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**Advantageous Leadership in Public Good Provision: The Case of an  
Endogenous Contribution Technology**

by

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**Abstract:** From the perspective of standard public good theory the total amount of greenhouse gas mitigation (or public good supply in general) will be lower in a leader-follower game than in a simultaneous Nash game so that strategic leadership is disadvantageous for climate policy. We show that this need no longer be true when the leading country has the option to employ a technology by which it can reduce its abatement costs and thus improve the productivity of its contribution technology. Our general result is illustrated by an example with Cobb-Douglas preferences and, finally, an empirical application to global climate policy is briefly discussed.

**JEL Classification:** C72, H41, O31, Q54, Q55

**Keywords:** Public goods, leadership, choice of technology, climate policy

## 1. Introduction

The potential and likely effects of leadership play a prominent role in the scientific and public debate on global public goods, for which climate protection is the most prominent example. On the one hand, climate policy in some countries like Germany has been driven by the hope that leadership by a country or a group of countries will improve public good provision. On the other hand, in the framework of standard public good theory (see, e.g., Sandler, 1992, pp. 57 – 58, and Varian, 1994) it has been shown that, due to crowding-out of the follower's contribution, the leader-follower (Stackelberg) game with sequential moves leads to a smaller public good supply than the game with simultaneous moves so that “the tendency toward underprovision is even more marked at the equilibrium of the sequential process than at the Nash-Cournot equilibrium” (Cornes and Sandler, 1996, p. 331). But also in a cooperative scenario, in which a bargaining solution is attained, leadership may be detrimental to public good supply (see Hoel, 1991, and Buchholz and Konrad, 1994). But there also are a lot of attempts that vindicate the position of leadership optimists (see Edenhofer et al., 2015, and Schwerhoff, 2016, for overviews), e.g. by taking into account that leadership may resolve uncertainties about the costs and benefits of public goods (see Hermalin, 1998, and Brandt, 2004) or may cause positive technological externalities which automatically reduce contribution costs in other countries (see Stranlund, 1996, or Buchholz, Eichenseer and Dippl, 2017). The interaction of information-transmission through signaling and technology spillovers may even foster the positive effects of leadership (Mideksa, 2016). Moreover, leadership proves to be successful when it facilitates communication (see Barbieri, 2012) or – by integrating features of behavioral economics – when the agents involved have other-regarding preferences or expectations of reciprocity (see Buchholz and Sandler, 2016). In this paper we add a further argument to support the belief that leadership can have a positive effect both on the level of public good supply and on the utilities of the two countries involved so that a Pareto improvement may result.

The mechanism, which underlies these positive effects of leadership, completely works within the standard framework of public good theory (see Bergstrom, Blume and Varian, 1986, and Cornes and Sandler, 1996). In particular, it does without assuming specific preferences or asymmetric information but sticks – in a scenario with certainty and complete information – to the conventional weak assumption that “governments are ... the narrow payoff-maximizers

postulated in models as those of Hoel (1991) and Varian (1994)” (Schwerhoff, 2016, p. 200). At the same time, the analysis takes an empirically relevant element of leadership behavior in climate policy into account, which consists in the development of new climate friendly technologies, which make greenhouse gas mitigation less expensive. Against this background, the main point of our analysis is that, by acting as the leader in the Stackelberg game, a country has a higher incentive to utilize a cost-saving “green” technology than in the Nash game, where strategic considerations may prevent countries to apply an improved contribution technology (see Buchholz and Konrad, 1994, and Ihuri, 1996). The positive effect on public good supply that is caused by the improved technology then may be so strong that it overcompensates the negative crowding-out effect that occurs in the usual leader-follower scenario.

The structure of the paper will be as follows: In Section 2 we describe an otherwise standard two-stage model of voluntary public good provision with two countries  $L$  and  $F$ , in which at stage 1 one of the two countries, country  $L$ , has the possibility to change over to a new contribution technology, which improves its productivity in public good provision. At stage 2 voluntary public good provision then takes place either in a Nash game or a Stackelberg game. Section 3 then first of all provides a condition that country  $L$  does not want to take this opportunity for technological improvement in the Nash game but adheres to the original less productive contribution technology. If country  $L$  instead is the leader in a Stackelberg game of public good provision it always has an incentive to apply a productivity-enhancing technology, which is also shown in Section 3. This Section concludes with a description of the subgame-perfect equilibria in the Nash and the Stackelberg case. The levels of public good supply in these subgame-perfect equilibria are compared in Section 4. There, we also provide a general condition, which ensures that public good supply in the leader-follower equilibrium with the new improved technology in country  $L$  exceeds public good supply in the original Nash equilibrium with the old less productive technology. In that case leadership in public good provision not only is beneficial for public good supply but also yields a Pareto improvement. In Section 5 it is confirmed through a Cobb-Douglas example that our general condition for an improved allocation through leadership is not void. In Section 6 we conclude by especially giving some brief hints at empirical applications of our theoretical results.

## 2. The Framework

We assume that there are two countries  $L$  and  $F$ , which have the same utility function  $u(x_i, G)$ , where  $x_i$  is private consumption of country  $i = L, F$  and  $G$  is public good supply. This utility function has the standard properties, i.e. it is twice continuously differentiable and strictly monotone increasing in both variables and quasi-concave. The first partial derivatives of  $u(x_i, G)$  w.r.t.  $x_i$  and  $G$  are denoted by  $u_1$  and  $u_2$ , respectively. Moreover, it is assumed that both the private and the public good are non-inferior. This implies that the (income) expansion paths  $e(G, \rho)$ , which connect all points in the  $x_i - G$ -diagram where the marginal rate of substitution  $mrs$  between the private and the public good is equal to some given  $\rho > 0$ , are well-defined and strictly monotone increasing in  $G$ .

The public good is produced by a summation technology, i.e.  $G = g_L + g_F$ , where  $g_L$  and  $g_F$  are country  $L$ 's and country  $F$ 's public good contributions. The contribution productivity parameters of both countries, which are their marginal rates of transformation  $mrt$  between private consumption and the public good, are assumed to be constant and equal to  $a_0 = 1$  in the initial state. But while country  $F$ 's productivity parameter will stay at  $a_0 = 1$  throughout the whole analysis, country  $L$  may through a binary choice – at a stage before the public good provision game starts – turn over to a technology with a higher productivity parameter  $a > 1$ . The costs of public good provision then fall to  $\frac{1}{a}$  for country  $L$ , which in the context of climate change means the transition to an improved cost-effective greenhouse gas abatement technology. Unlike, e.g., Stranlund (1996) there is no technology spillover from country  $L$  to country  $F$ .

