Transboundary pollution, clean technologies and international environmental agreements

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This chapter reviews recent developments on the analysis of the impact of clean technologies on the outcome of transboundary pollution games and on the size of stable environmental agreements. It is shown that given a fall in the emission-output ratio, countries may respond by increasing their emissions resulting in an increase in pollution stock and decrease in welfare. This rebound effect happens when the damage and/or the initial stock of pollution are relatively large and when the natural rate of decay of pollution is relatively small. This implies that clean technologies may not be a substitute for cooperation on mitigation.

The impact of cleaner technologies on the success of environmental agreements is then analyzed when countries are farsighted. In the case of three groups of countries, the grand coalition may be destabilized by the implementation of cleaner technologies, ultimately resulting in higher global emissions and lower global welfare. In the case of more than three countries, implementing cleaner technologies may result in a discrete jump, either upward or downward, of the largest stable coalition size and welfare.
1.1 INTRODUCTION

The development and diffusion of cleaner technologies to curb transboundary pollution has gained importance in recent years in light of the international policy debate surrounding climate change. In order to avoid the possibility of catastrophic environmental consequences, climate experts have proposed that the increase in average global temperature should be restricted to about 2°C, which requires stabilizing the concentration of greenhouse gases in the atmosphere at about 450 ppm CO₂ equivalent. On the one hand, some climate scientists claim that this can only be achieved by developing and implementing "breakthrough" technologies that reduce emissions dramatically (see, for example, [1], [2]). On the other hand, some claim that there already exists a portfolio of technologies owned by corporate institutions in developed countries, and that stabilization of the concentration of greenhouse gases requires the global diffusion and adoption of such technologies (see, for example, [3], [4]). While the benefits from more effective adaptation technologies are, in most cases, restricted to the countries/regions implementing them, those from more efficient mitigation technologies that cause discrete reductions in emissions have global benefits. The latter type of technologies, therefore, is a public good, such that the globally efficient level of R&D to develop such technologies can only be achieved through international cooperation on sharing the costs of R&D.¹ Both types of technologies, that is, more efficient mitigation and adaptation technologies, may, once adopted, affect the incentives of countries to cooperate on emission reduction by reducing the environmental damage associated with each unit of production or consumption.

Within this context, there arise several important policy relevant issues, some of which have been analyzed in the academic literature. This chapter summarizes the findings of existing studies analyzing the following questions: (i) Under what conditions is international cooperation on sharing costs of developing clean technologies likely to result in stable environmental agreements involving a large number of countries, leading

¹International organizations attempt to facilitate such international cooperation on cost sharing. For example, according to the UNFCCC, "the developed country Parties and other developed Parties included in Annex II shall take all practicable steps to promote, facilitate and finance, as appropriate, the transfer of, or access to, environmentally sound technologies and know-how to other Parties". http://unfccc.int/cooperation_and_support/technology/items/1126.php
to the globally efficient level of R&D? (ii) How do international environmental agreements (IEAs) on emission reduction affect the non-cooperative level of R&D and clean technology adoption? (iii) How do the adoption of cleaner mitigation and adaptation technologies affect the non-cooperative level of pollution stock and welfare, and the stability of IEAs on emission reduction?

These questions gain importance in light of recent decisions by policy makers worldwide to fund cleaner technologies. In the United States (US), the American Recovery and Reinvestment Act of 2009 included more than $70 billion in tax credits and direct spending for programs involving clean energy and transportation. According to The Economist (8 March 2014), Bloomberg New Energy Finance, a research firm, estimates that the clean-technology market in China exceeded $60 billion. Moreover, China’s carbon intensity, that is, emissions per unit of GDP has fallen by about 20% in the past five years and the government is aiming to cut it by 40-45% by 2020, compared with 2005. In the European Union (EU), the European Commission Directorate-General CLIMA’s NER300 funding program provides substantial funding for the large-scale adoption of low carbon energy technologies in Europe and is the world’s largest programme in this area. The European Commission’s goal is to increase the share of renewable energy to at least 27% by 2030, in line with its target to reduce EU domestic greenhouse gas emissions by 40% below the 1990 level by 2030. International organizations, such as the United Nations (UN), are also actively encouraging countries to fund the development of clean technologies. In 2009, the UN Environmental Program urged countries to allocate one third of the $2.5 trillion planned stimulus package (spent by the developed world to boost the economy under the financial crisis) for investing on ‘greening’ the world economy. The G8 summit held in July 2009 included a commitment by the members

