c} + z_B c(q_B(q_A))^2} \geq 0 \tag{64}$$

Notice that for $q_A = 0$ the effect of reciprocity is zero. We obtain three results from this equation:

- For positive inequality aversion ($z_B > 0$), the follower's abatement increases in the leader's abatement, since $r$ is strictly positive in this case.
- In the absence of inequality aversion ($z_B = 0$), the follower does not react at all to leadership ($r = 0$). This is in line with intuition on the role of inequality aversion.
- For the hypothetical case that country $B$ does not care for its own payoff ($y_B = 0$), we have $r = 1$ (see Equation (62)). In this case, the follower perfectly matches any abatement of the leader, again confirming intuition on the role of inequality aversion.

### 3.9 *Policy Emulation*

Policy emulation can be defined as the process whereby policies diffuse because of their normative and socially constructed properties rather than their objective characteristics (Gilardi, 2010; Heinze, 2011). This requires that policy makers apply the "logic of appropriateness" rather than the "logic of consequences," that is, they implement and design policies mainly because other countries have established respective norms. A norm could, for instance, be to strive for the "cooperative solution" by taking the effect of climate damages in all countries into account rather than domestic damages alone. In fact, in the current debate surrounding the carbon dioxide regulation proposed by the U.S. Environmental Protection Agency (EPA), this is one of the controversial issues, and there are warnings that solely considering domestic damages would "institutionalize the free-rider effect" (Stavins, 2014). That is, by not taking global damages into account, the United States would create or reinforce the norm of only considering local benefits. The final decision will establish a norm that will diffuse to other countries, though certainly not all.

tNorms need to be established on the international level between countries in order to be important for policy emulation. On the leader's side, research suggests that international standing, group identity, and hierarchy matter for the ability of countries to establish respective norms. Towns (2012), for example, highlights the relationship between setting up a norm and creating a hierarchical social order between states and its relevance for international policy diffusion "from below." Batalha and Reynolds (2012) indicate another mechanism at the level of groups of countries that already share the same principle beliefs and norms, that is, have a more or less similar identity. In such a setting, countries can exert leadership through establishing new norms in line with the group's social identity. Accordingly, the mechanism, which makes followers adhere to a leader's norm is called socialization. Following Torney (2012), successful socialization takes place if actors change their behavior as a result of wanting to be seen as members of society "in good standing." See also, for example, Terhalle and Depledge (2013) on this.

Against this background, we develop a simple model for policy emulation in which we formalize the uncertain adoption of a norm through socialization as a binary random variable $\epsilon$ with values (0,1) in the potential follower $i$'s profit functions. The particular norm we consider is whether the damages of all other countries are taken into account ($\epsilon$=1) or not ($\epsilon$=0) (see EPA case above):

$$\Pi_i = \varepsilon \cdot \left( \sum_{j \neq i} a_j Q \right) + a_i Q - \frac{c}{2} q_i^2$$

The probability that the follower cooperates can be denoted as $p_c$ and is a function of the leader's behavior $q_A$ and his specific pairwise socialization $S_{i,j}$ for a follower (see mentioned above). In order to establish the norm of cooperation, the leader must abate at the cooperative level $q_A = q_A^*$. For sake of simplicity focussing on a single follower, the expected reaction reads:

$$E[q_B] = p_c\left(q_A^*, S_{A,B}\right) \cdot \frac{2a}{c} + \left(1 - p_c\left(q_A^*, S_{A,B}\right)\right) \cdot \frac{a}{c} = \frac{1}{2} \cdot \left(1 + p_c\left(q_A^*, S_{A,B}\right)\right) \cdot q_A^*$$

The parameter $r$ in Equation (4) thus corresponds to

$$r_9 = \frac{1}{2} \cdot \left(1 + p_c\left(q_A^*, S_{A,B}\right)\right) \tag{65}$$

which ranges from 0.5 (noncooperative behavior) to 1 (fully cooperative behavior).

Countries particularly suited to exert leadership based on norms are the one in "good standing" (see mentioned above), and which are already part of a group with common identity. Apparent candidates are thus the G8 and the G20. Van de Graaf and Westphal (2011), for example, highlight the opportunities for the G8 and G20 to act as global steering committees for energy, and thus in a broader sense to exert leadership.