If the initial endowment (“income”) of country  $L$  is denoted by  $w_L$  and that of country  $F$  by  $w_F$  an allocation  $(x_1, x_2, G)$  is feasible for some given  $a \geq 1$  (and no resources are wasted) if and only if  $az_L + z_F = G$ , where  $z_i = w_i - x_i \geq 0$  denotes the part of income country  $i = L, F$  spends on public good provision. This feasibility constraint is obviously equivalent to  $ax_L + x_F + G = aw_L + w_F$ , which includes the original state as a special case when also country  $L$  has the productivity  $a = a_0 = 1$ . This aggregate budget constraint provides the foundation

for our characterization of interior Nash equilibria NE, where both countries make strictly positive contributions to the public good. To that end we observe in the spirit of the Aggregative Game Approach (see Cornes and Hartley, 2007) that in an interior NE the *mrs* of both countries must coincide with their respective *mrt*, which implies that country *L*'s position lies on the expansion path  $e(G, a)$  and that of country *F* on the expansion path  $e(G, 1)$ . Combining this with the feasibility constraint gives the following condition, which characterizes public good supply  $G^N(a)$  in an interior NE for some given contribution productivity  $a$ :

$$(1) \quad ae(G^N(a), a) + e(G^N(a), 1) + G^N(a) = aw_L + w_F.$$

Existence and uniqueness of the NE follow from normality of the public good and, given equal preferences of both countries, interiority of the NE is ensured when incomes of the both countries do not diverge too much (see, e.g., Cornes and Hartley, 2007).

Private consumption of country *L* in an interior NE is  $x_L^N(a) = e(G^N(a), a) < w_L$  and that of country *F* is  $x_F^N(a) = e(G^N(a), 1) < w_F$ . Country *L*'s public good expenditures then are  $z_L^N(a) = w_L - x_L^N(a)$ , which yields the public good contribution  $g_L^N(a) = az_L^N(a)$ . For country *F* we have  $g_F^N(a) = z_F^N(a) = w_F - x_F^N(a)$ . The utility levels of both countries in the NE are denoted by  $u_L^N(a) = u(x_L^N(a), G^N(a))$  and  $u_F^N(a) = u(x_F^N(a), G^N(a))$ , respectively. To define upper bounds for public good supply in an interior NE let, similar as in Andreoni (1988),  $\bar{G}_L(a)$  be defined by the condition  $e(\bar{G}_L(a), a) = w_L$  and  $\bar{G}_F(1)$  by  $e(\bar{G}_F(1), 1) = w_F$ . As expansion paths are increasing in  $G$  in an interior NE we clearly have  $G^N(a) < \bar{G}_L(a)$  and  $G^N(a) < \bar{G}_F(1)$ .

In the same situation the Stackelberg equilibrium SE for some given productivity  $a \geq 1$  results from maximizing utility of the leading country *L*, i.e.  $u(w_L - z_L, az_L + z_{RF}(az_L)) \rightarrow \max$ , where  $z_{RF}(az_L) = z_{RF}(g_L)$  is country *F*'s reaction function. The f.o.c. for this optimization problem, which characterizes the optimal level  $z_L^S(a)$  of country *L*'s public expenditures for the public good in an interior SE, then can be given by equating country *L*'s *mrs* with its *mrt* in the Stackelberg case, i.e. as

$$(2) \quad mrs(w_L - z_L^S(a), G^S(a)) = \frac{u_1(w_L - z_L^S(a), G^S(a))}{u_2(w_L - z_L^S(a), G^S(a))} = a(1 + z'_{RF}(az_L^S(a))),$$

where  $G^S(a) = az_L^S(a) + z_{RF}(az_L^S(a))$  is total public good supply in the SE and  $z'_{RF}(g_L) = \frac{\partial z_{RF}}{\partial g_L}$

is the slope of country  $F$ 's reaction path. Private consumption of country  $L$  in the SE for some given  $a$  is denoted by  $x_L^S(a) = w_L - z_L(a)$  and private consumption of country  $F$  is  $x_F^S(a)$ , which equals  $e(G^S(a), 1)$  in the interior case. Utility levels in the SE then are  $u_L^S(a) = u(x_L^S(a), G^S(a))$  and  $u_F^S(a) = u(x_F^S(a), G^S(a))$ .

Depending on the size of the productivity parameter  $a$  (and on the income distribution too as shown by Buchholz, Lommerud and Konrad, 1997) the SE may also become a corner solution, in which only one country actively contributes to the public good. For low levels of  $a$  (and  $w_L$ ) the SE is the standalone allocation of country  $F$ , which results from maximizing  $u(w_F - z_F, z_F)$  and leads to a level of public good supply denoted by  $G_F^A$ . Country  $L$  then attains the position  $(w_L, G_F^A)$ , which it only wants to leave if its  $mrt = a(1 + z'_{RF}(0))$  at  $z_L = 0$  exceeds  $mrs(w_L, G_F^A)$ . For high levels of  $a$  (and  $w_L$ ) the SE instead is the standalone equilibrium of country  $L$ , which results from maximizing  $u(w_L - z_L, az_L)$  and which leads to a level of public good supply denoted by  $G_L^A(a)$ . This follows because country  $F$  will stop contributing to the public good as soon as the public good contribution of country  $L$  attains the critical level  $\bar{G}_F(1)$ . This, however, implies that  $\bar{G}_F(1)$  is maximum public supply that can result in an interior SE, in which country  $F$  is a contributor. Consequently,  $u(w_L, \bar{G}_F(1))$  gives an upper bound for the utility level, which country  $L$  can have in an interior SE. If country  $L$ 's contribution productivity  $a$  is chosen high enough, the budget line  $G = -ax_L + aw_L$  will cut the indifference curve to the utility level  $u(w_L, \bar{G}_F(1))$ . Since  $\bar{G}_F(1) > G_F^A$  we, moreover, have  $u(w_L - \frac{G_L^A(a)}{a}, G_L^A(a)) > u(w_L, \bar{G}_F(1)) = u(w_L, G_F^A)$  so that country  $L$ 's standalone solution is also better for country  $L$  than being in  $F$ 's standalone solution. Therefore it is ensured that in this case the standalone allocation of country  $L$  is the SE.