\[\text{During the past five years in the US, wind and solar power use has more than doubled, accounting for 4.4 percent of the US electricity generation mix combined, up from just 1.9 percent in 2009. For more details, please refer to http://www.americanprogress.org/issues/green/report/2014/04/03/87092/galvanizing-clean-energy-investment-in-the-united-states/}\]


\[\text{For further details, please refer to http://ec.europa.eu/clima/policies/2030/index_en.htm}\]
to double public investment in the research and development of climate-friendly technologies by 2015. The agreement at the COP16 meeting held in Cancun in December 2010 includes a "Green Climate Fund" proposed to be worth $100 billion a year by 2020, to assist poorer countries in mitigating emissions, partially by financing investments in clean technologies (UNFCCC Press Release, 11 December 2010).

Given the investments being made by taxpayers and private enterprises of developed as well as developing countries, and by international organizations, it becomes important to analyze whether international cooperation may ensure that aggregate global expenditure on developing clean technologies corresponds to the globally efficient level. In the absence of an international agreement on R&D, how do private sector firms and governments adjust their R&D levels if an IEA on emission reduction is impending? Once clean technologies become available and widely adopted, what will be the impact on individual countries’ incentives to emit transboundary pollutants such as greenhouse gases? Section 2 summarizes the existing literature that addresses these questions. Section 3 presents, in more detail, our related work in [5], which examines the latter question within a transboundary stock pollution model where the transboundary pollutant accumulates into a stock over time, to reflect the case of greenhouse gases. Section 2 also summarizes the existing literature examining individual countries’ incentives to participate in international agreements designed to mitigate emissions of greenhouse gases if cleaner technologies are adopted globally. Finally, Section 4 discusses, in more detail, our related work in [6]. Specifically, we analyze the impact of the adoption of cleaner technologies on equilibrium emissions and welfare taking into account the impact the change in technology has on the size of a stable coalition formation.

1.2 LITERATURE REVIEW
The related literature may be divided into three main categories. The first examines the incentives of countries to participate in international agreements to share the cost of developing clean technologies. The second examines the incentives of countries to undertake R&D of cleaner technologies non-cooperatively, while anticipating the formation of an IEA on emission reduction. The third examines the incentives of countries to participate in international agreements to reduce emissions, given the implementation
of cleaner technologies.

1.2.1 International cooperation on R&D of clean technologies

The first category includes [7], [8], [9] and [10]. [7] considers a sequence of treaties: the first on cooperative R&D, and the second on collective adoption among the signatories of a breakthrough technology that causes emission of the transboundary pollutant to decrease discretely, emerging from the R&D undertaken in the first stage. He finds that, unless the technology adoption involves increasing returns in the form of network externalities, cooperation on R&D is only successful when the gains from cooperation are low, similar to the result derived in earlier studies on cooperation on emission reduction (see, for example, [11], [12]). This is because countries foresee that, in the second stage, one of two possibilities will arise. If the cost of adoption is sufficiently high, not many countries will adopt the technology, leading to low returns on the R&D investment. If the cost of adoption is sufficiently low, then despite many countries adopting the technology, the gains from cooperation will be low.

While [7] assumes a fixed cost of technology adoption, [9] allow the cost of adopting the cleaner technology in the second stage to vary inversely with the level of R&D undertaken in the first stage. This reflects the scenario where the higher the level of R&D, the lower the expected future costs of using this technology. According to [9], this scenario is applicable to Carbon Capture and Storage (CCS) and developing small batteries for electrical cars. Under these conditions, they find that, in contrast to [7], large coalitions which lead to substantial gain over the non-cooperative outcome can be stable. One of two outcomes occur in equilibrium. Either, an IEA forms where coalition members invest more in R&D, to compensate for the fact that the non-members free-ride on this investment, in order to benefit from the lower cost of adoption associated with R&D. Or, an IEA forms where coalition members invest less in R&D, but which is large enough to yield substantial gains from cooperation by avoiding overinvestment in R&D that would occur in the non-cooperative equilibrium.

[10] build on this work by introducing heterogeneity across countries in terms of the marginal damage from emissions. The countries that value emission reduction the most will have a greater incentive to cooperate on R&D, knowing that once the cleaner
technology is developed, it may be adopted by non-members as well - thereby mitigating emissions. These results suggest that even small coalitions may be successful in reducing global emissions significantly, and thereby improving global welfare. There may also exist equilibria where only some of the coalition members abate although all coalition members share the cost of R&D. These members have an incentive to participate in the IEA in order to benefit from other coalition members’ adoption of the cleaner technology which leads to lower emissions.

