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Leadership and Climate Policy

Abstract

This paper examines leadership in relation to supplying a global public good. Both the Kyoto Protocol and the Paris Agreement encourage the developed countries to take a lead in reducing emissions. Does a country benefit from taking a lead? When does leadership improve global welfare? The answer depends on how transparent the leader's abatement technology is for the followers. When there is no transparency and the leader has to abate to signal the abatement cost, leadership reduces global welfare unless the crowding-out effect is weak. If there is transparency and the follower can benefit from technology spillover effects, leadership reduces global welfare unless the spillover effect is sufficiently large. I find that transparency reduces global welfare unless the spillover effect is sufficiently large and the difference in abatement cost is small. This theory can rationalize the European Union's stance on climate policy while also explaining the perceived failure of the Kyoto Protocol.

JEL-Codes: C720, D810, F500, H210, Q380, Q580.

Keywords: global public goods, international relations, leadership.

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1 Introduction

"*Developed country Parties shall continue taking the lead by undertaking economy-wide absolute emission reduction targets. Developing country Parties should continue enhancing their mitigation efforts, and are encouraged to move over time towards economy-wide emission reduction...*" The Paris Agreement, Article 4.2

Man-made climate change is a market failure on a global scale. An effective solution requires an international emissions reduction agreement, which has proved extremely challenging to accomplish. Even the celebrated Paris Agreement that has taken 16 years of the UNFCC[1] has avoided negotiating each country's abatement (Tulkens, 2016; Weitzman, 2016). Instead, Article 3.1 of the UNFCC encourages leadership by stating that the "developed country Parties should take the lead in combating climate change." Similarly, Article 4.2 of the Paris Climate Agreement encourages developed countries to lead. Against the background of the free-rider problem, this raises an important question about the motivation for and viability of leadership in global emissions reductions. Is leadership beneficial to the leader?

To examine the role of strategic leadership, this paper uses a model of private provision of public goods. Although the analysis applies to any global public good, it is best motivated by climate change. The leader, say a developed country, can abate first and restructure its industrial base. The follower, say a less developed country, can restructure its industrial base after or together with the leader. What motivates a country to transform its industrial base before others? What are the contexts that give rise to leadership as an equilibrium outcome? Does leadership raise the total abatement and help solve global problems?

This paper examines different incentives motivating a leader country to enact climate policies prior to a follower country, in the absence of international agreements. If the follower has limited information regarding an exogenous abatement cost, the developed country may benefit from abating a lot in advance to signal a low abatement cost. A commitment not to abate much, as in the Kyoto Protocol or the U.S. Senate's Byrd-Hagel Resolution in 1997, signals that the abatement cost is high. Thus, the leader can benefit from signaling low cost by strategically abating a lot before the follower abates. Moreover, in an equilibrium that survives the intuitive criterion refinement, the leader cannot commit to hiding the private information. Anticipating this, the follower will presume that the cost is high unless the leader is abating a lot in advance.

[1] United Nations Framework Convention on Climate Change.

Even when there is no private information regarding costs, the leader may benefit from abating a lot in advance if the leader's abatement induces an endogenous cost-reducing spillover effect. It abates a lot in advance to let the follower take advantage of the technological spillovers and abate more. In this case, leadership allows the follower to benefit from abatement cost savings, thus improving the overall efficiency. The leader abates more in particular when the abatement cost is high due to the spillover effect.

If spillover effects can occur under private information, signaling and spillovers lead to the largest level of abatement. However, in reality, the trade-off between exogenous and endogenous cost savings can be significant. If the leader allows "transparency," so that the follower observes and learns about the leader's abatement technologies, then there is less uncertainty regarding the abatement cost. By being more transparent, the leader avoids supplying the extra abatement necessary to credibly signal a low abatement cost. However, without transparency, the follower does not learn about the cost except through observed abatement. In this case, the leader must abate more to credibly transmit information regarding the low abatement cost. In fact, the leader would benefit from being transparent and facilitate spillover effects to avoid the extra cost necessary for a credible signaling. However, this is socially inefficient since the private supply of a public good is sub-optimal.

Whereas information transmission and cost reduction can induce leadership, leadership is not always motivated by these factors, which raise total abatement. If the leader's abatement crowds out the follower's abatement, the leader benefits from committing to a low abatement. If the follower's abatement cost is convex, the follower raises its abatement by a lower amount than the leader's reduction in abatement. In this case, leadership can exacerbate the under-provision problem. If there is private information regarding the abatement cost, the total abatement increases unless the crowding-out effect is complete. This is because not all of the leader's abatement that signals cost is crowded out. However, if the crowding-out effect is complete, it undermines the signaling effect. When the leader abates more to credibly signal a low cost, the follower takes advantage of the leader's extra abatement and reduces its own abatement. If the crowding-out effect is complete, the follower reduces its abatement by the exact amount the leader raises it to signal cost. Hence, leadership becomes a burden-sharing mechanism that does not raise the total abatement in comparison to no leadership.

The spillover effect changes the trade-off between the crowding-out and signaling incentives. In doing so, it changes the equilibrium outcome by suppressing the follower's incentive to reduce its abatement. Since the leader's extra abatement re-

duces the follower's cost through the spillover effect, the spillover effect complements signaling incentives. In this case, leadership raises the total abatement even when crowding-out completely neutralizes the signaling effect. I find that leadership does not improve global welfare unless the spillover effect is sufficiently large.

In addition, the results also explain some puzzling facts about the policy stances of different nations. For example, a remarkable event in global climate policy occurred when the U.S. Senate passed the Byrd-Hagel Resolution (1997). This Resolution, which states "the United States should not be a signatory to any protocol ... which ... would result in serious harm to the economy of the United States," committed the U.S. to low abatement. It is a puzzle as to why politicians decided to opt out of a problem that could not be solved without the involvement of the U.S. Joseph Stiglitz (2006: 4) attributes such a decision to a "flawed political system where campaign contributions from oil companies and others who benefit from emissions play such a key role," while Depledge (2005) attributes it to the structural features of the U.S. political system. However, this paper offers a distinct rationale that does not depend on a political market failure. Specifically, the crowding-out effect alone can explain such a stance even in political systems with little influence from special interests.

Moreover, it is a puzzle as to why the EU has decided to legally commit itself to abate 20% by 2020. Thomas Schelling argues that agriculture in a developed nation such as the United States, or most of Europe, accounts for less than 5 percent of the gross national product, and the potential effect of climate on income in the West is minuscule (Schelling, 1992, 2011). Others worry that if the EU supplies more abatement, other countries will find it beneficial to reduce their abatement, thus undermining the EU's abatement (Böhringer, 2014). As a result, Buchholz and Sandler (2017) resort to incorporating different types of psychological preferences and "ethical arguments" to explain the EU's ambitious commitment.

The strategic leadership idea provides two different hypotheses regarding Europe's, or California's, commitment to higher abatement. First, if the EU benefits from signaling a low abatement cost, then a commitment to higher abatement to credibly signal the cost is rational. In fact, this explanation is consistent with the observed low carbon prices associated with the 20% abatement goal in the EU emissions trading market (Koch et al., 2014). In addition to information transmission, the EU could have been motivated by the possibility of technology spillover. Following the implementation of the EU's abatement policy, the cost of generating electricity from solar and wind power has been decreasing (Wagner et al., 2015). In fact, Chinese producers have benefited from EU's abatement policy by acquiring the necessary technologies and skills to produce photovoltaic (PV) solar panels (De La Tour et al., 2011).

In addition to rationalizing the policy stances of countries, the results point to an alternative explanation regarding the perceived failure of the Kyoto Protocol in encouraging developing countries to abate more. According to Nordhaus (2015), the Kyoto Protocol with small emissions reductions by a few countries is the only *legally binding emissions reduction* agreement. Despite the protocol's low ambition and limited participation in the first round, the intention has been to raise participation and abatement in subsequent rounds (Grubb et al., 2003). Yet, both the number of participating countries and pledged abatement under the second commitment round has decreased (Kallbekken, 2015). Why has the protocol failed to raise the number of participants and the amount of pledged abatement?

Strategic leadership suggests that by committing to a 5% abatement target, which is small relative to the magnitude of the problem and the number of countries, the Annex-I coalition lost an opportunity to ignite the rise of technologies that could potentially reduce the abatement cost for the rest of the world. More importantly, the coalition's tiny commitment signaled that either the abatement cost is high or the benefit from abatement is low in contrast to the main intention and motivation of the protocol.

How do these results advance the literature?

The paper contributes to various strands of literature. First, the paper builds upon and extends the economics of leadership literature inspired by Holmstrom (1982), advanced by Hermalin (1998), and summarized in Hermalin (2012). Like Varian (1994), it focuses on the efficiency consequence of voluntary leadership in the private provision of public goods. The private provision of public goods literature starts with Samuelson (1954) that establishes the private supply of public goods is suboptimal due to the non-appropriability and free-rider problems.[2] Holmstrom (1982) explores the challenge of the free-rider incentive in a strategic environment.

Hermalin (1998) explores the problem in Holmstrom (1982) and establishes that leadership improves efficiency if motivated by signaling benefits.[3] Komai et al. (2007) and Komai and Stegeman (2010) have studied the importance of centralizing information in the hand of the leader to facilitate leadership through signaling. Brandt (2004) and Eskeland (2013) studied the implications of Hermalin (1998) in relation to climate policy. However, since Hermalin (1998) abstracts from the crowding-out effect,

[2]After Samuelson (1954), studies by Olson (1965), Bergstrom et al. (1986), Andreoni (1988), Hoel (1991), Varian (1994), Barrett (2010) and many others, not cited here due to space constraints, have examined the private supply of public goods in a strategic setup and explored the consequences of the crowding-out effect, which is absent in Samuelson (1954).