### 3. Incentives for Technological Improvements in the Nash and in the Stackelberg Game

In the *Nash case* we are, analogous as in Buchholz and Konrad (1994) and Ihuri (1996), interested in whether starting from the initial NE, where both countries have the productivity parameter  $a_0 = 1$ , country  $L$  will decrease or increase its utility through a marginal increase of its contribution productivity. Differentiating  $u(w_L - z_L^N(a), G^N(a))$  w.r.t. to  $a$  and observing  $u_1(x_L^N(1), G^N(1)) = u_2(x_L^N(1), G^N(1))$  immediately shows that utility of country  $L$  falls if and only if

$$(3) \quad \frac{\partial z_L^N}{\partial a} > \frac{\partial G^N}{\partial a}$$

holds at  $a_0 = 1$ . To specify criterion (3) further let  $\hat{e}_1$  and  $\hat{e}_2$  denote the partial derivatives of the expansion path  $e(G, \rho)$  w.r.t.  $G$  and  $\rho$  at  $(x^N(1), G^N(1))$ , respectively, where  $x^N(1) = x_L^N(1) = x_F^N(1) = e(G^N(1), 1)$ . Differentiating  $z_L^N(a) = w_L - x_L^N(a) = w_L - e(G^N(a), a)$  w.r.t.  $a$  at  $a_0 = 1$  gives

$$(4) \quad \frac{\partial z_L^N}{\partial a} = -(\hat{e}_1 \frac{\partial G^N}{\partial a} + \hat{e}_2),$$

while differentiating condition (1) w.r.t.  $a$  also at  $a_0 = 1$  yields

$$(5) \quad \frac{\partial G^N}{\partial a} = \frac{z_L^N(1) - \hat{e}_2}{1 + 2\hat{e}_1} > 0.$$

Based on this we obtain the following, which provides some extension of Buchholz and Konrad (1994), Ihuri (1996) and Hattori (2005).

**Proposition 1:** If

$$(6) \quad w_L < x^N(1) - \frac{\hat{e}_1 \hat{e}_2}{1 + \hat{e}_1}$$

there exists some critical level  $\bar{a} > 1$  with  $u_L^N(\bar{a}) = u_L^N(1)$  so that country  $L$  does not benefit from choosing any contribution productivity  $a \in [1, \bar{a}]$  and moving to the corresponding new NE. If country  $L$ 's income  $w_L$  decreases while total income  $w_L + w_F$  remains constant, the threshold  $\bar{a}$  increases.



**Proof:** Observing  $z_L^N(1) = w_L - x^N(1)$  the first part of the assertion follows by combining (3), (4) and (5) and applying the intermediate value theorem since  $u(x^N(a), G^N(a))$  is a continuous function of  $a$ , whose value exceeds  $u_L^N(1)$  if  $a$  is large enough. The second part holds since for any  $a > 1$ , redistribution of income from country  $L$  to country  $F$  makes the right hand side of condition (1) smaller. Monotonicity of the expansion paths  $e(G, a)$  and  $e(G, 1)$  then implies that  $G^N(a)$  and  $x_L^N(a) = e(G^N(a), a)$  and thus  $u_L^N(a) = u(x_L^N(a), G^N(a))$  decrease through such a redistribution while  $u_L^N(1)$  does not change. QED

If condition (6) is not fulfilled we set  $\bar{a} = 1$ , which indicates that country  $L$  would increase its utility in the Nash game by choosing a productivity parameter  $a > 1$ . To facilitate the exposition we, in addition, impose a monotonicity condition, which says that utility  $u_L^N(a)$  of country  $L$  in the NE is either increasing in  $a$  (if  $\bar{a} = 1$ ) or hump-shaped (if  $\bar{a} > 1$ ). Then  $u_L^N(a) > u_L^N(1)$  if  $a > \bar{a}$ .

Proposition 1 in particular shows that a negative incentive for technological progress becomes more likely if income of country  $L$  is relatively small. This is intuitively plausible since in this case country  $L$ 's expenditure for the public good in the original NE is relatively small so that it cannot benefit much from falling costs of its contribution. As normality implies  $\hat{e}_1 > 0$  and  $\hat{e}_2 < 0$  and thus  $x^N(1) - \frac{\hat{e}_1 \hat{e}_2}{1 + \hat{e}_1} > x^N(1)$ , it is – irrespective of the underlying preferences in both countries – always possible to meet condition (6) through a redistribution of income from country  $L$  to country  $F$  that brings country  $L$ 's income close enough to  $x^N(1)$ . Note that such a transfer will not change public good supply and private consumption in the NE as long as  $w_L > x^N(1)$  and  $w_F > x^N(1)$  holds. This reflects Warr's neutrality result (see, e.g., Cornes and Sandler, 1996, pp. 164-165) but also is an immediate consequence of the characterization of the NE as provided by condition (1).

In order to explore the incentives for technological improvement, which the leading country  $L$  has in the *Stackelberg case*, we look at the entire possibility curve along which country  $L$  moves, when it varies its expenditure for the public good anticipating the reaction of the follower country  $F$ . Remember from the end of Section 2 that country  $F$  will stop contributing to the public good as soon as country  $L$ 's public good supply  $G_L^A(a)$  in its standalone

solution has attained  $\bar{G}_F(1)$ . As a function of its public good expenditure  $z_L$  the possibility curve of country  $L$  therefore is given by

$$(7) \quad G_p(z_L, a) = az_L + z_{RF}(az_L)$$

if  $z_L < \bar{z}_L(a) := \frac{\bar{G}_F(1)}{a}$ . Then a positive public good contribution  $z_{RF}(az_L)$  of country  $F$  results. If, however,  $z_L \geq \bar{z}_L(a)$  we have  $G_p(z_L, a) = az_L$ , i.e. country  $F$  makes no public good contribution anymore and country  $L$  is in its standalone position. In Figure 1 the two segments of  $G_p(z_L, a)$  meet at the point  $P(a)$ .