## 4. Leader Characteristics

The follower's responsiveness to the leader's abatement, $\sum_j \frac{\partial q_B^j(q_A)}{\partial q_A} = \sum_j r_j$, is a major determinant of leadership effectiveness. We thus characterize for which countries $\sum_j r_j$ will take high values, based on the results of Section 3. There is no unique way of grouping the country characteristics. We suggest a classification into ability, credibility, and similarity. In addition, the country's size and the follower characteristics are important.

The strength of the leader contributes positively to the follower's responsiveness. A leader with a strong ability to respond to a price on carbon with technology development fosters technology diffusion (Section 3.4). This makes it cheaper for followers to engage in abatement since technological solutions will be available. A leader with a good ability to design policy can effectively enhance policy learning (Section 3.5); when followers have suitable policy solutions at hand they will be more willing to abate. Ability, in the sense of informational advantage, increases the prospect of signaling (Section 3.7) important information to followers. This signaled information could motivate followers to abate.

The follower's responsiveness will also depend on the credibility of the leader. A country in good standing is more likely to establish an international norm of implementing climate policy, which can then affect other countries through policy emulation (Section 3.9). A country able to credibly commit to a certain level of abatement is more likely to signal (Section 3.7) successfully. Credibility is also important for reciprocity (Section 3.8), since only genuine and substantial leadership abatement will motivate other countries to abate cooperatively as well.

Similarity to followers in terms of development and economic structure will also determine leadership responsiveness. This has a behavioral component as followers are more likely to reciprocate (Section 3.8) with countries in a similar situation and are more likely to emulate policy (Section 3.9) implemented in a country with a common identity. It also has an informational component as countries can learn most from the policy design (Section 3.5) and policy cost (Section 3.6) in countries that function in similar ways. Given this, highly developed countries are well suited to engage successfully in leadership since they have the greatest influence on their highly emitting peers.

The effect of the country's size depends on whether we consider leadership in relative terms, reducing emissions by a certain percentage, or leadership in absolute terms, reducing emissions by a given absolute amount. Both approaches have advantages. We opt for leadership in absolute terms since absolute abatement is what matters for mitigating climate change. The absolute amount of abatement is a major determinant of the negative effects of free riding (Section 3.1), energy market leakage (Section 3.2), and trade leakage (Section 3.3) as well as the positive effect of technology diffusion (Section 3.4). However, for a large country, the "rest of the world," affected by these four effects, is smaller. This reduces the rate of leakage or spill-over. Relative abatement drives all other effects, because they work through behavioral or informational channels, which depend on the stringency of the policy. For the effects in Sections 3.5 to 3.9, a given absolute amount of abatement will thus be most effective in a small country.

Finally, the follower characteristics will determine the effectiveness of leadership. Free riding (Section 3.1) will be stronger if the followers have high marginal benefits or high abatement costs. Energy market leakage (Section 3.2) will be stronger if the international carbon energy price elasticity is low. Trade leakage (Section 3.3) will be greater if the followers have a high marginal productivity of labor.

## 5. Conclusion

In this paper, we have proposed a game theoretic framework to analyze leading by example in climate change mitigation and have reviewed the mechanisms which would be triggered by leadership. We find that the different leakage effects are countered by a broad range of effects stimulating a positive reaction of the follower. The positive reactions arise from information transmission and behavioral effects. Empirical estimates of their magnitude are lacking in the context of global climate change mitigation, however. Thus, in the light of our assessment of positive and negative effects, we conclude that the response to unilateral climate change mitigation is not necessarily negative but ambiguous. Notably, this conclusion puts into perspective the widely held view among economists that responses are generally negative. However, whether positive or negative effects dominate remains an open question. Without further empirical investigation into the order of magnitude of the positive effects, we think it impossible to predict precisely whether the net effect of leadership would be positive or negative.

Our analysis, however, allows us to qualitatively determine how the effectiveness of leadership depends on the characteristics of both the leader and the follower. The most important leader characteristics can be summarized as ability, credibility, and similarity to large emitters. The size of a country has an ambiguous effect on the effectiveness of leadership. Some effects depend on the level of mitigation relative to the size of the economy because follower countries can infer or learn information from the stringency of policy. Other effects depend on the absolute level of mitigation because they affect prices (of traded goods) or quantities (of emissions or technological innovations). The leadership effectiveness of a given absolute level of mitigation thus also depends on which degree of stringency it implies for the country.

The unilateral incentives for abatement are an important driver of unilateral climate policy in the absence of internationally coordinated policy. However, they also remain key determinants for national climate policies in the context of the new global climate governance architecture. At the center of the Paris Agreement are the so-called Nationally Determined Contributions (NDCs) through which sovereign countries determine the ambition of their climate change mitigation targets following national interests, subject to a process of regular stock taking and revision. Within the framework of the Paris Agreement, leadership shifts from undertaking unilateral emission reductions to leadership in NDC ambition and NDC implementation. The incentive of others to respond remains the same as identified in this study.