[3]The literature focusing on leadership and efficiency includes Acemoglu and Jackson (2015), Brandt (2004), Bolton et al. (2013), Eskeland (2013), Hermalin (2012), Hermalin (1998), and Stavins (2016).

Varian (2004: 15) suggests extending Varian (1994) to the case in which "leadership plays a role of signaling to the other agents" as in Hermalin (1998). The focus of this paper on the interaction between private information and crowding-out effects speaks directly to Varian (2004). Moreover, by introducing the crowding-out effect in Hermalin (1998), this paper examines a trade-off between the crowding-out and information transmission mechanisms. In particular, the paper shows that the crowding-out effect can reduce and even neutralize the information transmission effect. This is in direct contrast to Hermalin (1998) and Brandt (2004).

Moreover, this paper also advances the leadership literature that builds upon Varian (1994) in various directions. First, it extends Varian (1994) to situations that give rise to spillover effects. The paper shows that when spillover effects are present, leadership is not only beneficial to the leader, but it also raises the overall efficiency. This is because when a country abates first, both countries abate more compared to the alternative of abating simultaneously. This result is in direct contrast to Varian (1994: 165) who concludes that "the ability to commit to a contribution exacerbates the free-rider problem." Moreover, considerations of the spillover effect generate a trade-off between the crowding-out effect emphasized by Varian (1994) and the spillover effect that pushes abatement in the opposite direction from the crowding-out effect. In contrast to the literature, this paper demonstrates that the leader reduces its abatement when the abatement cost is low and raises its abatement when the abatement cost is high.

Furthermore, this paper examines the role of the interaction among the key drivers of the private supply of public goods, plagued by the free-rider incentive, by bringing together the information transmission, spillover, and crowding-out effects. Leadership, when all the three mechanisms are taken together, enhances efficiency whenever there is a spillover effect. Although the consequence of signaling for the total abatement can be neutralized entirely by the crowding-out effect, signaling amplifies the spillover effect and thereby raises the effect of spillover on efficiency. In equilibrium, with the three effects together, the leader commits to a high abatement to take advantage of the spillover effect when the cost is high and to signal the cost when the cost is low. Moreover, there is an equilibrium in which the follower alone supplies more abatement than the total abatement that the two would have supplied without leadership. These results supplement the literature by providing a theoretical argument for unilateral climate actions and uncovering insights that can explain why some countries might engage in a unilateral supply of a public good.

Second, the paper advances the literature on the role of transparency in leadership. In seminal papers, Komai et al. (2007) and Komai and Stegeman (2010) have

established the importance of centralizing information to facilitate leadership through signaling. Transparency can exacerbate inefficiency as information transmission under transparency requires no extra abatement. However, the spillover effect changes this result. In fact, in contrast to the leadership literature, I find that transparency improves welfare when spillover effects incentivize the follower to abate more when cost differences are small.

Third, unlike the leadership literature, this paper endogenizes the timing of abatement. This enables an analysis of the situations in which leadership in the private supply of public goods arises as an equilibrium outcome. In this sense, it builds upon industrial organization's optimal timing literature pioneered by Hamilton and Slutsky (1990)[4] and extends it to the context of public goods.

Fourth, the paper advances the unilateral climate policy literature pioneered by Hoel (1991) studying the effectiveness of a single country's abatement in solving a global problem.[5] If a country abates more than what is dictated by its pure self-interest and other countries partially crowd out their abatement, Hoel (1991: 69) concludes that "a unilateral emission reductions undertaken by one country need not help to solve global environmental problems." Varian (1994) discusses the same problem and asks if unilateral commitment improves efficiency when the crowding-out effect is complete. Varian (1994: 165) concludes that "the ability to commit to a contribution exacerbates the free-rider problem." This paper, in contrast, finds that considerations of spillover and information transmission incentives can reverse the conclusions. For example, I find an equilibrium in which the follower alone supplies more abatement under leadership when compared to the total combined abatement of both the leader and the follower without leadership.

The rest of the paper proceeds as follows. I outline a simple model of private contributions to the public good and state the notion of leadership in the context of private contributions to a public good in Section 2. Next, I examine various incentives for leadership. Afterwards, I investigate the implications of the interactions between different motives of leadership for the total abatement before the concluding discussion in the last section.

[4]These include Hindriks and Nishimura (2015), Schmidt and Strausz (2014), Amir and De Feo (2014), Normann (2002), Mailath (1993), and Gal-Or (1987).

[5]This literature includes Aghion et al. (2019), Buchholz and Konrad (1994), Coleman (2014), Eisenack and Kähler (2016), Harstad (2012), Helm and Wirl (2016), and Hémous (2016).

2 Basic Model

A public good, the global environment, is relevant for two countries. The emissions reduction or abatement of country i is x_i.[6] The best way to interpret abatement in the model is as a long-term restructuring, perhaps transformation, of a polluting industrial base to the one that is compatible with long-term environmental sustainability.

Both countries benefit from total abatement in the form of avoided economic and non-economic costs due to environmental degradation. These avoided outcomes include shifts in temperature and rainfall altering the intensity and frequency of hurricanes, droughts, heatwaves, reduce economic output, as well as increasing the sea level, risks of social and political unrest, etc. (IPCC, 2014). Thus, total abatement gives a benefit of $B\left(x_i + x_{-i}\right)$ with the properties $B''(.) \leq 0 < B'(.)$ to both countries. Supplying abatement involves a private abatement cost of $k_i C_i(x_i)$, which has properties of $C_i'(.) > 0$, $C_i''(.) \geq 0$, and $k_i > 0$. This cost can take many forms: the economic and social cost of restructuring the industrial base as well as the political cost of enacting and sustaining abatement policies. Country i's net-benefit function from abatement is given by

$$u^i\left(x_i, x_{-i}\right) = B\left(x_i + x_{-i}\right) - k_i C_i\left(x_i\right). \tag{1}$$

With respect to the timing of abatement, the private supply of public goods may or may not involve leadership. To be precise about leadership and clarify the difference from other interpretations of leadership in the literature, leadership in the private supply of abatement is defined as follows.

Definition. *Abatement is supplied under leadership if a country is a Stackelberg leader in supplying abatement. There is no leadership in abatement if countries abate simultaneously.*

A country is a leader (L) if it transforms its industrial base before the other. The country observing how much the leader has abated before it decides how much to abate is the follower (F).[7] This definition of leadership is similar to Acemoglu and Jackson (2015), Bolton et al. (2013), Eskeland (2013), Hermalin (2012), Hermalin (1998), and Stavins (2016).[8] In the absence of leadership, the two countries abate simultaneously.

[6] The country not i has a subscript of $-i$.

[7] The results in this paper generalize to many followers.

[8] Thus, the leader country does not have formal authority over the follower, in contrast to an other strand of literature relating leadership to authority, such as Ahlquist and Levi (2011), Bertrand and Schoar (2003), Besley et al. (2011), Chattopadhyay and Duflo (2004), Jones and Olken (2005), and Myerson (2011).

Since (1) is general, several applications fit the model despite being motivated by means of climate policy. One example is investments among members of a defense alliance such as NATO. NATO's common budget is financed through direct contributions with an agreed cost-sharing formula. However, most of its activities are financed through voluntary indirect contributions by its member states, which, in turn, depend upon a country's investment in national defense. Since each member state benefits from a collective defense, a member's investment in its own defense has a public good property. If a member state, such as the U.S., invests more to modernize its defense against terrorism, cybercrime, opportunistic invasions, and conquests, other member states benefit. Thus, x_i and x_{-i} can be interpreted as investments in national defense that constitute indirect contributions, whereas direct contributions are fixed to some positive constants.

3 Motives for Leadership

A crucial question regarding the incentives for leadership is: can a country, perhaps a more developed and innovative country with greater experience in various domestic environmental regulations, benefit from abating prior to a less innovative developing country? To examine the incentives for leadership and facilitate a comparison with the leadership literature inspired by Holmstrom (1982) and advanced in Hermalin (2012), I first follow Hermalin (2012) and assume that

$$B = v \sum_{i \in \{L,F\}} x_i. \tag{2}$$

It is important to note that this assumption abstracts from the *crowding-out property*, meaning, the property that the contribution from one country crowds out the contribution of another. Later, I extend (2) to take into account the crowding-out incentives. The following benchmark result is helpful for isolating the independent role of different motives for taking a leadership role.

Benchmark Result. *Suppose (2) holds and* $C_i''(.) > 0$. *An agent does not benefit from being the first to move. Moreover, leadership is efficiency-neutral.*

In the absence of leadership, agents abate simultaneously and the unique equilibrium solves

$$v = k_L C_L'(x_L^*) \text{ and} \tag{3}$$

$$v = k_F C_F'(x_F^*). \tag{4}$$

In the presence of leadership, abatements of the leader and the follower also satisfy (3) and (4) respectively. Thus, if the preference for public goods does not exhibit the crowding-out property, leadership makes no difference relative to no leadership. It also follows that each country's payoff does not change with leadership. Subsequently, leadership is both efficiency-and welfare-neutral.

The benchmark result points to an important insight – understanding leadership in the private supply of public goods requires additional incentives beyond free-riding without the crowding-out property. To this end, I extend the benchmark model in different directions to isolate and explore the consequences of various incentives for leadership.

3.1 Signaling Low Cost

Abating in advance can be crucial when there is private information that has to be conveyed in a credible manner. The costs include the economic and social cost of restructuring the industrial base or the political cost of enacting and sustaining abatement policies. The private information may concern the cost of one or more aspects of the restructuring process.[9] Emphasizing the importance of uncertainty regarding abatement costs, Stavins et al. (2007: 1–2) point out that "[in] particular, policies should be designed to account for uncertainty regarding emissions reduction costs, much of which will not be resolved before policies must be enacted."