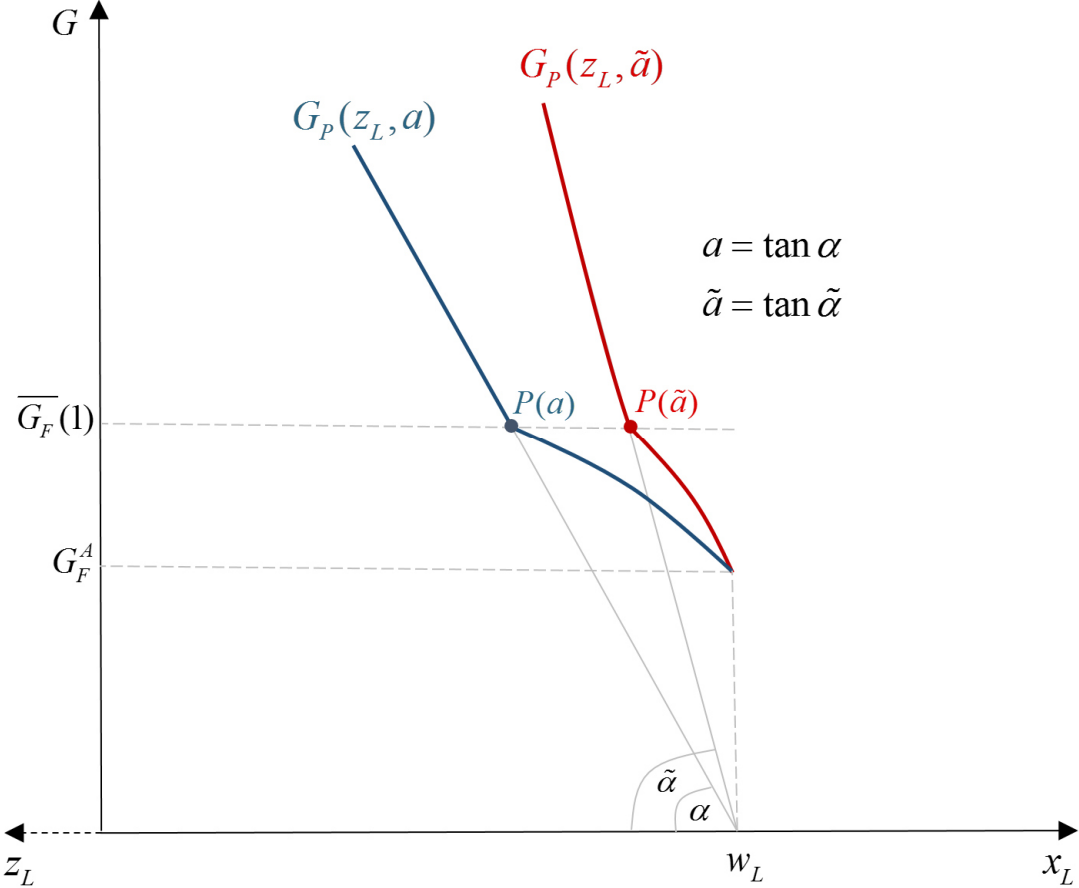


Figure 1

If now  $a$  is increased (from  $a$  to  $\tilde{a}$ ) it is obvious that the standalone segment is shifting outwards and the point  $P(a)$  is shifting to the right. For the interior segment this is shown by taking the derivative of  $G_p(z_L, a)$  w.r.t.  $a$ , which gives

$$(8) \quad \frac{\partial G_P}{\partial a}(z_L, a) = z_L(1 + z'_{RF}(az_L)) > 0.$$

The inequality sign in (8) holds since  $z'_{RF}(g_L) > -1$ , which follows from normality of the public good and which means that an increase of country  $L$ 's public good contribution is not be completely crowded out by country  $F$ . At the same time, the point  $P(\tilde{a})$  lies to the right of  $P(a)$  since  $\bar{z}_L(a) = \frac{\bar{G}_F(1)}{a}$  is decreasing in  $a$ . Taken together an increase of  $a$  shifts country  $L$ 's entire possibility curve outwards (as visualized in Figure 1), which implies that the incentives for applying a contribution technology with  $a > a_0 = 1$  are unequivocally positive for country  $L$ . This generalizes a special result, which Hattori and Yamada (2016) have obtained for the Cobb-Douglas case.

**Proposition 2:** If country  $L$  is the leader in the Stackelberg game it will never lose when it chooses a higher productivity parameter when the technological improvement is costless. It will increase its utility when it actively contributes to the public good after the technological change.

**Proof:** Country  $L$  does not benefit from the outward shift of its possibility curve only if it remains a non-contributor after the increase of the productivity parameter. But also in this case it will not be hurt by the technological change because the SE still is the standalone allocation of country  $F$ . QED

Proposition 1 and Proposition 2 then directly lead to the description of the subgame-perfect equilibria of the entire two-stage game, where  $a_N^*$  and  $a_S^*$  denote country  $L$ 's technology choices in the subgame-perfect equilibrium in the Nash and in the Stackelberg scenario.

**Proposition 3:** Assume that at stage 1 country  $L$  has the binary choice between the original contribution productivity  $a_0 = 1$  and some higher  $a > 1$ . If there is a Nash contribution game at the second stage the subgame-perfect contribution productivity is  $a_N^* = 1$  if  $a \leq \bar{a}$  and  $a_N^* = a$  if  $a > \bar{a}$ . In the Stackelberg case the subgame-perfect contribution productivity always is  $a_S^* = a$ .

As a special case of Proposition 3 we have  $a_N^* = a > 1$  if condition (6) is not fulfilled and thus  $\bar{a} = 1$  holds.

In the following section we compare the levels of public good supply in the subgame-perfect equilibria in the Nash case and in the Stackelberg case, i.e.  $G^N(a_N^*)$  with  $G^S(a_S^*)$ .

#### 4. Increasing Public Good Supply through Leadership: A General Condition

As a first step, we infer the effect that an increase of productivity has on the level of public good supply in the SE. It is assumed that for an initially given productivity parameter  $a$  an interior SE results, where country  $L$ 's public good contribution is  $g_L^S(a) = az_L^S(a)$ .