If some countries take the lead, there are no binding or enforceable mechanisms in the Paris Agreement to prevent free riding. But the Agreement intends to discourage free-riding in an effort to avoid negative responses to leadership in climate policy. Article 4.3[5] in particular records the explicit intention of the signatories to submit a "progression" in the NDCs, such that NDCs cannot be weakened in response to any action taken by climate policy leaders. However, countries can still free-ride by submitting a weak

NDC, refusing progress in ambition or hardly going beyond their business as usual. In addition, the treaty does not specify any consequences for the case that a country misses its NDC.

The positive reactions, on the other hand, will arguably be strengthened by the Paris Agreement. For example, technology diffusion, as discussed in Section 3.4 will benefit from the Technology Mechanism of the agreement (Art. 10). Moreover, new mitigation policies will be implemented or existing ones strengthened, and consequently the uptake of new technologies will benefit from prior development by a leader. For example, the National Solar Mission to deploy solar power on a large scale will be a cornerstone policy of India's NDC. The previous, and still ongoing, technological development of solar power technologies in "leading countries" thus makes an immediate difference for climate action in India. In addition, the global stocktakes, occurring at regular intervals, will facilitate "naming" the contributions of other nations, and will foster "shaming" countries into reciprocating any leadership in ambitious NDCs that becomes apparent. Finally, as argued by Rietig (2014), regular international meeting of the parties to the agreement under the UNFCCC umbrella will facilitate round tables and showcasing of best practices and lessons learned (Aldy, 2014), which reduces policy uncertainty and encourages policy learning and emulation. Already ongoing activities in this direction in the G20 context, which stand in close relation to the Paris Agreement, suggest that positive effects might increasingly materialize.

## NOTES

1. In addition, we assume that the cost–benefit structure of the payoff $\Pi_A$ is not affected by leader or follower abatement.
2. The implicit function is: $\frac{\bar{E}}{e_A} + \gamma_B (L_B^D)^{\beta_B} (F_B)^{1-\beta_B} = \frac{\omega}{1-\omega} \frac{\gamma_B \beta_B}{\theta_B} (L_B^D)^{\beta_B - 1} (F_B)^{1-\beta_B} \{\theta_A (L_A - (\frac{\bar{E}}{q_A \gamma_A})^{\frac{1}{\beta_A}} (F_A)^{\frac{\beta_A - 1}{\beta_A}}) + \theta_B (L_B - L_B^D)\}$
3. The optimization in Equation (27) in the absence of the additional constraint $\bar{E} = e_A D_A$ gives the first-order condition $\frac{\theta_A}{\theta_B} = \frac{\beta_A D_A}{\frac{\partial D_B}{\partial L_B^D} L_A^D}$.
4. Equation (55) gives the relative position of $a$ inbetween $c^l$ and $c^h$. The larger the gap between benefits $a$ and high costs $c^h$, the higher the losses incurred by the follower for erroneously assuming that costs are low.
5. "Each Party's successive nationally determined contribution will represent a progression beyond the Party's then current nationally determined contribution and reflect its highest possible ambition, reflecting its common but differentiated responsibilities and respective capabilities, in the light of different national circumstances."

## References

Aghion, P., Bolton, P., Harris, C. and Jullien, B. (1991) Optimal learning by experimentation. *The Review of Economic Studies* 58(4): 621–654.

Aldy, J.E. (2014) The crucial role of policy surveillance in international climate policy. *Climatic Change* 126(3-4): 279–292.

Bala, V. and Goyal, S. (1998) Learning from neighbours. *The Review of Economic Studies* 65(3): 595–621.

Barrett, S. (1994) Self-enforcing international environmental agreements. *Oxford Economic Papers* 46(Supplement 1): 878–894.

Batalha, L. and Reynolds, K.J. (2012) Aspiring to mitigate climate change: superordinate identity in global climate negotiations. *Political Psychology* 33(5): 743–760.

Bergstrom, T., Blume, L. and Varian, H. (1986) On the private provision of public goods. *Journal of Public Economics* 29(1): 25–49.

Bohm, P. (1993) Incomplete international cooperation to reduce $CO_2$ emissions: alternative policies. *Journal of Environmental Economics and Management* 24(3): 258–271.