Despite such uncertainty, the more developed country has better experience with abatement from prior environmental regulations. Examples include the EU's air quality management policies, the U.S. Clean Air Act (Schmalensee and Stavins, 2013), and Norway's International Climate and Forest Initiative (Tollefson, 2009). Since the more developed country has already addressed various domestic environmental problems, it is reasonable to assume that the more developed country is better informed about the abatement cost compared to a country lacking a similar experience.

The simplest way to isolate and capture the implication of this mechanism is by introducing private information in the benchmark model using (2) and assuming that costs are correlated. Suppose that only the leader knows the correct value of $k_i \in \{\underline{k}_i, \bar{k}_i\}$ such that $\underline{k}_i < \bar{k}_i$, and $\Delta_{k_i} \equiv \bar{k}_i - \underline{k}_i$. The follower's prior belief is $\Pr(k_F = \underline{k}_F) = \hat{\mu}$ and $\Pr(k_F = \bar{k}_F) = 1 - \hat{\mu}$. In addition, for $i \in \{L, F\}$, let

$$\hat{k}_i \equiv \hat{\mu}\underline{k}_i + [1 - \hat{\mu}]\bar{k}_i \tag{5}$$

[9]For example, Rodrik (1991) discusses uncertainties surrounding the economic cost and political acceptability of economy-wide industrial restructuring in a developing country. Rodrik (2014a: 478) "green technologies are subject to significant ex-ante uncertainty. The uncertainty may be due to unforeseen scientific and technological developments..."

and $x_i(k_i)$ solves

$$v = k_i C_i'(x_i). \tag{6}$$

In the absence of leadership, the Bayesian equilibrium involves that the follower abates $x_F(\hat{k}_F)$ whereas the high-cost type leader abates $x_L(\bar{k}_L)$ and the low-cost type leader abates $x_L(\underline{k}_L)$ that satisfies (6). Under leadership, abatement can signal the marginal cost being high or low. This, in turn, affects the follower's abatement through the posterior belief regarding abatement costs.[10] I restrict attention to the perfect Bayesian equilibrium (PBE) that survives the intuitive criterion refinement of Cho and Kreps (1987).[11]

If the value of k_F was known to the follower, optimal abatements would satisfy (6) for $k_i \in \{\underline{k}_i, \bar{k}_i\}$. Nevertheless, due to the leader's incentive to affect the follower's updated belief and the follower's ex-post updated belief, the optimal abatements may change under incomplete information. Under leadership, the leader can benefit if the follower abates $x_F(\underline{k}_F)$ instead of $x_F(\hat{k}_F)$, where $x_F(.)$ satisfies (6). In particular, the incentive can be strong if the high-cost type leader can benefit from imitating the low-cost type leader. When this is the case, a credible transmission of information requires a separating equilibrium.[12] Upon observing the leader's abatement, the follower updates its belief and its best response satisfies $v = \mathbb{E}[k_F]C_F'(x_F)$. The follower's abatement is higher when $\mathbb{E}[k_F] = \underline{k}_F$ than when $\mathbb{E}[k_F] = \bar{k}_F$ or when $\mathbb{E}[k_F] = \hat{k}_F$. In this case, the leader's abatement affects the follower's abatement only through the transmission of information regarding the abatement cost. In fact, the high-cost type leader prefers to mimic the low-cost type so that the follower abates a higher amount, believing that $k_F = \underline{k}_F$ instead of $k_F = \bar{k}_F$.

In any separating equilibrium, the leader's types choose different abatements. A separating equilibrium for two types has to satisfy two constraints that ensure separation. First, the high-cost type leader's net benefit cannot be higher than the net benefit it would have obtained if its true type was known to the follower. That is, for $x_F(.)$ that satisfies (6),

$$vx_F(\underline{k}_F) + vx_L - \bar{k}_L C_L(x_L) \leq \max_{x_L} \left\{ vx_F(\bar{k}_F) + vx_L - \bar{k}_L C_L(x_L) \right\}. \tag{7}$$

This constraint gives the lower bound for all separating strategy equilibrium abatements by the low-cost type leader. For $x_L(.)$ and $x_F(.)$ that satisfy (6), the constraint

[10] However, purposeful signaling is unnecessary only if the high-cost type does not find it beneficial to mimic the low-cost type leader and encourage the follower to supply higher abatement.

[11] The formal definition of PBE and the intuitive criterion adapted to the model is stated in the appendix.

[12] I do not focus on pooling equilibrium in the remainder of this paper since it does not involve transmission of information.

becomes

$$v[x_F(\underline{k}_F) - x_F(\bar{k}_F)] \leq \bar{k}_L[C_L(x_L) - C_L(x_L(\bar{k}_L))] - v[x_L - x_L(\bar{k}_L)]. \tag{8}$$

Intuitively, in any separating equilibrium, the high-cost leader's extra benefit from mimicking the low-cost type and convincing the follower to abate extra $v[x_F(\underline{k}_F) - x_F(\bar{k}_F)]$ is lower than the extra cost of deviating its abatement x_L from $x_L(\bar{k}_L)$; in other words, the optimal abatement in the absence of the incentive for mimicry. Let $\bar{x}_L$ be the high-cost type leader's abatement that makes the high-cost type leader indifferent between imitating the low-cost type leader and being truthful. In this case, $\bar{x}_L$ is the lowest amount the low-cost leader has to abate to credibly inform the follower that the cost is low. It is also the least-cost separating abatement. Note that information transmission requires higher abatement in comparison to no information transmission whenever $\bar{x}_L \geq x_L^*$ for $v = \underline{k}_L C_L'(x_L^*)$. If $\bar{x}_L$ is lower than x_L^*, then the complete information choice is sufficient for credibly conveying information.

Second, the low-cost type has to find it in its interest to engage in separating itself, which is why the low-cost type's net benefit in a separating equilibrium cannot be lower than its worst payoff:

$$vx_F(\underline{k}_F) + vx_L - \underline{k}_L C_L(x_L) \geq \max_{x_L} \left\{ vx_F(\bar{k}_F) + vx_L - \underline{k}_L C_L(x_L) \right\}. \tag{9}$$

Thus, constraints (8) and (9) define the lower and upper bound abatement for the set of separating equilibrium abatement for the low-cost type. The high-cost type chooses its truthful abatement. However, only the separating equilibrium with the low-cost type's abatement of $\bar{x}_L$ and the high-cost type's truthful abatement $x_L(\bar{k}_L)$ survives the intuitive criterion refinement.

In addition, in any pooling equilibrium, the follower abates $x_F(\hat{k}_F)$ that satisfies (6). Since $x_L(\underline{k}_L)$ is the abatement that maximizes $\{vx_L - \underline{k}_L C_L(x_L)\}$, the low-cost type leader's payoff from any pooling equilibrium cannot exceed the value $vx_F(\hat{k}_F) + vx_L(\underline{k}_L) - \underline{k}_L C_L(x_L(\underline{k}_L))$. Thus, the separating equilibrium satisfying the intuitive criterion is the unique equilibrium if the low-cost leader type's utility from the least cost separating equilibrium (i.e., $vx_F(\underline{k}_F) + v\bar{x}_L - \underline{k}_L C_L(\bar{x}_L)$) exceeds the value $vx_F(\hat{k}_F) + vx_L(\underline{k}_L) - \underline{k}_L C_L(x_L(\underline{k}_L))$. A sufficient condition that ensures the unique separating strategy equilibrium is:

$$v[x_F(\underline{k}_F) - x_F(\hat{k}_F)] \geq [vx_L(\underline{k}_L) - \underline{k}_L C_L(x_L(\underline{k}_L))] - [v\bar{x}_L - \underline{k}_L C_L(\bar{x}_L)]. \tag{10}$$

The condition in (10) states that the leader's extra benefit from getting the fol-

lower credibly informed in comparison to being uninformed has to be greater than the leader's net utility cost of abating more to get the follower credibly informed. The following proposition summarizes this result.

Proposition 1. *Suppose only the leader knows the correct value of k and conditions in (8), (9), and (10) hold. Then there exists a unique equilibrium that survives the intuitive criterion. The optimal abatement solves (6) when the abatement cost is high. If the abatement cost is low, the follower's abatement solves (6) whereas the leader's abatement is $\bar{x}_L$* (i.e., $\max\{\bar{x}_L, x_L(\underline{k}_L)\}$)*, where $x_L(\underline{k}_L)$ solves (6) given $k_L = \underline{k}_L$.*

The total abatement that signals cost under leadership is $x_F(\underline{k}_F) + \bar{x}_L$ whereas the total abatement without leadership from (6) is $x_F^*(\hat{k}_F) + x_L^*(\underline{k}_L)$. As long as extra abatement is necessary to signal cost, leadership improves efficiency in comparison to no leadership. Moreover, the low-cost leader's utility in the absence of leadership is $v[x_F^*(\hat{k}_F) + x_L^*(\underline{k}_L)] - \underline{k}_L C_L(x_L^*(\underline{k}_L))$. If (10) is satisfied, the leader is better off with abating first and signaling a low cost in comparison to its utility without leadership if the abatement cost is low. The following proposition summarizes these results.

Proposition 2. *If the leader has learned about the value of k_L before it chooses to abate and (10) holds, then the total abatement is higher with leadership than without leadership. The follower benefits from abating after the leader instead of abating simultaneously.*

The follower benefits from leadership for two reasons. First, the leader abates a higher amount to transmit information and this raises efficiency since abatement is undersupplied to begin with. Second, the information is valuable to the follower. Thus, leadership can arise in the presence of private information regarding the abatement cost. If the informed country has a choice to abate first, in any equilibrium that survives the intuitive criterion refinement, it cannot commit to not reveal cost. Thus, the uninformed country is better off abating second since it can still decide to ignore the information and abate on the basis of its prior information. If transmitting information does not require the informed country to incur extra distortionary abatement, the informed country prefers to abate before the uninformed country.[13] If transmitting information does require the informed country to incur extra distortionary abatement when the cost is low, then the uninformed country benefits from abating second in

[13]However, there is another equilibrium leadership in which the uninformed country abates first and the informed country second. Given that the uninformed country abates first, the informed country is indifferent between abating simultaneously and abating second. Given that the informed country abates second, the uninformed country is indifferent between abating simultaneously and abating first.

order to take advantage of the signaling-induced increase in abatement and the correct information. The informed country does not deviate to abate simultaneously if the extra cost for signaling is less than the marginal benefit arising when the uninformed country abates believing that the abatement cost is low.