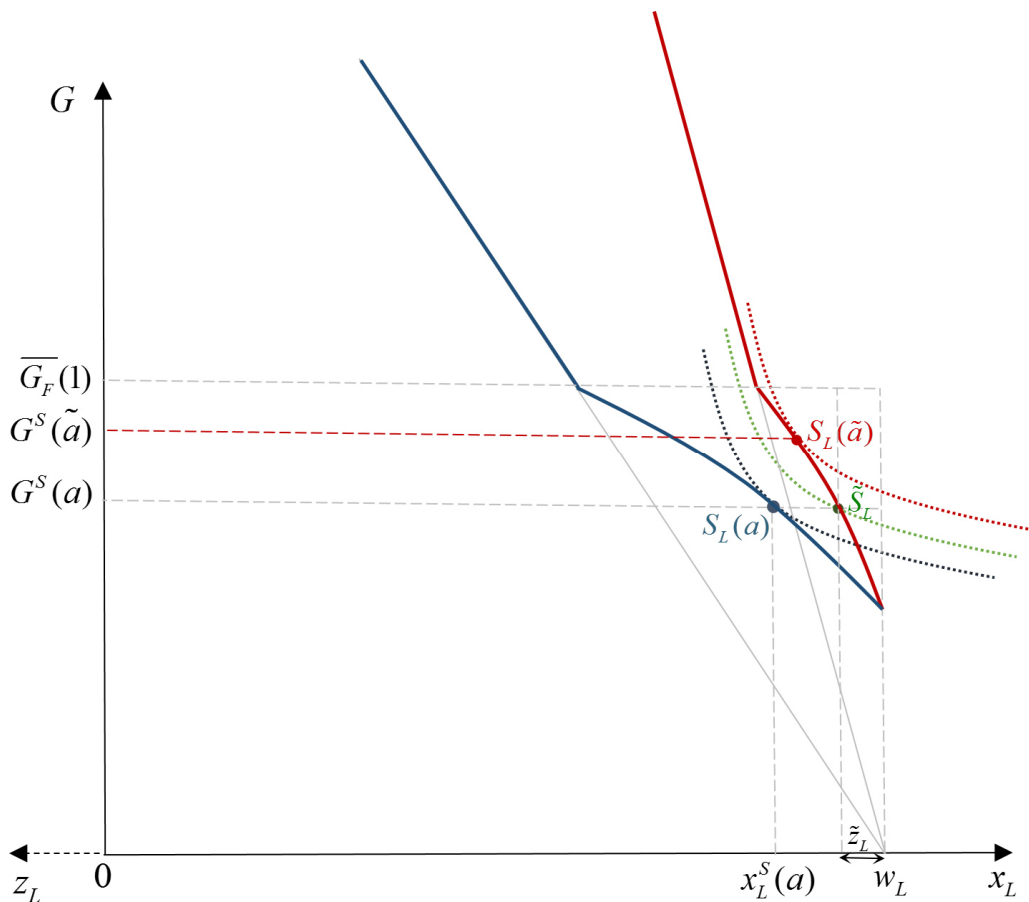


Figure 2

If country  $L$ 's contribution productivity rises to some  $\tilde{a} > a$  we suppose, for a moment, that country  $L$  adapts by reducing its expenditure for the public good to  $\tilde{z}_L = \frac{g_L^S(a)}{\tilde{a}}$ . Since this keeps  $L$ 's public good contribution constant at  $g_L^S(a)$  the reaction of country  $F$  and hence total public good supply  $G^S(a)$  do not change. In Figure 2 this means that the position of

country  $L$  moves to the right on the parallel to the  $x_L$ -axis ( $z_L$ -axis) passing through the point  $S_L(a) = (x_L^S(a), G^S(a))$ .

On the one hand, it follows from normality that in country  $L$ 's new position  $\tilde{S}_L$  the *mrs* between the private and the public good is lower than in  $S_L(a)$ , i.e. that the indifference becomes flatter. On the other hand (7) yields that

$$(9) \quad \frac{\partial G_p}{\partial z_L}(\tilde{z}_L, \tilde{a}) = \tilde{a}(1 + z'_{RF}(g_L^S(a))) > a(1 + z'_{RF}(g_L^S(a))) = \frac{\partial G_p}{\partial z_L}(z_L^S(a), a),$$

so that in  $\tilde{S}_L$  country  $L$ 's possibility curve for  $\tilde{a}$  is steeper than the possibility curve in  $S_L(a)$  so that all points on the possibility curve for  $\tilde{a}$  lie below  $\tilde{S}_L$ . These considerations lead to the following result:

**Proposition 4:** An increase of the leading country  $L$ 's contribution productivity from  $a$  to some  $\tilde{a} > a$  leads to a higher public supply in the SE when the SE for  $a$  is interior or the standalone solution of country  $L$ .

**Proof:** If the SE for  $a$  is interior the assertion follows from the explanation of Figure 1 above. If instead the SE is the standalone solution of country  $L$  the result follows since by normality  $G_L^A(a)$  is increasing in  $a$ . QED

For any contribution productivity in all other points of the possibility curve public good supply exceeds that in the standalone solution of country  $F$ . Thus, if the SE is this corner solution public good supply can never fall through an increase of  $L$ 's contribution productivity.

As a second step we show that the original NE, where both countries have the same contribution productivity  $a_0 = 1$ , can be partially mimicked as an SE for an appropriately chosen productivity parameter  $\hat{a}$  of country  $L$ . Analogous as in the demonstration of Proposition 4 we adjust country  $L$ 's public good expenditure so that its effective contribution to the public good stays at  $g_L^N(1)$  when its contribution productivity varies. For any  $a > 1$  country  $L$ 's public good expenditures thus are reduced to  $\hat{z}_L(a) = \frac{g_L^N(1)}{a}$  and its private consumption in-

creases to  $\hat{x}_L(a) = w_L - \hat{z}_L(a)$ . Country  $L$ 's position  $(\hat{x}_L(a), G^N(1)) = (w_L - \frac{g_L^N(1)}{a}, G^N(1))$

hence moves to the right on a parallel to the  $x_L$ -axis when  $a$  is increased. The productivity parameter  $\hat{a}$ , for which public good supply in the SE becomes equal to  $G^N(1)$ , then is determined by the following condition:

$$(10) \quad mrs(\hat{x}_L(\hat{a}), G^N(1)) = \hat{a}(1 + z'_{RF}(\hat{a}\bar{z}(\hat{a}))) = \hat{a}(1 + z'_{RF}(g_L^N(1))).$$