1.2.2 Non-cooperative R&D of clean technologies and IEAs on emission mitigation

The second stream of the literature examines non-cooperative investment in R&D of cleaner technologies when an IEA on emission reduction is impending. [3] examines the incentives of private sector firms to invest in R&D when they anticipate the formation of an IEA on emission reduction. They build on the basic framework presented in [7], but without allowing for international cooperation on R&D. Instead, [3] allows for the existence of international intellectual property rights, IPRs, that are perfectly enforceable (similar to those that are granted by trade-related intellectual property rights, TRIPS), enabling the patent holder to charge a license fee for the abatement technology after members and non-members of the IEA have decided on their abatement commitment. The greater the abatement level committed to by the IEA, the less elastic the demand for the cleaner technology, and the higher the license fee that the patent holder is able to charge. Anticipating this, fewer countries join the IEA, and those that join commit to a lower level of abatement than in the absence of IPRs. This, in turn, reduces demand for the cleaner technology, making it less profitable for the innovator to invest in R&D in the first place, despite the fact that development of the cleaner technology would improve global welfare. [3] labels this as the "climate holdup problem" caused by IEAs on emission mitigation.

Other papers to contribute to this topic include [13], who find that individual countries underinvest in R&D if they foresee an IEA on emission reduction in the future. This is because each country has an incentive to commit to dirty technologies so as to shift the burden of abatement to countries with cleaner technologies once the IEA is
signed. [14] shows that when the size as well as length of the IEA are endogenous, such hold up problems may act as a credible threat, thereby reducing the incentive of individual countries to free-ride on the IEA. [15], rather than focusing on R&D, analyzes the incentives for polluting firms to diffuse and adopt cleaner technologies in a framework in which governments negotiate an international environmental agreement on emission reduction. They find that these incentives depend on whether the underlying environmental policy instrument is an emission tax or an emission standard. In contrast to a national setting, where emission taxes are typically found to provide a greater incentive to firms to adopt a more efficient abatement technology than an emission standard, within the international setting, they find that the opposite may hold.

1.2.3 Adoption of clean technologies and stability of IEAs on emission mitigation

The third stream of the literature examines the change in the incentive of countries to join IEAs on emission mitigation when they adopt cleaner technologies. [16] builds on the IEA of [11] by allowing countries to endogenously choose both emission and abatement levels, rather than only one of the two, as has been the case in most of the existing IEA literature. They find that, within this setting, a lower marginal cost of abatement, which can be interpreted as the adoption of a cleaner technology, increases the number of signatories in the stable coalition. Another paper to come to this conclusion is [17]. [17] uses a non-parametric approach to modeling each country’s gain from joining the IEA, without relying on a convex marginal abatement cost function, as has been assumed in most of the existing IEA literature. Moreover, they consider cleaner technologies that globally reduce marginal abatement cost, similar to [16], whereas most other papers consider technological innovations that reduce total abatement costs, while increasing marginal abatement costs over some range of abatement levels. Within this setting, they find that reductions in marginal abatement costs increase equilibrium membership of the IEA. [16] and [17], in line with majority of the existing IEA literature, use the internal and external stability criteria, as presented by [18] to evaluate coalition stability, by which a given coalition is said to be stable if no member has an incentive to unilaterally leave the coalition, taking as given other members’ participation, and no non-member
has an incentive to unilaterally join the coalition. By contrast, [6] use the "farsighted" stability criteria, by which each country takes into account how its provisional decision to join or leave the coalition would affect others’ participation decisions.\textsuperscript{6} [6] find that, when countries are farsighted, the adoption of a cleaner technology may result in smaller stable coalitions. A detailed summary of this paper is presented in Section 4.