Bolton, P. and Harris, C. (1999) Strategic experimentation. *Econometrica* 67(2): 349–374.

Bolton, G.E. and Ockenfels, A. (2000) Erc: A theory of equity, reciprocity, and competition. *The American Economic Review*, 90(1): 166–193.

Bosetti, V. and De Cian, E. (2013) A good opening: the key to make the most of unilateral climate action. *Environmental and Resource Economics* 56(2): 255–276.

Brandt, U.S. (2004) Unilateral actions, the case of international environmental problems. *Resource and Energy Economics* 26(4): 373–391.

Brekke, K.A., Kverndokk, S. and Nyborg, K. (2003) An economic model of moral motivation. *Journal of Public Economics* 87(9): 1967–1983.

Buchholz, W. and Sandler, T. (2016) Successful leadership in global public good provision: incorporating behavioural approaches. *Environmental and Resource Economics* 1–17.

Callander, S. (2011) Searching for good policies. *American Political Science Review* 105(04): 643–662.

Caparrós, A., Péreau, J.-C. and Tazdaït, T. (2004) North-south climate change negotiations: a sequential game with asymmetric information. *Public Choice* 121(3-4): 455–480.

Coats, J.C., Gronberg, T.J. and Grosskopf, B. (2009) Simultaneous versus sequential public good provision and the role of refunds: an experimental study. *Journal of Public Economics* 93(1): 326–335.

Copeland, B.R. and Taylor, M.S. (2004) Trade, growth, and the environment. *Journal of Economic Literature* 42(1): 7–71.

Cornes, R. and Sandler, T. (1996) *The Theory of Externalities, Public Goods, and Club Goods*. Cambridge: Cambridge University Press.

Dechezleprêtre, A., Glachant, M., Haščič, I., Johnstone, N. and Ménière, Y. (2011) Invention and transfer of climate change–mitigation technologies: a global analysis. *Review of Environmental Economics and Policy* 5(1): 109–130.

Di Maria, C. and Van der Werf, E. (2008) Carbon leakage revisited: unilateral climate policy with directed technical change. *Environmental and Resource Economics* 39(2): 55–74.

Dolowitz, D.P. and Marsh, D. (2000) Learning from abroad: the role of policy transfer in contemporary policy-making. *Governance* 13(1): 5–23.

Eaton, J. and Kortum, S. (1999) International technology diffusion: theory and measurement. *International Economic Review* 40(3): 537–570.

Edenhofer, O., Lessmann, K., Kemfert, C., Grubb, M. and Köhler, J. (2006) Induced technological change: exploring its implications for the economics of atmospheric stabilization: synthesis report from the innovation modeling comparison project. *The Energy Journal* 27(Special Issue# 1): 57–108.

Elliott, J., Foster, I., Kortum, S., Munson, T., Pérez Cervantes, F. and Weisbach, D. (2010) Trade and carbon taxes. *American Economic Review* 100(2): 465–469.

Elofsson, K. (2007) Cost uncertainty and unilateral abatement. *Environmental and Resource Economics* 36(2): 143–162.

Espinola-Arredondo, A. and Munoz-Garcia, F. (2010) Keeping Negotiations in the Dark: Environmental Agreements Under Incomplete Information. Working Paper, Available at SSRN: https://ssrn.com/abstract=1724960.

Espinola-Arredondo, A. and Munoz-Garcia, F. (2011) Free-riding in international environmental agreements: a signaling approach to non-enforceable treaties. *Journal of Theoretical Politics* 23(1): 111–134.

Felder, S. and Rutherford, T.F. (1993) Unilateral $CO_2$ reductions and carbon leakage: the consequences of international trade in oil and basic materials. *Journal of Environmental Economics and Management* 25(2): 162–176.

Frey, B.S. (1999) Morality and rationality in environmental policy. *Journal of Consumer Policy* 22(4): 395–417.

Friedman, J.W. (1968) Reaction functions and the theory of duopoly. *The Review of Economic Studies* 35(3): 257–272.

Gerlagh, R. and Kuik, O.J. (2014) Spill or leak? Carbon leakage with international technology spillovers: a CGE analysis. *Energy Economics* 45(C): 381–388.

Gilardi, F. (2010) Who learns from what in policy diffusion processes? *American Journal of Political Science* 54(3): 650–666.

Gillingham, K., Newell, R.G. and Pizer, W.A. (2008) Modeling endogenous technological change for climate policy analysis. *Energy Economics* 30(6): 2734–2753.