Given  $\hat{a}$  according to (10) the f.o.c. condition (2), which characterizes country  $L$ 's optimal behavior in an interior SE, is clearly satisfied when country  $L$  chooses  $\bar{z}(a)$  as its expenditure for the public good. A productivity parameter  $\hat{a}$  for which condition (10) is satisfied actually exists: If  $a = 1$  we have

$$(11) \quad mrs(\hat{x}_L(1), G^N(1)) = mrs(x^N(1), G^N(1)) = 1 > 1 + z'_{RF}(g_L^N(1))$$

as  $z'_{RF}(g_L^N(1)) < 0$ , i.e. the left hand side of (10) exceeds the right hand side. Since, moreover,  $z'_{RF}(g_L^N(1)) > -1$  the linear function  $a(1 + z'_{RF}(g_L^N(1)))$  is increasing in  $a$  with  $\lim_{a \rightarrow \infty} a(1 + z'_{RF}(g_L^N(1))) = \infty$ . At the same time normality implies that  $mrs(\hat{x}_L(a), G^N(1))$  is a decreasing function of  $a$ , for which  $\lim_{a \rightarrow \infty} mrs(\hat{x}_L(a), G^N(1)) = \lim_{a \rightarrow \infty} mrs(w_L - \frac{g_L^N(1)}{a}, G^N(1)) = mrs(w_L, G^N(1)) < \infty$  holds. Therefore, the right hand side of (10) will exceed the left hand side if the productivity parameter gets large enough. As the implied functions are continuous the intermediate value theorem ensures the existence of a unique productivity parameter  $\hat{a}$ , for which the equality of the both sides in (10) actually obtains. We thus have the following result:

**Proposition 5:** Assume that the original NE, where both countries have the same contribution productivity  $a_0 = 1$ , is interior. Then there exists a threshold  $\hat{a} > 1$  so that  $G^S(a) > G^N(1)$  holds for all  $a > \hat{a}$ . Moreover,  $u_L^S(a) > u_L^N(1)$  and  $u_F^S(a) > u_F^N(1)$ , i.e. the SE for  $a$  is Pareto superior to the NE for  $a_0 = 1$ . If instead  $a \leq \hat{a}$  we have  $G^S(a) \leq G^N(1)$ ,  $u_L^S(a) > u_L^N(1)$  and  $u_F^S(a) \leq u_F^N(1)$ .

**Proof:** The result on the changes of public good supply is a direct consequence of Propositions 4 and the properties of the critical level  $\hat{a}$ . Concerning the change of utilities first note that given  $\hat{a}$  utility of country  $L$ 's is higher than in the original NE as it attains the same public

good supply  $G^N(1)$  with a lower expenditure for the public good. Utility of country  $F$ , however, is the same as in the original NE if  $a = \hat{a}$ . For any  $a > \hat{a}$  country  $L$  then will improve further in the SE because as a Stackelberg leader it could have  $G^N(1)$  even with a lower expenditure for the public good than in the SE for  $\hat{a}$ . Country  $F$  also becomes better off: As Proposition 4 implies that  $G^S(a) > G^S(\hat{a}) = G^N(1)$  country  $F$  is moving outwards on the expansion path  $e(G, 1)$ , when  $L$ 's contribution productivity rises from  $\hat{a}$  to  $a > \hat{a}$ , which clearly increases  $F$ 's utility. When for some  $a > \hat{a}$  the SE instead becomes country  $L$ 's standalone allocation with public good supply  $G_L^A(a)$  observe that interiority of the original NE implies  $x_F^N(1) = x^N(1) < w_F$  and that  $G_L^A(a) > \bar{G}_F(1) > G^N(1)$ . Hence,  $u(w_F, G_L^A(a)) > u(x_F^N(1), G^N(1))$ , i.e. country  $F$ 's utility in such an SE also exceeds that in the original NE. The assertion for the case  $a < \hat{a}$  is proven in a similar way. QED

Comparing Proposition 1 and Proposition 5 indicates that it may be difficult to have, on the one hand, negative incentives for technological improvement in the Nash game and a higher public good supply in the SE than in the original NE on the other: While the first requirement is fulfilled by low values of the productivity parameter  $a$ , the second requirement demands high levels of  $a$ . It is only possible to satisfy both requirements simultaneously, when the regions for  $a$  that follow from Propositions 1 and 5, respectively, overlap so that in this case leadership becomes favorable for public good supply and utility of both countries. This turns out as a special case of the following Proposition, which summarizes the central results of this paper.

**Proposition 6:** Assume that the original NE with productivity  $a_0 = 1$  in both countries is interior and that at stage 1 country  $L$  has the choice between the original contribution productivity  $a_0 = 1$  and some higher contribution productivity  $a > 1$ . Then the differences in public good supply between the subgame-perfect equilibria in the Nash and Stackelberg case are as follows:

- (i) If  $\hat{a} \geq \bar{a}$  we always have  $G^S(a_S^*) < G^N(a_N^*)$ .
- (ii) If  $\hat{a} < \bar{a}$  we have  $G^S(a_S^*) < G^N(a_N^*)$  if  $a < \hat{a}$  or  $a \geq \bar{a}$  and  $G^S(a_S^*) > G^N(a_N^*)$  if  $a \in [\hat{a}, \bar{a})$ .

If  $\hat{a} < \bar{a}$  and  $a \in [\hat{a}, \bar{a})$  the subgame-perfect equilibrium in the Stackelberg case Pareto dominates the subgame-perfect equilibrium in the Nash case.

**Proof:** An identical contribution productivity  $a \geq 1$  in both countries implies  $G^N(a) > G^S(a)$ , which is shown analogous to the proof by Cornes and Sandler (1996, p. 331). Proposition 3 then directly yields the assertion of Proposition 6 for the case  $a > \bar{a}$  since then  $a_N^* = a_S^* = a$ . If instead  $a \leq \bar{a}$  we get  $a_N^* = 1$ , while again  $a_S^* = a$ . In this case, the assertion is an immediate consequence of Proposition 5. QED

It is, however, not obvious that the condition  $\hat{a} < \bar{a}$ , which implies advantageous leadership both w.r.t the level of public good supply and the utility of both countries and thus yields the most interesting part of Proposition 6, can really be satisfied. Therefore we have to provide an example, in which  $\bar{a} > \hat{a}$  actually holds. This will be done in the next section by assuming Cobb-Douglas preferences in both countries.