3.2 The Spillover Effect

The benchmark result is based on the model in which the leader country's abatement does not affect the follower country's abatement cost. However, the abatement cost of a developing country can be affected by a developed country's abatement.

To begin with, there is very strong empirical evidence regarding technological spillover effects (Bloom et al., 2013). More so when it comes to environmentally cleaner technologies. Dechezleprêtre et al. (2014: 53) estimate using an econometric model and report that "knowledge spillovers from clean technologies appear comparable in scope to those in the IT sector." According to Wagner et al. (2015), the cost of silicon photovoltaic (PV) solar panels has fallen by 80% since 2008[14], and De La Tour et al. (2011: 761) write that "Chinese producers have acquired the technologies and skills necessary to produce PV products through two main channels: the purchasing of manufacturing equipment in a competitive international market and the recruitment of skilled executives from the Chinese diaspora who built pioneer PV firms."

To examine the consequence of the spillover effect, I extend the benchmark model by retaining complete information and allowing the possibility that the leader's abatement can induce reductions in the follower's abatement cost. Let the cost-reducing spillover effects change the follower's cost to $k_F[C_F(x_F) - \theta x_F x_L]$ such that $\theta > 0$.[15] In this case, the follower's utility function in (1) together with (2) becomes

$$u^F(x_L, x_F) = v \sum_{i \in \{L,F\}} x_i - k_F[C_F(x_F) - \theta x_F x_L]. \tag{11}$$

With leadership, the follower's optimal abatement solves:

$$v + \theta k_F \tilde{x}_L = k_F C_F'(\tilde{x}_F). \tag{12}$$

Comparing (12) with (4), it is clear that the follower abates more in response to the leader's higher abatement when cost-saving spillover is present. In addition, the leader chooses x_L by maximizing $B(x_L + x_F) - k_L C_L(x_L)$ while taking into account that its

[14] In addition, Bollinger and Gillingham (2014) estimate the learning-by-doing cost reductions and show the importance of international spillover effects in solar PV installations whereas Tang and Popp (2016) do the same in relation to wind turbine installations.

[15] This assumption regarding the spillover effect is standard since at least Spence (1984).

abatement raises the follower's abatement. The leader's optimal abatement solves:

$$v + \frac{\theta}{C_F''(\tilde{x}_F)} v = k_L C_L'(\tilde{x}_L). \tag{13}$$

Similarly, comparing (13) with (3) indicates that the leader commits to a higher abatement by taking into account the cost-saving spillover effects to the follower.

Without leadership, the benchmark result, (3) and (4), continues to hold. Thus, the total abatement with leadership (i.e., $\tilde{x}_L + \tilde{x}_F$) is higher than the total abatement without leadership (i.e., $x_L^* + x_F^*$). Moreover, the indirect utility functions under leadership are: $u^L(\tilde{x}_L, \tilde{x}_F) = v\tilde{x}_L + v\tilde{x}_F - k_L C_L(\tilde{x}_L)$ and $u^F(\tilde{x}_L, \tilde{x}_F) = v\tilde{x}_L + v\tilde{x}_F - k_F[C_F(\tilde{x}_F) - \theta\tilde{x}_F\tilde{x}_L]$. However, if both countries abate simultaneously choosing abatements in (3) and (4), the leader's indirect utility function becomes $u^L(x_L^*, x_F^*) = vx_L^* + vx_F^* - k_L C_L(x_L^*)$. It follows that $u^L(\tilde{x}_L, \tilde{x}_F) > u^L(x_L^*, x_F^*)$ since the leader chooses $\tilde{x}_L$ when x_L^* is possible with the follower's abatement $\tilde{x}_F$ being greater than x_F^*. To see that the follower benefits from leadership, note that the follower could have chosen x_F^* when the leader chooses a higher abatement $\tilde{x}_L$ and obtain a higher indirect utility than $u^F(x_L^*, x_F^*)$. If $\tilde{x}_F$ is chosen when x_F^* is available, then $u^F(\tilde{x}_L, \tilde{x}_F) > u^F(\tilde{x}_L, x_F^*) > u^F(x_L^*, x_F^*)$. The following proposition summarizes the consequence of introducing a cost saving spillover effect in the benchmark model.

Proposition 3. *If the leader's abatement can reduce the follower's cost according to (11), both the leader and the follower benefit from abating under leadership relative to abating without leadership.*[16] *Moreover, the total abatement is higher with leadership than without leadership.*

If the leader's abatement generates a cost-saving spillover effect that reduces the follower's marginal cost, the leader would abate more to let the follower take advantage of the cost-saving spillover effect and abate more. Even when the leader commits to its level of abatement without leadership, the spillover effect incentivizes the follower to abate more. This, in turn, raises the indirect utility of the leader, motivating it to abate first. Clearly, the spillover effect raises the total abatement, which is undersupplied to begin with, and thus improves efficiency.

It is important to note that spillover effects can also take the form of policy ideas

[16] If the cost-saving spillover effect reduces the follower's cost to such an extent that it is better to be a leader than a follower, a war of attrition type equilibrium might emerge. However, in reality there are extra trade-related benefits that make being the first mover more valuable. For example, Brandt (2004: 376) writes that "Austria, which, by strict environmental regulation through setting strict standards on SO_2, experienced export success due to the development of environmentally friendly technologies. Germany and the Netherlands followed Austrian regulation and Austrian exports flowed to Germany and the Netherlands in the years that followed."

that reduce the abatement cost. Rodrik (2014b: 194) underscores the importance of policy ideas as: "New ideas about what can be done – innovative policies – can unlock what otherwise might seem like the iron grip of vested interests." These types of innovative policies – such as emissions trading schemes and conservation contracts for tropical forests – have been tried first by a leader country and the successful ones are being adopted in the rest of the world (Stavins, 2016). The cost savings that non-innovating countries benefit from exemplify the role of technological spillovers.

To sum up, the economic theory of leadership in Hermalin (1998) and Komai et al. (2007) motivates leadership on the basis of private information. In this case, there is a fixed difference between a low abatement cost and a high abatement cost, and the leader may find it beneficial to credibly inform that the abatement cost is low. However, leadership can arise even in the absence of signaling.[17] In this case, for a given cost and rate of spillover effect, the leader's abatement reduces the initial cost. Thus, in the presence of incentives for transmitting information regarding a low abatement cost or cost-saving spillover, both the leader and the follower benefit from leadership in comparison to the case without leadership. Moreover, the total abatement increases with leadership compared to without leadership, meaning that leadership enhances efficiency.

3.3 The Spillover Effect with Cost Uncertainty

Since leadership can arise as an equilibrium outcome in the presence of signaling and spillover incentives, the consequence of the interaction between the spillover or signaling effects for efficiency is significant. To simplify the analyses of the interaction between the spillover effect and the information transmission incentive, I assume that costs in (1) and (11),

$$k_i C_i(x_i) = k_i x_i + (c/2)x_i^2, \text{ for } i \in \{L, F\}. \tag{14}$$

Otherwise, I continue with the same assumption regarding private information, equilibrium concept, and equilibrium refinement criterion as in the previous section.

Suppose the leader's abatement results in cost-saving spillover effects despite the abatement cost being known privately. In this case, the leader's abatement has two effects: it signals cost and it generates cost-saving spillover effects for the follower.

For a given x_L the follower observes, its best response is a function of posterior

[17] For example, the Porter hypothesis is one of the earliest motivation for leadership based on technology incentives Porter and van der Linde (1995) and Ambec et al. (2013).

belief and the spillover parameter:

$$x_F = \frac{v - \mathbb{E}[k_F]}{c} + \theta \frac{\mathbb{E}[k_F]}{c} x_L.$$

If the high-cost leader's true type is known to the follower and this is common knowledge, the high-cost leader's indirect utility becomes

$$\max_{x_L} \{v[\frac{v - \bar{k}_F}{c} + \frac{\theta \bar{k}_F}{c} x_L + x_L] - \bar{k}_L C_L(x_L)\} = v\frac{v - \bar{k}_F}{c} + \frac{[v - \bar{k}_L + \frac{\theta \bar{k}_F}{c}]^2}{2c}.$$

with the optimal abatement of $x_L = \frac{v - \bar{k}_L}{c} + \theta \frac{\bar{k}_F}{c} \frac{v}{c}$. After beliefs regarding the cost are updated, the follower's optimal abatement becomes $x_F = \frac{v - \bar{k}_F}{c} + \frac{\theta \bar{k}_F}{c}[\frac{v - \bar{k}_L}{c} + \theta \frac{\bar{k}_F}{c} \frac{v}{c}]$. Separation between the high-cost type and the low-cost type requires that the high-cost type's net benefit from successful mimicry cannot be higher than the net benefit it would have obtained had its true type been known to the follower. That is,

$$\frac{v}{c}(v - \underline{k}_F + \theta \underline{k}_F x_L) + (v - \bar{k}_L) x_L - \frac{c}{2} x_L^2 \leq \frac{v}{c}(v - \bar{k}_F) + \frac{[v - \bar{k}_L + \frac{\theta \bar{k}_F}{c}]^2}{2c}. \tag{15}$$

The least-cost separating strategy abatement binds (15). The following proposition summarizes the main result.