Harrington, W., Morgenstern, R.D. and Nelson, P. (2000) On the accuracy of regulatory cost estimates. *Journal of Policy Analysis and Management* 19(2): 297–322.

Heinze, T. (2011) Mechanism-based thinking on policy diffusion. A review of current approaches in political science. KFG Working Paper Series, No. 34.

Hermalin, B.E. (1998) Toward an economic theory of leadership: leading by example. *American Economic Review* 88(5): 1188–1206.

Hermalin, B.E. (2007) Leading for the long term. *Journal of Economic Behavior & Organization* 62(1): 1–19.

Hoel, M. (1991) Global environmental problems: the effects of unilateral actions taken by one country. *Journal of Environmental Economics and Management* 20(1): 55–70.

Jaffe, A.B., Newell, R.G. and Stavins, R.N. (2003) Technological change and the environment. In Mäler, K.-G. and Vincent, J.R. (eds.), *Environmental Degradation and Institutional Responses*, *Volume 1 of Handbook of Environmental Economics* (pp. 461–516). Amsterdam: Elsevier.

Jakob, M. and Lessmann, K. (2012) Signaling in international environmental agreements: the case of early and delayed action. *International Environmental Agreements: Politics, Law and Economics*, 12(4): 309-325.

Johansson-Stenman, O. and Konow, J. (2010) Fair air: distributive justice and environmental economics. *Environmental and Resource Economics* 46(2): 147–166.

Keller, W. (2004) International technology diffusion. *Journal of Economic Literature* 42(3): 752–782.

Konrad, K.A. and Thum, M. (2014) Climate policy negotiations with incomplete information. *Economica* 81(322): 244–256.

Kossoy, A., Peszko, G., Oppermann, K., Prytz, N., Klein, N., Blok, K., Lam, L., Wong, L. and Borkent, B. (2015) *State and Trends of Carbon Pricing 2015*. Washington, D.C.: World Bank Group.

Lange, A. and Vogt, C. (2003) Cooperation in international environmental negotiations due to a preference for equity. *Journal of Public Economics* 87(9-10): 2049–2067.

Lessmann, K., Kornek, U., Bosetti, V., Dellink, R., Emmerling, J., Eyckmans, J., Nagashima, M., Weikard, H.-P. and Yang, Z. (2015) The stability and effectiveness of climate coalitions. *Environmental and Resource Economics* 62(4): 811–836.

Lovely, M. and Popp, D. (2011) Trade, technology, and the environment: does access to technology promote environmental regulation? *Journal of Environmental Economics and Management* 61(1): 16–35.

Markowitz, H. (1952) Portfolio selection. *The Journal of Finance* 7(1): 77–91.

Moxnes, E. and Van der Heijden, E. (2003) The effect of leadership in a public bad experiment. *Journal of Conflict Resolution* 47(6): 773–795.

Nordhaus, W. (2015) Climate clubs: Overcoming free-riding in international climate policy. *The American Economic Review* 105(4): 1339–1370.

Ostrom, E. (2010) Polycentric systems for coping with collective action and global environmental change. *Global Environmental Change* 20(4): 550–557.

Ostrom, E. (2012) Green from the grassroots. Available online at http://www.project-syndicate.org/commentary/green-from-the-grassroots (Last accessed March 6, 2017).

Ostrom, E., Burger, J., Field, C.B., Norgaard, R.B. and Policansky, D. (1999) Revisiting the commons: local lessons, global challenges. *Science* 284(5412): 278–282.

Parker, C. and Karlsson, C. (2014) Leadership and international cooperation. In R. Rhodes and P. 't Hart (eds.), *The Oxford Handbook of Political Leadership* (pp. 580–594). Oxford: Oxford University Press.

Popp, D., Newell, R.G. and Jaffe, A.B. (2010) Energy, the environment, and technological change. In Hall, B.H. and Rosenberg, N. (eds.), *Handbook of the Economics of Innovation, Volume 2, Handbook of the Economics of Innovation* (pp. 873–937). Amsterdam: North-Holland.

Rietig, K. (2014) Reinforcement of multilevel governance dynamics: creating momentum for increasing ambitions in international climate negotiations. *International Environmental Agreements: Politics, Law and Economics* 14(4): 371–389.

Rivas, M.F. and Sutter, M. (2011) The benefits of voluntary leadership in experimental public goods games. *Economics Letters* 112(2): 176–178.