## 5. A Cobb-Douglas Example

Let both countries have the same symmetric Cobb-Douglas utility function  $u(x_i, G) = x_i G$  for  $i = L, F$ . The marginal rate of substitution at  $(x_i, G)$  is  $mrs(x_i, G) = \frac{G}{x_i}$  so that the expansion paths for some given marginal rate of substitution is  $e(G, \rho) = \frac{G}{\rho}$ . For the partial derivatives we thus have  $e_1(G, \rho) = \frac{1}{\rho}$  and  $e_2(G, \rho) = -\frac{G}{\rho^2}$ .

For a given contribution productivity  $a$  of country  $L$  it follows from condition (1) that in this special case the interior NE is characterized by

$$(12) \quad G^N(a) = x_F^N(a) = \frac{aw_L + w_F}{3} \quad \text{and} \quad x_L^N(a) = \frac{aw_L + w_F}{3a}.$$

The interiority conditions  $x_L^N(a) < w_L$  and  $x_F^N(a) < w_F$  for the NE then are

$$(13) \quad \frac{1}{2}q < a < 2q,$$



where  $q := \frac{w_F}{w_L}$  is the ratio of both countries' income levels. If the initial NE for  $a = a_0 = 1$ ,

what we have assumed in our general analysis, is to be interior condition (13) boils down to

$$(14) \quad \frac{1}{2} < q < 2$$

Since  $\hat{e}_1 = 1$  and  $\hat{e}_2 = -G^N(1) = -\frac{w_L + w_F}{3}$  it follows from Proposition 1 that country  $L$  has no incentive to apply an improved technology and to leave the original NE, i.e. that  $\bar{a} = \bar{a}(q) > 1$ , if

$$(15) \quad w_L < x^N(1) + \frac{G^N(1)}{2} = \frac{3}{2}G^N(1) = \frac{w_L + w_F}{2} \Leftrightarrow q > 1.$$

Thus country  $L$  has no incentive to adopt an improved technology when it is poorer than country  $F$ . Given  $q > 1$  the threshold level  $\bar{a}(q)$ , below which technological improvement is not profitable for country  $L$ , then is calculated from

$$(16) \quad u_L^N(\bar{a}(q)) = \frac{(\bar{a}(q)w_L + w_F)^2}{9\bar{a}(q)} < \frac{(w_L + w_F)^2}{9} = u_L^N(1),$$

which gives

$$(17) \quad \bar{a}(q) = q^2.$$

Concerning the Stackelberg game we first note that maximizing country  $F$ 's utility  $(w_F - z_F)(g_L + z_F)$  for a given  $g_L$  yields country  $F$ 's reaction function

$$(18) \quad z_{RF}(g_L) = \frac{1}{2}(w_F - g_L),$$

which has the constant slope  $z'_{RF} = -\frac{1}{2}$ . To determine an interior SE for some given contribu-

tion productivity  $a$  the leading country  $L$  thus maximizes utility  $(w_L - z_L) \cdot (az_L + z_{RF}(az_L)) = \frac{1}{2}(w_L - z_L) \cdot (w_F + az_L)$ . From the f.o.c. we have  $z_L^S(a) = \frac{aw_L - w_F}{2a}$ . Thus an interior solution

with  $z_L^S(a) > 0$  is obtained if and only if  $q < a$ . If instead  $q \geq a$  a corner SE with country  $F$  as the sole contributor to the public good arises.

An interior SE clearly results if according to Proposition  $a$  is chosen so that public good in the SE identical to that in the original interior NE. To determine in our special case the threshold level  $\hat{a} = \hat{a}(q)$  from condition (10) we observe that  $\hat{x}_L(a) = w_L - \frac{g_N^L(1)}{a} = w_L - \frac{2w_L - w_F}{3a}$

so that (10) turns into

$$(19) \quad mrs(\hat{x}_L(\hat{a}(q)), G^N(1)) = \frac{\frac{w_L + w_F}{3}}{\left(w_L - \frac{2w_L - w_F}{3\hat{a}(q)}\right)} = \hat{a}(q) \left(1 - \frac{1}{2}\right) = \hat{a}(q)(1 - z'_{RF}).$$

Solving (19) for  $\hat{a}(q)$  yields

$$(20) \quad \hat{a}(q) = \frac{1}{3}(4 + q).$$

Combining (17) and (20) then gives that  $\bar{a}(q) > \hat{a}(q)$ , i.e. that according to Proposition 6 it becomes possible that public good supply and the utilities of both countries are larger in the subgame-perfect equilibrium of the Stackelberg case than in the subgame-perfect equilibrium of the Nash case, if  $3q^2 - q - 4 > 0$ . Determining the zeros of this quadratic function yields

$$(21) \quad \bar{a}(q) > \hat{a}(q) \Leftrightarrow q > \frac{4}{3}.$$

In summary, it follows from condition (13), (14), (17), (20) and (21) that any combination  $(q, a)$  can provide

$$(22) \quad q \in \left(\frac{4}{3}, 2\right) \quad \text{and} \quad a \in \left(\frac{1}{3}(4 + q), q^2\right).$$

In this context note that the upper bound condition (16) is stronger than (13) if  $q < 2$ . The  $(q, a)$ -combinations, which satisfy the condition (21), are visualized in Figure 3.