Proposition 4. *Suppose that the abatement cost is given by (14), the leader is privately informed about k_L, and $\hat{\theta} \equiv c\frac{v - \bar{k}_L}{\underline{k}_F + \bar{k}_F} + c\sqrt{[\frac{v - \bar{k}_L}{\underline{k}_F + \bar{k}_F}]^2 - \frac{2v\Delta_{k_F} - [\Delta_{k_L}]^2}{v\Delta_{k_F}[\underline{k}_F + \bar{k}_F]}}$. (i) There exists a unique separating equilibrium that survives the intuitive criterion refinement. (ii) In equilibrium, abatement is:*

$$\begin{aligned} x_L &= \frac{v - \bar{k}_L}{c} + \frac{\theta \bar{k}_F}{c} \frac{v}{c} \\ x_F &= \frac{v - \bar{k}_F}{c} + \frac{\theta \bar{k}_F}{c} x_L, \end{aligned} \tag{16}$$

when the abatement cost is high. If the abatement cost is low and $\theta \leq \hat{\theta}$, the abatement is

$$\begin{aligned} x_L &= \frac{v - \underline{k}_L}{c} + \frac{\theta \underline{k}_F}{c} \frac{v}{c} \\ x_F &= \frac{v - \underline{k}_F}{c} + \frac{\theta \underline{k}_F}{c} x_L. \end{aligned} \tag{17}$$

If the abatement cost is low and $\theta > \hat{\theta}$, the abatement is

$$\begin{aligned} x_L &= \frac{v-\underline{k}_L}{c} + \frac{\theta \underline{k}_F}{c}\frac{v}{c} + \frac{\sqrt{2v\Delta_{k_F} - \theta v \Delta_{k_F}[\frac{\theta}{c}\frac{v}{c}[\underline{k}_F + \bar{k}_F] + 2\frac{v-\bar{k}_L}{c}]} - \Delta_{k_L}}{c} \\ x_F &= \frac{v-\underline{k}_F}{c} + \frac{\theta \underline{k}_F}{c} x_L. \end{aligned} \tag{18}$$

(iii) Leadership enhances efficiency in comparison to simultaneous abatement.

Note that (16) implies that the spillover effect incentivizes the high-cost type leader to abate more. Moreover, (15) implies that by increasing the spillover parameter, imitating the low-cost type becomes more tempting. Thus, (18) implies that the low-cost leader must raise its abatement level even more, in comparison to the case in which the spillover effect is absent, to credibly signal that the cost is low.[18] The first term of $x_L(\underline{k}_L)$ is the amount of abatement under complete information that corresponds to (3), the second term captures the spillover effect under complete information, and the third term captures the interaction between the private information and spillover incentives. Even if the spillover effect complements signaling by making mimicry more tempting and raising the least-cost separating abatement, the interaction term highlights the deeper trade-off between exogenous cost-saving due to private information and endogenous cost-saving due to the spillover effects. The interaction term is decreasing in θ and this is intuitive – the importance of exogenous cost saving decreases if endogenous cost saving is high. Also note that the third term is always positive as long as the spillover effect does not reduce costs to zero. The extra abatement due to the interaction is efficient since abatement is inefficiently undersupplied to begin with. Thus, leadership motivated by the spillover and information transmission effects corresponds to the intuitive notion that a leader leads by *being an example* – doing more of what it wants its follower to do more of.

3.4 Leadership and Transparency

While signaling and spillovers lead to the largest level of abatement, in reality, the trade-off between exogenous and endogenous cost savings can be significant. If the leader allows "transparency", so that the follower observes and learns the leader's abatement technologies, then the uncertainty regarding the exogenous cost differences is absent. By allowing transparency, the leader avoids supplying the extra abatement necessary to credibly signal a low-cost. However, the follower does not learn from the leader and exploits spillover effects in the absence of transparency. In this case, the

[18] If $\theta < \hat{\theta}$, then $x_L(\underline{k}_L) = \frac{v-\underline{k}_L}{c} + \frac{\theta \underline{k}_F}{c}\frac{v}{c}$ and extra abatement is not necessary for signaling.

leader must abate more to credibly transmit information about the low-cost. Does the leader benefit from transparency? Is it good for the world? The following proposition summarizes the main result.

Proposition 5. *If the leader has to choose between a commitment to transparency and no transparency, the leader always prefers to commit to transparency. The leader's commitment to transparency reduces global welfare when the spillover effect is small, and it enhances global welfare whenever Δ_{k_F} is small.*

Proof. See the appendix.

The leader prefers transparency to avoid the cost of transmitting information, yet it reduces social welfare. The intuition as to why transparency can be counterproductive is as follows: with no transparency, the leader has to abate more to signal cost. The extra abatement raises total abatement, which is undersupplied to begin with. With transparency, the leader benefits from transparency since it avoids the cost of signaling and there is a spillover effect. When the spillover effect is low, both the leader and the follower abate less in total in comparison to the extra abatement to signal cost if there was no transparency. However, transparency improves social welfare if Δ_{k_F} is small. This is due to the extra abatement required to transmit information is lower.

4 Extension

The analysis so far has abstracted away from the crowding-out incentive. The crowding-out incentive induces the follower to reduce its abatement when the leader raises its abatement and vice versa. This reaction is due to the property $\frac{\partial^2 B(x_L+x_F)}{\partial x_L \partial x_F} < 0$, which manifests itself through carbon leakage arising from fossil fuel price changes and competitiveness in energy-intensive tradable goods if one broadens the mechanism to work through prices, for example in Hoel (1991) and Sinn (2012). The simplest way to capture the crowding-out effect and depart from the literature about the economics of leadership summarized in Hermalin (2012) is to add the term $-\frac{b}{2}[\sum_{i\in\{L,F\}} x_i]^2$ to (2):

$$B = v \sum_{i\in\{L,F\}} x_i - \frac{b}{2}[\sum_{i\in\{L,F\}} x_i]^2. \tag{19}$$

Even though the existence of the crowding-out incentive is a consequence of the strict concavity of $B(x_L + x_F)$, its strength is determined by the slope of the follower's marginal cost. The crowding-out effect is said to be complete (moderate) if the marginal cost of abatement is constant (increasing) in abatement and, subsequently,

the follower changes its abatement by the same (less than the) amount the leader changes its abatement.

4.1 Crowding-Out Effect and Leadership

A crucial question is whether the crowding-out incentive alone can motivate leadership. If so, what is the effect on efficiency? To isolate the role of the crowding-out incentive and answer these questions, I assume complete information and no spillover effect for the time being. These assumptions are relaxed in the next subsections.

Proposition 6. *Suppose $B(.)$ is given by (19), and the follower's abatement cost function has the property, $k_F C_F''(.) > 0$. Then an agent benefits from abating first. Moreover, the total abatement under leadership is strictly lower than the total abatement without leadership. If a country can choose abatement timing with and without leadership, there is no pure strategy equilibrium in which the countries abate with leadership.*[19]

Proof. In the absence of leadership, countries abate simultaneously and the unique equilibrium solves $v - b(x_L^* + x_F) = k_L C_L'(x_L^*)$ and $v - b(x_L + x_F^*) = k_F C_F'(x_F^*)$. Note that the marginal benefit from the public good to each country is always positive whenever the total abatement is less than v/b, which is the amount of total abatement a social planner would have chosen if abatement were to cost nothing. Thus, both countries abate a positive amount without leadership. Under leadership, the leader reduces its abatement from x_L^* to $\frac{k_F C_F''}{b+k_F C_F''}(v - b(\tilde{x}_L + x_F)) = k_L C_L'(\tilde{x}_L)$ and the follower's abatement solves $v - b(\tilde{x}_L + \tilde{x}_F) = k_F C_F'(\tilde{x}_F)$. Since the leader can commit to its abatement level without leadership, it cannot be worse off from being the first mover. In fact, by committing to a lower amount of abatement than the one without leadership, the leader incentivizes the follower to carry a higher burden of abatement and improve its own welfare. When the leader reduces its abatement to commit to a lower level, the follower raises its abatement by $\frac{dx_F}{dx_L} = -\frac{b}{b+k_F C_F''}$ as a result of the crowding-out effect. If $C_F'' > 0$ (i.e., the crowding-out effect is moderate), then the increase in the follower's abatement does not compensate for the decrease in abatement,meaning that the total abatement under leadership becomes lower than the total abatement under no leadership. Thus, a country benefits from being the first mover and leadership reduces efficiency when the crowding-out effect is moderate.[20]

[19]The result in this proposition is general and it can be proven for any concave function $B(.)$.

[20]The Byrd-Hagel Resolution (1997) is an example of a commitment not to abate a lot alone. The resolution can be understood as a commitment not to abate a lot alone in a crowding-out environment. There is a similar incentive issue in NATO. Allan Meltzer (2003: 19) writes that the U.S. "invested

The crowding-out effect that makes leadership beneficial for the leader is also the reason why there cannot be a leadership equilibrium. This is because in any sequential abatement, the follower abates more, yet obtains a lower benefit since the total abatement is lower than than it would have been had the leader and follower abated simultaneously. In the presence of the crowding-out incentive, both the leader and the follower find it in their interest to move first instead of abating sequentially. This is because the benefit of committing to a low abatement is way higher than the benefit of sharing the burden of abatement when abating simultaneously. Thus, no country prefers to follow given it can abate simultaneously. *Q.E.D.*

4.2 Crowding-Out Effect and Efficiency

After establishing that the crowding-out incentive alone can motivate leadership while also aggravating the undersupply problem, the next natural question is about how the crowding-out incentive interacts with the spillover and signaling incentives. Since abatement is undersupplied to begin with, the implication of the interaction for efficiency is relevant. To simplify the analysis of the interactions, I focus on a complete crowding-out incentive and a perfect correlation of costs (i.e., $k_i = k$).[21] Finally, to clarify the power of each mechanism, I present the interaction between the signaling and crowding-out effect before I introduce the spillover effect on top of the two incentives.