Roemer, J.E. (2015) Kantian optimization: a microfoundation for cooperation. *Journal of Public Economics* 127: 45–57. [The Nordic Model.]

Shipan, C.R. and Volden, C. (2008) The mechanisms of policy diffusion. *American Journal of Political Science* 52(4): 840–857.

Siebert, H. (1979) Environmental policy in the two-country-case. *Journal of Economics* 39(3): 259–274.

Sinn, H.-W. (2008) Public policies against global warming: a supply side approach. *International Tax and Public Finance* 15(4): 360–394.

Stavins, R. (2014) What are the benefits and costs of epa's proposed co2 regulation? Available online at http://www.robertstavinsblog.org/2014/06/19/what-are-the-benefits-and-costs-of-epas-proposed-co2-regulation/ (Last accessed March 6, 2017).

Steinbacher, K. and Pahle, M. (2016) Leadership and the energiewende: German leadership by diffusion. *Global Environmental Politics* 16(4): 70–89.

Tavoni, M. and Tol, R.S. (2010) Counting only the hits? The risk of underestimating the costs of stringent climate policy. *Climatic Change* 100(3-4): 769–778.

Terhalle, M. and Depledge, J. (2013) Great-power politics, order transition, and climate governance: insights from international relations theory. *Climate Policy* 13(5): 572–588.

Tobin, J. (1958) Estimation of relationships for limited dependent variables. *Econometrica* 26(1): 24–36.

Torney, D. (2012) Assessing EU leadership on climate change-the limits of diffusion in EU relations with China and India. KFG Working Paper Series, No. 46.

Towns, A.E. (2012) Norms and social hierarchies: understanding international policy diffusion "from below." *International Organization* 66(02): 179–209.

Van de Graaf, T. and Westphal, K. (2011) The G8 and G20 as global steering committees for energy: opportunities and constraints. *Global Policy* 2(s1): 19–30.

Volden, C. (2006) States as policy laboratories: emulating success in the children's health insurance program. *American Journal of Political Science* 50(2): 294–312.

Volden, C., Ting, M.M. and Carpenter, D.P. (2008) A formal model of learning and policy diffusion. *American Political Science Review* 102(03): 319–332.

## Appendix A: Derivations for Section 3

### A.1 *Technology diffusion: Derivation of Equation* (41)

Consider the demand for the input factor energy from Equation (39)

$$E_i = A^{\mu-1} Y_i \left(\frac{\tau_i}{p_i}\right)^{-\mu} \tag{A1}$$

$$= A^{\mu-1} Y_i \tau_i^{(1-\alpha_i)(-\mu)} \tag{A2}$$

The index now denotes the country. The carbon tax in country $A$, $\tau_A$, is the price of the input energy. Recall that we consider technology to be common knowledge, so that $A = A_A = A_B$. The second equation makes use of Equation (33). We now insert equation (A2) for $s \in \{A, B\}$ into Equation (40) and solve for $A$:

$$A = \left(\zeta_A \tau_A^{(1-\alpha_A)\gamma \frac{-\mu}{\mu-1}}\right)^{\frac{\theta}{1-\gamma}} \left(\zeta_B \tau_B^{(1-\alpha_B)\gamma \frac{-\mu}{\mu-1}}\right)^{\frac{1-\theta}{1-\gamma}} \tag{A3}$$

Inserting $Y_i = q_i^{-\varepsilon_i} = \tau_i^{-\alpha_i \varepsilon_i}$ and (A3) into (A2) we have

$$E_A = \zeta_A^{\frac{(\mu-1)\theta}{1-\gamma}} \tau_A^{\theta m_A + n_A} \zeta_B^{\frac{(1-\theta)(\mu-1)}{1-\gamma}} \tau_B^{(1-\theta) m_B} \tag{A4}$$

$$E_B = \zeta_A^{\frac{(\mu-1)\theta}{1-\gamma}} \tau_A^{\theta m_A} \zeta_B^{\frac{(1-\theta)(\mu-1)}{1-\gamma}} \tau_B^{(1-\theta) m_B + n_B} \tag{A5}$$