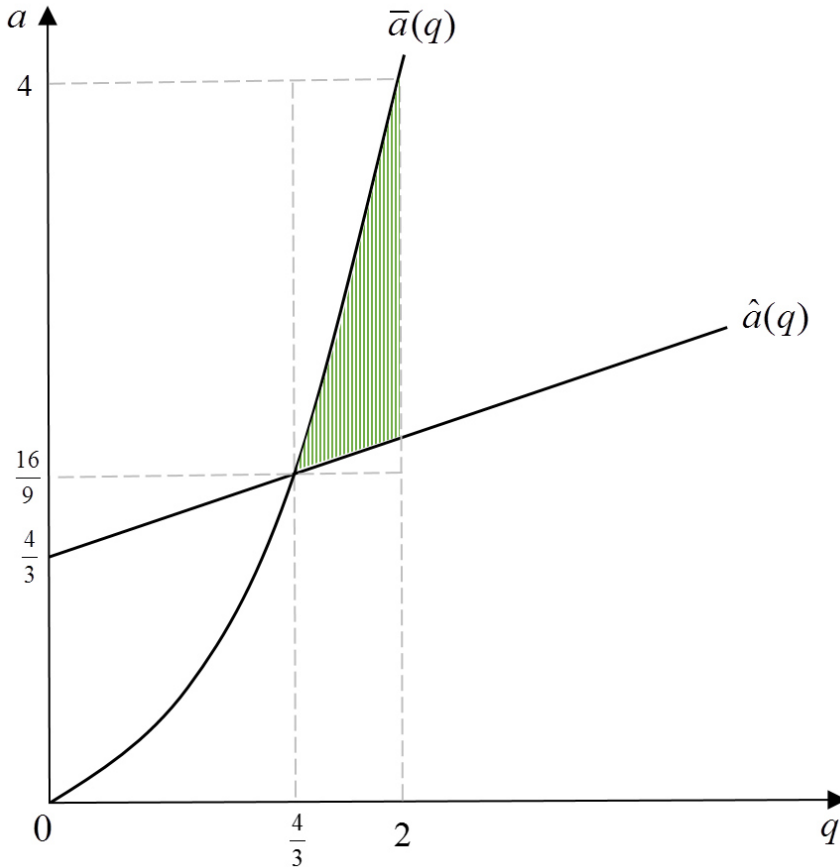


Figure 3

A specific numerical example thus, e.g., is provided by letting  $w_L = 2$  and  $w_F = 3$ , i.e.  $q = \frac{3}{2}$ ,

and  $a = 2$ . In the Nash game an interior initial NE with  $G^N(1) = x^N(1) = \frac{5}{3} = 1,67$

$< 2 = \min\{w_L, w_F\}$  results so that  $u_L^N(1) = u_F^N(1) = \left(\frac{5}{3}\right)^2 = \frac{25}{9} = 2,78$ . The NE for  $a = 2$  is in-

terior, too. It is given by  $G^N(2) = \frac{2 \cdot 2 + 3}{3} = \frac{7}{3} = x_F^N(2) < 3 = w_F$  and

$x_L^N(2) = \frac{G^N(2)}{2} = \frac{7}{6} < 2 = w_L$ . Utility of country  $L$  is  $u_L^N(2) = \frac{7}{6} \cdot \frac{7}{3} = \frac{49}{18} = 2,72 < 2,78 = u_L^N(1)$ .

This confirms that country  $L$  does not want to adopt the improved public good production technology in the Nash case.

In the Stackelberg case country  $L$ 's optimal public good expenditure is  $z_L^S(2) = \frac{1}{4}$ , so that country  $L$  contributes  $g_L^S(2) = 2 \cdot \frac{1}{4} = \frac{1}{2}$  to the public good. Country  $F$  then reacts by choosing  $z_{RF}(g_L^S(2)) = z_F^S(2) = \frac{1}{2} \left( 3 - \frac{1}{2} \right) = \frac{5}{4}$ . An interior SE is obtained, in which total public good supply is  $G^S(2) = \frac{1}{2} + \frac{5}{4} = \frac{7}{4} = 1,75 > 1,67 = G^N(1)$ , which is higher than in the Nash game. Private good consumption of country  $L$  and country  $F$  in this SE are  $x_L^S(2) = w_L - z_L^S(2) = 2 - \frac{1}{4} = \frac{7}{4}$  and  $x_F^S(2) = w_F - z_F^S(2) = 3 - \frac{5}{4} = \frac{7}{4}$ , respectively. This equality of the private consumption levels, however, is a peculiarity of the special example. Utilities of both countries in the SE then are equal too, i.e.  $u_L^S(2) = u_F^S(2) = \left( \frac{7}{4} \right)^2 = \frac{49}{16} = 3,06 > 2,78 = u_L^N(1) = u_F^N(1)$ . This confirms that a Pareto improvement over the initial NE is attained.

Looking at  $u_L^S(2)$ , moreover, directly shows that country  $L$  will actually prefer the interior solution calculated just now over the two standalone solutions, which also are potential candidates for a SE: Country  $L$ 's utility in its own standalone allocation is  $\frac{w_L}{2} \cdot \frac{2w_L}{2} = 1 \cdot 2 = 2$  as in this case country  $L$  spends half of its income  $w_L$  on public good supply and its public good productivity is  $a = 2$ . In country  $F$ 's standalone allocation country  $L$  spends nothing on the public good so that its private consumption is  $w_L$  while country  $F$  spends half of its income  $w_F$ . Country  $L$ 's utility thus is  $w_L \cdot \frac{w_F}{2} = 2 \cdot \frac{3}{2} = 3$ .

## 6. Conclusion

In public good theory, it appears to be a common belief that leadership will aggravate the underprovision problem, which is a typical feature of non-cooperative public good provision and which also is of great empirical relevance with regard to global climate policy. Without leaving the standard framework of public good theory, this assertion, however, needs no longer to be true if the leading country can choose the technology, by which it generates its public good contribution. Rather, leadership may remove the obstacle, which could prevent

the application of a cost-saving abatement technology in the Nash game, and by application of this improved contribution technology, public good supply may become larger and utility of both countries may increase in the leader-follower game. It has been the central message of this paper that such a possibility exists. The example that confirms this result, moreover, has shown that this effect becomes more likely if the poorer country acts as a leader since the incentives to adopt the improved technology in the Nash case are particularly weak in this case.

For some rather tentative empirical application of our theoretical analysis look at China as an important player in global climate policy. In the process following the Paris agreement (and after political changes that happened most dramatically in the US but also in the EU), high hopes for a substantial progress in combating climate change are resting on this country, which by now seems to have adopted a leadership position in global climate policy. Statements by high-ranking Chinese representatives at the Davos meeting of the World Economic Forum in January 2017 are indicative of such a change of attitude (see, e.g., Tabuchi, 2017). In this context, a central role is attributed to the development and application of cost-saving abatement technologies like renewables, e.g. by asserting that China's "leadership had identified low-carbon technologies as the technologies of the future ..." (Hilton, 2016). For a further interpretation note that in 2015 China's total net national product has been 11 trillion Dollars, while that of the US was 60 percent more amounting to about 18 trillion Dollars. The fact that, somewhat paradoxically, leadership by the "poorer" country may be favorable for technological improvement complies with our theoretical results as we have shown that in the Nash case having a low income reduces a country's innovation incentives (see Proposition 1), while such a disincentive effect never occurs when this country acts as a Stackelberg leader (see Proposition 2). Against this background, we not only have shed some light on the relationship between leadership in public good provision and technological progress in general but also may have outlined some rationale for recent trends in global climate policy.

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