The crowding-out incentive undermines signaling. If there is no private information, the follower's best response is $\max\{(v-k)/b - x_L, 0\}$. Since the follower raises abatement by the amount the leader reduces it, the leader benefits from abating at a very low level to obtain the maximized utility of $(v^2 - \underline{k}^2)/(2b)$ when the cost is low and $(v^2 - \bar{k}^2)/(2b)$ when the cost is high. With private information regarding the abatement cost, however, the abatement signaling a low cost interacts with the crowding-out effect. In this case, the leader raises its abatement to signal cost although the leader has a motive to reduce its abatement to take advantage of the crowding-out incentive.

In a separating equilibrium, the follower's best response is $\max\{(v-\mathbb{E}[k])/b - x_L, 0\}$. The leader's higher abatement affects the follower's abatement in two ways. First, it

heavily not just in mounting defense but in developing military technology. Europeans, knowing that they would be defended, could give less than proportional effort... [They] limited their commitment to a smaller share than the United States of total spending on military weapons, manpower, and the development of weapons systems and technology."

[21] The result for a moderate crowding-out effect and/or imperfect correlation of cost is available from the author upon request.

induces the follower to raise abatement by Δ_k/b by credibly conveying information regarding the abatement cost. Second, when the leader's abatement increases, the follower is incentivized to reduce its abatement. If the cost difference is sufficiently high, then the leader abates more to benefit from information transmission, whereas if the degree of concavity of the utility function is large or if the cost difference is sufficiently low, then the leader abates less to take advantage of the crowding-out incentive.

Proposition 7. *Suppose the crowding-out effect is complete and there is no spillover effect. Then, there exists a unique separating equilibrium that survives the intuitive criterion refinement. The equilibrium abatement, when the cost is low, is:*

$$\hat{x}_L = \Delta_k[\bar{k} + \underline{k}]/[2b\bar{k}], \text{ and} \tag{20}$$

$$\hat{x}_F = [v - \underline{k}]/b - \hat{x}_L; \tag{21}$$

and, when the cost is high,

$$\hat{x}_L = 0, \text{ and}$$

$$\hat{x}_F = (v - \bar{k})/b. \tag{22}$$

The intuition is straightforward. In the presence of a crowding-out incentive, under complete information, both types would abate a low amount to obtain the maximized utility of $(v^2 - \underline{k}^2)/(2b)$ if the cost is low and $(v^2 - \bar{k}^2)/(2b)$ if the cost is high. However, under incomplete information, each leader's type benefits from abatement of $(v^2 - \underline{k}^2)/(2b)$ (and $(v^2 - \bar{k}^2)/(2b)$) if the follower believes that the cost is low (high) and abates on the basis of this belief. The least-cost separating abatement solves $(v^2 - \underline{k}^2)/(2b) - \bar{k}x_L = (v^2 - \bar{k}^2)/(2b)$. In an attempt to credibly signal information, the low-cost type would have to abate more than the amount under complete information. However, its effect on overall efficiency is minimal.

Proposition 8. *Suppose the crowding-out effect is complete, there is no spillover effect, and* $\mu \in (\bar{\mu}, 1]$ such that $\bar{\mu} \equiv \sqrt{[\underline{k}/(\Delta_k)]^2 + [\underline{k}/(\Delta_k)][\bar{k} + \underline{k}]} - \underline{k}/(\Delta_k)$. *Then, there exists a unique equilibrium that survives the Intuitive Criterion refinement. (i) In equilibrium, leadership does not improve efficiency in comparison with simultaneous abatement despite the higher abatement by the leader.*[22] *(ii) Similarly, leadership does not improve global welfare despite the leader's extra abatement.*

[22]However, if $\mu \in [0, \bar{\mu})$, *the least-cost pooling strategy is the unique equilibrium that survives the intuitive criterion refinement.*

Despite the leader's higher abatement, however, the crowding-out effect keeps the total abatement at the same level as the amount under complete information. Thus, introducing the full crowding-out effect not only reduces the positive signaling effect on total abatement, as discovered by Hermalin (1998), but also neutralizes the signaling effect even if the leader abates extra to signal a low cost. In this sense, a leadership driven by private information fosters abatement burden sharing without changing the total abatement.

The spillover effect complements signaling. After exploring the power of crowding-out incentives in undermining signaling, it is time to introduce the spillover effect in the trade-off between the signaling and crowding-out effects. If the abatement cost is high, there is no incentive to transmit information in a separating equilibrium. In this case, the interaction between the crowding-out effect and the spillover effect gives rise to a trade-off. The crowding-out effect incentivizes the leader to abate less, whereas the spillover effect incentivizes the leader to abate more. This trade-off induces the leader's abatement to balance the opposing incentives. The follower chooses its abatement to $\max_{x_F} \{B(x_F + x_L) - [1 - \theta x_L]kx_F\}$, and the best response becomes

$$x_F = \max\left\{(v - \bar{k})/b - x_L + (\theta\bar{k}/b)x_L, 0\right\}. \tag{23}$$

The best response captures the trade-off between the crowding-out effect $(v-\bar{k})/b-x_L$ and the spillover effect $\theta x_L\bar{k}/b$. If the value of $\max\left\{(v - \bar{k})/b - x_L + (\theta\bar{k}/b)x_L, 0\right\}$ is $(v - \bar{k})/b - x_L + \theta x_L\bar{k}/b$, then the relevant benefit to the leader from total abatement becomes $B(x) = [v^2 - [1 - \theta x_L]^2\bar{k}^2]/2b$. Thus, the leader's problem is reduced to $\max_{x_L}\left\{[v^2 - [1 - \theta x_L]^2\bar{k}^2]/2b - \bar{k}x_L\right\}$. Since the leader's benefit is concave in x_L, the first-order condition results in an interior solution, whenever $\bar{k} > b$,

$$[1 - \theta x_L]\bar{k} = b/\theta, \tag{24}$$

whose solution is given (25). The result in (24) is best understood using Figure 1.

If $b < \theta\underline{k}$, the leader abates an extra amount with the spillover effect in comparison to the case without the spillover effect. As can be seen from Figure 1, the extra abatement is higher if $\bar{k}$ is higher. If the cost is high but can be brought down with the spillover effect, then the leader abates more to reduce the abatement cost for the follower. This, in turn, results in a higher abatement by both the leader and the follower in comparison to the abatements when the cost is lower. This is because the leader finds it optimal to raise its abatement whenever the strategic benefit of a reduction in the follower's abatement cost is higher than the strategic cost of the

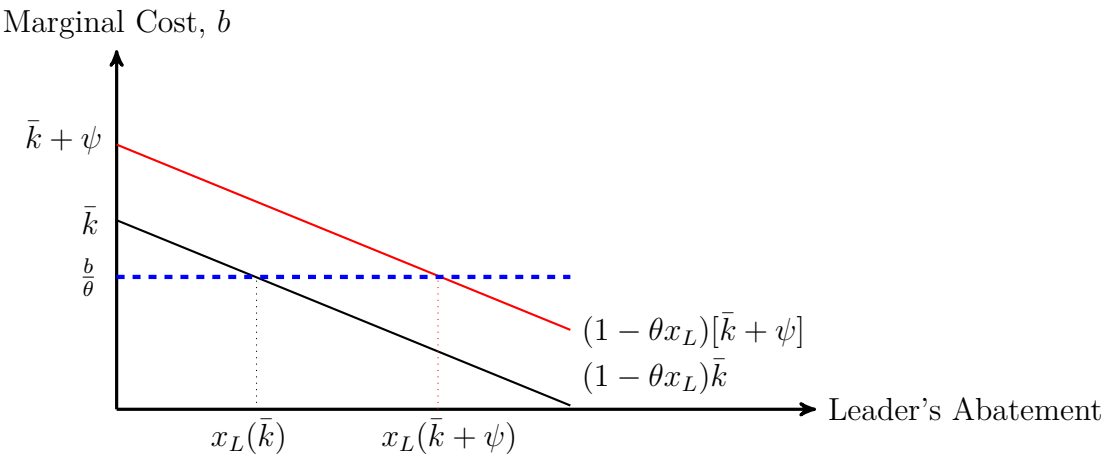

Figure 1: Leader's abatement in the presence of the crowding-out and spillover effects. The optimal abatement for a high (higher) abatement cost is $x_L(\bar{k})$ $[x_L(\bar{k}+\psi)]$.

crowding-out effect. The following proposition summarizes the main result of this section.

Proposition 9. *Suppose the crowding-out effect is complete and $b < \theta\underline{k}$. There exists a unique separating equilibrium that survives the intuitive criterion refinement. (i) The equilibrium abatement when the abatement cost is high is*

$$x_L^* = 1/\theta - b/(\bar{k}\theta^2), \tag{25}$$

$$x_F^* = [v-\bar{k}]/b + [\bar{k}/b - 1/\theta] - x_L^*. \tag{26}$$

(ii) The leader's abatement is strictly increasing in abatement costs.
(iii) The equilibrium abatement when the abatement cost is low and $\Lambda \equiv 1-(\underline{k}/\bar{k})^2$, is

$$x_L^{**} = 1/\theta - b/(\underline{k}\theta^2) + (b/\theta^2\underline{k})(\Delta_k/\bar{k} + (\sqrt{\Lambda}-\Lambda)\bar{k}/\underline{k}), \text{ and} \tag{27}$$

$$x_F^{**} = (v-\underline{k})/b + ((\theta\underline{k}-b)/b)x_L^{**}.^{23} \tag{28}$$

(iv) In equilibrium, each agent abates more under leadership than under no leadership. However, if $\theta \leq b/\bar{k}$, then (v)

$$x_L(k_i) = 0 \text{ and}$$

$$x_F(k_i) = (v-k_i)/b, \text{ for } k_i \in \{\bar{k}, \underline{k}\}, \tag{29}$$

and (vi) leadership does not improve global welfare.