Solving (A4) for $\tau_A$ and substituting into (A5) yields $E_B$ as a function of $E_A$,

$$E_B = \zeta_A^{\frac{(\mu-1)\theta}{1-\gamma}} \left( E_A \zeta_A^{-\frac{(\mu-1)\theta}{1-\gamma}} \zeta_B^{-\frac{(1-\theta)(\mu-1)}{1-\gamma}} \tau_B^{(1-\theta)m_B} \right)^{\frac{\theta m_A}{\theta m_A + n_A}} \zeta_B^{\frac{(1-\theta)(\mu-1)}{1-\gamma}} \tau_B^{(1-\theta)m_B + n_B} \tag{A6}$$

$$= E_A^{\frac{\theta m_A}{\theta m_A + n_A}} \left[ \zeta_A^{\frac{(\mu-1)\theta}{1-\gamma}\left(\frac{n_A}{\theta m_A + n_A}\right)} \zeta_B^{\frac{(1-\theta)(\mu-1)}{1-\gamma}\left(\frac{n_A}{\theta m_A + n_A}\right)} \tau_B^{(1-\theta)m_B \frac{n_A}{\theta m_A + n_A} + n_A} \right] \tag{A7}$$

In the following, we provide a detailed discussion of the reaction function (42) for technology leadership: The part $\theta m_A$ reflects how strongly the economy reacts to a carbon tax by improving low-carbon technology. The part $n_A$ reflects how strongly the economy reacts by substituting away from carbon. We can see this by looking more closely at these terms:

- The technology part can be written as $\theta m_A = [\mu - 1] \cdot [-\theta(1-\alpha_A)\rho\gamma \frac{1}{\mu-1}] < 0$. The first part, $\mu - 1 < 0$ is the elasticity of demand for the energy intensive good with respect to the factor specific technology for carbon emissions, see Equation (A2). It reflects that lower emissions are needed when the factor specific technology for carbon emissions improves.
- The second part, $-\theta(1-\alpha)\rho\gamma\frac{1}{\mu-1} < 0$, is the elasticity of the factor-specific technology for carbon emissions with respect to carbon taxes of country $A$, see Equation (A3). It reflects that country $A$ improves carbon efficiency as a reaction to an increase in carbon taxes. This improved world technology benefits both country $A$ and country $B$, which is why the term appears both in the numerator and the denominator. Large country size $\theta$ thus has a positive effect on leadership effectiveness, since research in large countries has an important effect on world technology.
- The substitution part can be written as $n_A = (1-\alpha_A)(-\mu) + -\alpha_A\varepsilon_A$. The first part of it, $(1-\alpha_A)(-\mu) < 0$ is the elasticity of carbon emissions with respect to the carbon taxes of country $A$, see Equation (A2). It reflects that producers of the energy-intensive good substitute away from carbon emissions toward other production factors, because its price increases relatively to the other production factors.
- The second part, $-\alpha_A\varepsilon_A < 0$, is the elasticity of demand for the energy intensive good with respect to the carbon taxes of country $A$, see Equations (32) and (33). It reflects that less of the energy-intensive good is demanded when one of its inputs becomes more expensive.

  A large elasticity of demand $\varepsilon_A$ has a negative effect on leadership effectiveness. The reason is that a country with a low elasticity of demand cannot reduce emissions well by substituting away from energy-intensive products. Instead it has to improve low-carbon technology, from which other countries can then benefit through spillovers. A high elasticity of the price for the energy-intensive good with respect to carbon taxes, $\alpha_A$, has a negative effect on leadership effectiveness. The reason is that a high $\alpha_A$ provides an incentive to substitute away from energy-intensive goods when the carbon tax rises. Therefore, the incentive to invest in technology is reduced.

## A.2 *Cost Uncertainty*

The following appendix illustrates within a simplified model that (i) the standard deviation of abatement cost uncertainty for the follower after learning, $\sigma_B(c_B|c_A)$, does not depend on the actual value of $c_A$ that has been learned and (ii) that $\frac{\partial}{\partial q_A}E_A[q_B] > 0$ holds. In addition, we see that $E_A[E_B[c_B|c_A]] = E_B[c_B]$ holds.

The model of uncertainty and learning follows a Bayesian approach. The follower has information about its marginal abatement costs over a range of abatement values, the output of models for example.