[23] Normally, one expects that $x_L^* = max\{1/\theta - b/(\underline{k}\theta^2), 1/\theta - b/(\bar{k}\theta^2) + b\bar{k}(\sqrt{\Lambda}-\Lambda)/(\theta\underline{k})^2\}$. In this case, the inequality is clear. This is because, under complete information, the high-cost type abates more than the low-cost type due to the spillover effect (i.e., $1/\theta - b/(\underline{k}\theta^2) < 1/\theta - b/(\bar{k}\theta^2)$).

The follower's best response (23) to the leader's abatement (25) is given in (26). The second term of (26) shows that the follower raises its abatement due to the spillover effect, although it crowds out the leader's abatement as shown in the third term of (26). Thus, if the abatement cost is high, the key trade-off is between the spillover effect that induces the leader to abate more and the crowding-out and signaling effects that induce the leader to abate less. When the abatement cost is high and $\theta\bar{k} > b$, the total abatement under leadership is higher than the corresponding abatement without leadership for two reasons. First, the high-cost leader type abates a higher amount than compared to its simultaneous abatement. Second, the spillover effect reduces the follower's abatement cost and thus the follower also abates more net of what it crowds out. However, if the crowding-out effect dominates the spillover effect (i.e., $b > \theta\bar{k}$), then the results based on the crowding-out effect alone continue to hold and leadership does not improve efficiency.

The discussion so far has focused on the high-cost case. What if the abatement cost is low? In the separating equilibrium in which the abatement cost is low, all three effects give rise to two distinct trade-offs. In Propositions 7 and 8, it is shown that although the crowding-out effect incentivizes the leader to commit to low abatement, the presence of private information overrides this temptation and the leader abates a higher amount to credibly signal that the abatement cost is low. How does the spillover effect alter the trade-off between the crowding-out effect and the signaling effect? Note that the high-cost type leader has an incentive to mimic the low-cost type so that the follower abates more believing that the abatement cost is low instead of high. Credible information transmission calls for the low-cost type to abate at a sufficiently high level that the high-cost type would never rationally abate. The signaling effect incentivizes the leader to abate more (less) when the cost is low (high). However, the spillover effect incentivizes the leader to abate more (less) when the cost is high (low).

Focusing on the relevant case in which the follower supplies positive abatement, the follower's best response is $x_F = [v - [1 - \theta x_L]\mathbb{E}[k]]/b - x_L$. Accounting for the follower's best response, the leader's relevant benefit becomes $B(x_L) = [v^2 - [[1 - \theta x_L]\mathbb{E}[k]]^2]/2b$, which is a function of the follower's belief regarding cost and cost reduction due to the spillover effect.

With a low cost, the leader raises its abatement due to the signaling and spillover effects. The low-cost leader's abatement (27) has two different components: the first term is the amount of abatement the low-cost type would abate under complete information. The second term, which is an interaction of the three mechanisms, is the extra abatement the low-cost type has to supply to credibly convey its type. Since $\underline{k} < \bar{k}$, the second term is always positive. Quite intuitively, this extra abatement

decreases as $\underline{k}/\bar{k} \to 1$. Similarly, the extra abatement decreases if θ increases. This is because, from the follower's perspective, the exogenous difference in cost decreases as θ increases. Since the high-cost type abates more due to a higher spillover effect, it becomes increasingly more expensive for the low-cost type to distinguish itself from the high-cost type.

Similarly, the follower's abatement has an extra component, $(\theta\underline{k}/b)x_L^*$, when compared with the case without the spillover effect (21) . This component captures the reinforcement between the spillover and signaling effects as well as the drag due to the crowding-out effect undermining the reinforcement. Thus, first, in the absence of the spillover effect, the crowding-out effect neutralizes the signaling effect. Second, the spillover effect θ amplifies the signaling effect that implies a higher $x_L^*(\underline{k})$. Third, although the effect on efficiency is positive, the crowding-out effect b undermines it. Thus, if leadership is motivated by all three incentives and the abatement cost is low, then it improves efficiency in comparison to no leadership as long as $x_L^*(\underline{k})$ in (27) is positive.

Proposition 10. Let $\hat{\theta}(\underline{k}, b) \equiv b/\underline{k}$. *If* $\theta > \hat{\theta}(\underline{k}, b)$, *(i) The follower alone supplies more abatement than the total abatement that the two of them would have supplied without leadership. (ii) Leadership does not improve global welfare unless* $\theta > \hat{\theta}(\underline{k}, b)$.

Proof. (i) If $b < \theta\underline{k}$, then it follows that $(b/\theta) < \bar{k}$. This, in turn, implies that $(\bar{k} - b/\theta)^2 > 0 \Rightarrow (b/\theta)^2 - 2(b/\theta)\bar{k} + \bar{k}^2 > 0$, which, in turn, implies that $b/(\theta^2\bar{k}) - 2/\theta + \bar{k}/b > 0 \Rightarrow \bar{k}/b - 1/\theta > 1/\theta - b/(\theta^2\bar{k}) = x_L^*(\bar{k})$. Thus, $x_F^*(\bar{k}) > (v - \bar{k})/b$, and since without leadership, the total abatement is $x_F^* + x_L^* = (v - \bar{k})/b$[24], the follower alone under leadership abates more than the total abatement without leadership if $k = \bar{k}$. If $k_i = \underline{k}$, the leader supplies a positive abatement of $x_L(\underline{k}) = x_L^*(\bar{k}) + b\bar{k}(\sqrt{\Lambda} - \Lambda)/(\theta\underline{k})^2$. The follower's abatement is $x_F(\underline{k}) = (v - \underline{k})/b + (\theta\underline{k} - b)\, x_L(\underline{k})/b$, which is always greater than $x_F^* + x_L^* = (v - \underline{k})/b$ whenever $x_L(\underline{k}) > 0$ and $b < \theta\underline{k}$. *Q.E.D.*

With a complete crowding-out effect incentive, the leader commits to the minimum possible abatement. Nevertheless, despite the incentive to abate a low amount as a result of a complete crowding-out, the leader would abate extra due to the spillover effect if $\theta > \hat{\theta}(\underline{k}, b)$. If the leader commits to the extra abatement that generates the spillover effect, then the follower alone abates more than the total abatement the two of them would have supplied in the absence of leadership.

[24] Although there are multiple equilibria regarding individual abatement without leadership, all equilibria lead to a unique cost-contingent total abatement.

5 Concluding Discussion

In 2014, the *Wall Street Journal* hosted a debate on the topic: "Should the U.S. Take Unilateral Action on Climate Policy?" A similar question will continue to be raised in many countries in the absence of a global agreement with tight links between national abatements and the overall goal of limiting climate change. This paper has examined alternative incentives for a unilateral climate policy and their implications for efficiency. The results suggest that leadership is attractive for the first mover when the crowding-out, the spillover, or the signaling effects are present.

The crowding-out effect suggests that it was not irrational for the U.S. Senate to pass the Byrd-Hagel Resolution (1997) that committed the U.S. to not pursue abatement in federal policy. Although Stiglitz (2006) faults such decisions as special interest politics, the crowding-out effect – a commitment to avoid large abatements – provides a rational explanation for the American behavior.

Similarly, it has also been a puzzle in the literature as to why the EU has committed itself to reducing emissions by 20% from the emissions level in 1990 by 2020. The analysis of this paper can explain the commitment to significant unilateral abatement through technology spillover, signaling, or their interaction.

First, this bold abatement is justified if domestic regulations can make green technologies more profitable and this, in turn, reduces the abatement cost of the rest of the world.[25] The evidence due to Calel and Dechezleprêtre (2016) indicates that the EU's unilateral abatement has caused a 10% growth in low-carbon innovation. Focusing on Irish firms alone, Anderson et al. (2010: 1) find that "despite declining emissions prices and policy related uncertainty, 48% of responding Irish firms employed new machinery or equipment, 74% made process or behavioral changes, and 41% switched fuels to some degree that contributed to emissions reductions during the pilot phase [of the European Emissions Trading System]." Wagner et al. (2015) document that the cost of silicon photovoltaic solar panels has fallen by 80% since 2008. Although the diffusion of low-carbon innovation is too early to notice, there is some evidence that it is taking place. For example, De La Tour et al. (2011) argue that the Chinese have acquired the solar PV technology from Europe. Moreover, Dechezleprêtre et al. (2011) present compelling evidence that about 80% of the innovation of low-carbon

[25] In the context of California, which is committed to reducing its emissions to the 1990 level by 2020, Matthew Kahn (2010: 11) writes that if "California's entrepreneurs, universities, and state government incentives embedded in AB 32's implementation could generate new 'green tech' ideas, then these new approaches can be exported around the world and decouple economic growth and greenhouse gas production. I believe that AB 32 will accelerate green learning and experimentation, and some of the resulting ideas will be game changers." David Victor (2010: 6) also has similar expectations: " State actions help demonstrate that practical emissions controls are feasible and not overly costly. The states are also 'laboratories' where new ideas are tested."

technologies in 2000–2005 originates from Germany, Japan, and the United States and the rest of the countries are mainly adopters. Thus, bold unilateral abatement measures can induce technological spillovers that can reduce other countries' abatement costs.

Second, a bold abatement is justified if the EU is credibly signaling that the abatement cost is low. Indeed, the low carbon price in the emissions trading market for a 20% abatement path by 2020 is consistent with the signaling explanation. The EU ETS price per ton of CO_2 started high at €30 in 2008. However, it decreased to €3 in April 2013 and it has remained below €10. The main hypotheses for the low price are the deep economic crisis in the EU, CDM credits, and redundant policies. Yet, the ex-post econometric analysis of Koch et al. (2014: 684) concludes that " 90% of the variations of [EU allowance] price changes remains unexplained" by these candidate explanations regarding the low price. This suggests that abatement costs must have been low to begin with.

In addition, strategic leadership can explain the Kyoto Protocol's perceived failure to induce non-Annex I countries to reduce their emissions. The prevailing explanation, for example in Aldy et al. (2003), is that the protocol is plagued by the free-rider problem that manifested itself in participation and compliance problems. In this regard, Nordhaus (2015: 1339–1340) writes that: "the result of free riding is the failure of the only significant international climate treaty, the Kyoto Protocol, and the difficulties of forging effective follow-up regimes." In addition to the prevailing explanations, the strategic leadership approach suggests that the protocol's ambition is too weak to induce innovation and cost-saving spillover effects. Moreover, the fact that the Annex-I nations committed to a small abatement goal signaled to other countries that the abatement cost could be high.

Does leadership raise total abatement and enhance efficiency? This paper predicts that leadership can improve efficiency if spillover effects are possible. The natural next step is to empirically examine the predictions of the model. At the country level, one can consider the EU to be a leader and India or China a follower. At the state level, one can consider California as a leader and the remaining U.S. states as followers. Although establishing credible evidence regarding the motives for leadership has to be limited to anecdotal evidence, the effect on the efficiency of leadership is straightforward to test empirically. The analysis predicts that the covariance between the leader's abatement and the follower's abatement is negative if the crowding-out effect is the main driver of leadership. Otherwise, if the covariance is positive, then leadership enhances efficiency. This line of analysis is left for future research.

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Appendix

Definition of PBE and the intuitive criterion adapted to the model.

A set $\{(x_L, x_F) \in \mathbb{R}^2_+, \mu(\underline{k}_F \mid x_L) : x_L \to [0,1]\}$ forms a PBE for the leadership game if the following conditions are satisfied: (i) sequential rationality of the follower's strategy (i.e., $\tilde{x}_F(\mathbb{E}k_F) \equiv \arg\max_{x_F} \mathbb{E}u^F(x_F, x_L)$) and the leader's strategy (i.e., $\tilde{x}_L(k_L) \equiv \arg\max_{x_L} u^L(x_L, x_F)$). (ii) Consistency of beliefs on an equilibrium path:

$$\tilde{x}_L(\underline{k}_L) \neq \tilde{x}_L(\bar{k}_L) \Rightarrow \mu(\underline{k}_F \mid \tilde{x}_L(\underline{k}_L)) = 1 \ \& \ \mu(\bar{k}_F \mid \tilde{x}_L(\bar{k}_L)) = 0$$

$$\tilde{x}_L(\underline{k}_L) = \tilde{x}_L(\bar{k}_L) \Rightarrow \mu(\underline{k}_F \mid \tilde{x}_L) = \hat{\mu}.$$

Thus, PBE is defined by a set $x_L \in \mathbb{R}_+$, $x_F \in \mathbb{R}_+$ and $\mu(\underline{k}_F \mid x_L) : x_L \to [0,1]$ such that beliefs are consistent with Bayes' rule on an equilibrium path and the strategies are sequentially rational at every node given the belief system. Nevertheless, since PBE imposes no restrictions on the follower's beliefs off the equilibrium path of abatement, there is often a large number equilibria. I focus only on those PBEs that survive the Intuitive Criterion of Cho and Kreps (1987). Formally, following Fudenberg and Tirole (1991: 448–449), the intuitive criterion can be restated as follows. Fix a given equilibrium strategy and let $u^L_*(.)$ be the expected equilibrium payoff of the leader whose type is k', $k'' \in \{\underline{k}_L, \bar{k}_L\}$. For each leader's abatement $\check{x}_L$, let the best response $BR(k_L, \check{x}_L) = arg\max_{x_F} \sum_{k_L \in \{\underline{k}_L, \bar{k}_L\}} \mu(k_L|\check{x}_L) u^F(k_L, x_f + \check{x}_L)$ and the set $J(\check{x}_L)$ be the set of types in $\{\underline{k}_L, \bar{k}_L\}$ such that

$$u^L_*(k') > \max_{x_F \in BR(k_L, \check{x}_L)} u^L(k', \check{x}_L + x_F), \text{ and}$$

$$u^L_*(k'') < \min_{x_F \in BR(k_L \setminus J(\check{x}_L), \check{x}_L)} u^L(k'', \check{x}_L + x_F),$$

then the equilibrium fails to survive the intuitive criterion. That is, $J(\check{x}_L)$ is the set of types that obtain less than the equilibrium payoff by abating $\check{x}_L$ given that the follower does not choose a dominated abatement. The equilibrium fails to survive the Intuitive Criterion if there exists a leader type that would necessarily obtain a higher utility by abating $\check{x}_L$ than in equilibrium.

Proof of Proposition 5. If the leader commits to transparency, the optimal abatement of both countries becomes

$$x_L = \frac{v - k_L}{c} + \frac{\theta k_F}{c} \frac{v}{c}$$

$$x_F = \frac{v - k_F}{c} + \frac{\theta k_F}{c}\left(\frac{v - k_L}{c} + \frac{\theta k_F}{c}\frac{v}{c}\right).$$

Moreover, the indirect utility of the leader and the follower becomes

$$u_T^L = \frac{v}{c}(v - k_F) + \frac{1}{2c}\left(v - k_L + \theta k_F \frac{v}{c}\right)^2.$$

Recalling that $\hat{k}_i \equiv \hat{\mu}\underline{k}_i + (1-\hat{\mu})\,\bar{k}_i$, the leader's ex-ante expected utility from committing to transparency is

$$\mathbb{E}[u_T^L] = \frac{v}{c}(v - \hat{k}_F) + \frac{\hat{\mu}(v - \underline{k}_L + \theta\underline{k}_F\frac{v}{c})^2 + (1-\hat{\mu})(v - \bar{k}_L + \theta\bar{k}_F\frac{v}{c})^2}{2c}. \tag{30}$$

Let

$$\phi \equiv v\frac{2v - \hat{k}_F - \hat{k}_L}{c} + \frac{\hat{\mu}((v-\underline{k}_L)^2 + (v-\underline{k}_F)^2) + (1-\hat{\mu})((v-\bar{k}_L)^2 + (v-\bar{k}_F)^2)}{2c}, \tag{31}$$

then the ex-ante expected welfare from committing to transparency is

$$\begin{aligned}
\mathbb{E}[W_T] \;=\; & \phi + \hat{\mu}\theta\underline{k}_F[(\frac{v}{c})^2 + \frac{v}{2c}\frac{v-\underline{k}_L}{c} + \frac{v-\underline{k}_L}{c}\frac{v-\underline{k}_F}{c}] \\
& + (1-\hat{\mu})\theta\bar{k}_F[(\frac{v}{c})^2 + \frac{v}{2c}\frac{v-\bar{k}_L}{c} + \frac{v-\bar{k}_L}{c}\frac{v-\bar{k}_F}{c}] \\
& + \hat{\mu}(\frac{\theta\underline{k}_F}{c})^2[v(\frac{v-\underline{k}_F}{c}) + \frac{v^2}{2c}] + (1-\hat{\mu})(\frac{\theta\bar{k}_F}{c})^2[v(\frac{v-\bar{k}_F}{c}) + \frac{v^2}{2c}] \\
& + \frac{\hat{\mu}(\frac{\theta\underline{k}_F}{c}(v-\underline{k}_L) + (\frac{\theta\underline{k}_F}{c})^2 v)^2}{2c} + \frac{(1-\hat{\mu})(\frac{\theta\bar{k}_F}{c}(v-\bar{k}_L) + (\frac{\theta\bar{k}_F}{c})^2 v)^2}{2c}.
\end{aligned} \tag{32}$$

On the other hand, if the leader commits to no transparency, the best response of the follower is $x_F = \frac{v - \mathbb{E}[k_F]}{c}$ after observing the leader's abatement and updating its belief. In any separating equilibrium, each type chooses a different abatement. Separation requires that the high-cost type's net benefit cannot be higher than the net benefit it would have obtained if its true type was known to the follower. This constraint gives the lower bound for all separating strategy equilibrium abatements by the low-cost type leader. If the lower bound is higher than the low-cost type's abatement under complete information, then the complete information choice is fully separating. If it is lower, it takes extra abatement to signal cost. This requires that $v > \frac{(\Delta_{k_L})^2}{2\Delta_{k_F}}$ for the lower bound for the set of separating strategy equilibria is given by the above constraint. If $v > \frac{(\Delta_{k_L})^2}{2\Delta_{k_F}}$, then there exists a unique separating equilibrium that survives the Intuitive Criterion. Abatement is given by $x_F = \frac{v - \underline{k}_F}{c}$

and $x_L = \frac{v-\underline{k}_L}{c} + \frac{\sqrt{2v\Delta_{k_F}}-\Delta_{k_L}}{c}$ if the abatement cost is low and $x_F = \frac{v-\bar{k}_F}{c}$ and, $x_L = \frac{v-\bar{k}_L}{c}$ if the abatement cost is high. The leader's ex-ante expected utility from committing to no transparency is:

$$\mathbb{E}[u^L_{NT}] = \frac{v}{c}(v-\hat{k}_F) + \frac{\hat{\mu}\,(v-\underline{k}_L)^2 + (1-\hat{\mu})(v-\bar{k}_L)^2 - \hat{\mu}(\sqrt{2v\Delta_{k_F}} - \Delta_{k_L})^2}{2c}. \quad (33)$$

Ex-ante expected welfare from committing to no transparency

$$\mathbb{E}[W_{NT}] \;=\; \phi + \frac{\hat{\mu}[(\sqrt{2v\Delta_{k_F}} - \Delta_{k_L}) - \frac{(\sqrt{2v\Delta_{k_F}}-\Delta_{k_L})^2}{2}]}{c}. \quad (34)$$

Comparing (30) with (33), one can notice that the leader always benefits from transparency. Moreover, comparing (32) with (34), one can also notice that transparency reduces global welfare when $\theta \to 0$ and it enhances welfare when $\Delta_{k_F} \to 0$. *Q. E. D.*