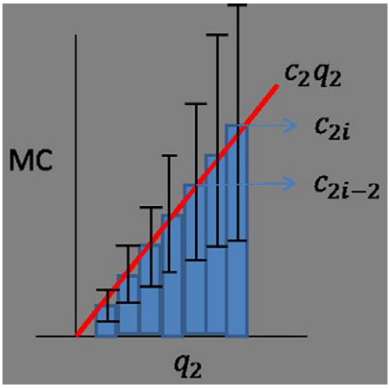

**Figure A1.** Uncertainty about Abatement Costs. [Colour figure can be viewed at wileyonlinelibrary.com]

This information specifies marginal abatement costs $c_B^k$ for the next additional unit of abatement at abatement level $q_B^k$. In order to obtain a quadratic abatement cost curve for the follower,

$$MC_B = c_B q_B \tag{A8}$$

the OLS-formula for a fit gives:

$$c_B = \frac{1}{\sum_k^n \left(q_B^k\right)^2} \sum_k^n c_B^k q_B^k \tag{A9}$$

for a range of observations along the abatement $q_B^1, ..., q_B^n$. We now assume that the marginal costs are uncertain, which induces the slope of the marginal costs to become an uncertain parameter, see Figure A1. The realizations of the marginal costs for a specific abatement level are correlated with the realizations of the leader $c_A^k$ according to a bivariate normal distribution:

$$\left(c_A^k, c_B^k\right) \propto N\left(\mu_A^k, \mu_B^k, \sigma_A^k, \sigma_B^k, \rho^k\right) \tag{A10}$$

Hence, we can calculate the expected value of $c_B$:

$$E_B[c_B] = \frac{1}{\sum_k^n \left(q_B^k\right)^2} \sum_k^n \mu_B^k q_B^k \tag{A11}$$

And the variance, assuming for simplification no correlation between different realizations of $c_B^k$ for the follower:

$$\sigma_B^2(c_B) = \frac{1}{\left(\sum_k^n \left(q_B^k\right)^2\right)^2} \sum_k^n \left(\sigma_B^k\right)^2 \left(q_B^k\right)^2 \tag{A12}$$

Under Bayesian learning, these values become updated until the abatement of the leader $q_A = q_A^j$:

$$E_B[c_B | c_A] = \frac{1}{\sum_k^n \left(q_B^k\right)^2} \left[ \sum_{k=1}^j \left\{ \mu_B^k + \rho^k \frac{\sigma_B^k}{\sigma_A^k} \left(c_A^k - \mu_A^k\right) \right\} q_B^k + \sum_{k=j+1}^n \mu_B^k q_B^k \right] \tag{A13}$$

$$= \langle c_B \rangle + \frac{1}{\sum_k^n \left(q_B^2\right)^2} \left[ \sum_{k=1}^{j} \left\{ \rho^k \frac{\sigma_B^k}{\sigma_A^k} \left(c_A^k - \mu_A^k\right) \right\} q_B^k \right] \tag{A14}$$

$$\sigma_B^2(c_B|c_A) = \frac{1}{\left(\sum_k^n \left(q_B^k\right)^2\right)^2} \left[ \sum_{k=1}^{j} \left\{1 - \left(\rho^k\right)^2\right\} \left(\sigma_B^k\right)^2 \left(q_B^k\right)^2 + \sum_{k}^{n} \left(\sigma_B^k\right)^2 \left(q_B^k\right)^2 \right] \tag{A15}$$

$$= \sigma_B^2(c_B) - \frac{1}{\left(\sum_k^n (q^k)^2\right)^2} \left[ \sum_{k=1}^{j} (\rho^k)^2 \left(\sigma_B^k\right)^2 \left(q_B^k\right)^2 \right] \tag{A16}$$

Hence, uncertainty decreases under learning independent of the realizations of leader costs while the updated expected value $E_B[c_B|c_A]$ depends on the actual realizations of $c_{Ai}$. We can now determine the expected values for the leader:

$$E_A[E_B[c_B|c_A]] = E_B[c_B] \tag{A17}$$

$$E_A\left[\sigma_B^2(c_B|c_A)\right] = \sigma_B^2(c_B|c_A) = \sigma_B^2(c_B) - \frac{1}{\left(\sum_k^n \left(q_B^k\right)^2\right)^2} \left[ \sum_{k=1}^{j} (\rho^k)^2 \left(\sigma_B^k\right)^2 (q_B^k)^2 \right] \tag{A18}$$

The derivative of the standard deviation needs to be approximated by differences due to the discrete nature of our model. Increasing leader abatement translates to increasing the index $j$ that indicates how many abatement costs values are updated:

$$\frac{\partial}{\partial q_A} E_A\left[\sigma_B^2(c_B|c_A)\right] \approx \frac{\Delta E_A\left[\sigma_B^2(c_B|c_A)\right]}{\Delta q_A} = \frac{\Delta E_A\left[\sigma_B^2(c_B|c_A)\right]}{\Delta j} \frac{\Delta j}{\Delta q_A} < 0 \tag{A19}$$

Hence, the reaction function of the follower only depends on relative abatement of the leader.