The papers mentioned thus far in the literature review focus on abatement technologies. There is a separate stream of the literature that examines the role of adaptation technology. More efficient adaptation technology includes liming of lakes to counter acidification, building levees to prevent floods, or designing effective flood evacuation programs, on the incentive of countries to participate in IEAs.\textsuperscript{[23]} consider the case of two countries and examine the impact of a unilateral improvement in productivity and adaptative capacity. Adaptation expenditures reduce the damage from emissions and an improvement of adaptative capacity is captured by the fact that a given expenditure on adaptation results in a larger decrease in damages from pollution. They separately consider the impact of a change in adaptative capacity on the non-cooperative and the cooperative equilibrium. It is shown that such improvements result in larger emissions both locally, in the country where the adaptative capacity increases, and globally. Under the non-cooperative behavior, the increase in emissions may even result in a decrease in global welfare. \textsuperscript{[24]} consider the impact of a global improvement of adaptative capacity on the incentive to free ride on an agreement and on the gains from a global agreement between any given number of countries. It is shown that a more efficient adaptation technology diminishes the incentive of individual countries to free-ride on a global agreement over emissions. The more efficient is adaptation at reducing marginal damage from emissions, the less aggressive each country is in its emission strategy. The reasoning is as follows. In the absence of adaptation, in response to an increase in other countries’ emissions, the only option available to a given country is to decrease its own emissions through regulation. In the presence of adaptation, however, when other countries increase emissions, the given country may, instead of reducing its own emissions, decrease its own damage by increasing adaptation. The greater the efficiency

\textsuperscript{6}Other papers to apply the concept of farsightedness to IEAs include [19], [20], [21] and [22]. These papers do not allow for the adoption of cleaner technologies.
of the adaptation technology, the greater the substitutability between mitigation and adaptation in response to changes in the level of others’ emissions. Thus, the more efficient is adaptation at reducing marginal damage from emissions, the less aggressive each country is in its emission strategy, and therefore, the lower the gap between the global emission levels under non-cooperation and under full cooperation, making it less costly to cooperate on emission strategies. In [24], the lower incentives of individual countries to free-ride on a global agreement over emissions coincide with greater gains from cooperation. This is an optimistic result, in contrast to the result in most of the IEA literature (see, for example, [11]). Since the cost of adaptation is assumed to be convex in the level of adaptation, failing to reach a cooperative equilibrium on emissions increases the cost to each individual country as more adaptation is undertaken under a more efficient adaptation technology in the non-cooperative equilibrium. This explains why the gains from cooperation increase as more adaptation is undertaken. This result relies on our assumption that countries undertake adaptation and emissions simultaneously. If adaptation decisions are undertaken prior to mitigation, countries may use adaptation strategically to reduce their own future mitigation effort at the expense of others’ (see [25]).

1.2.4 Dynamic models of transboundary pollution and IEAs

Most of the papers mentioned in the literature review thus far consider a static setting, in the sense that pollution damage is assumed to depend on emission flows. In order to capture the reality of climate change, it is necessary to consider a framework where emissions are allowed to accumulate into a stock of pollution over time, and damage depends on this stock. Papers that allow for such a dynamic framework include, for example, [26] which compares the effects of emission taxes and quotas when a regulator and firms have asymmetric information about abatement costs, and firms make investment decisions that affect their future abatement costs. [27] show that the timing of implementing optimal emission reduction policy depends on the set of policy instruments available: climate-specific R&D targeting instruments and carbon taxes. [28] allows for a polluting technology and a clean one, where the latter is more expensive and requires investment in capacity, and derive the optimal pollution stock and creation of nonpol-
luting production capacity, weighing the tradeoffs among consumption, investment and adjustment costs, and environmental damages.

Whilst the above papers are useful for analyzing the dynamic aspects of investing in clean technologies in the presence of stock pollutants, which is applicable to the case of climate change, they do not explicitly account for transboundary pollution. The following papers build on the above papers by modeling transboundary pollution.

[29] compares the outcome under international policy coordination and the open loop equilibrium when there is no coordination, that is, when countries non-cooperatively commit to a time path instead of conditioning their emission strategies on the pollution stock at each instant. They show that the level of production and the stock of clean technology are both higher under the non-cooperative equilibrium. They do not model the coalition formation game which induces the countries to go from the non-cooperative to the fully cooperative equilibrium. This is addressed by [30], who design a transfer scheme that induces the cooperative levels of abatement and satisfies overall individual rationality for the different regions involved. Specifically, they consider an asymmetric game where there exist two regions, one upstream and another downstream. Since emissions flow in the downstream direction, the upstream region is unaffected by pollution damage, whereas the downstream region is affected by the emissions of both regions. The transfer payment from the downstream to the upstream region provides an incentive to the upstream region to invest in technology that would reduce its emissions.

[29] (section 8) and [30] consider the case where the ratio of emissions to output, which represents a measure of the cleanliness of technology, is endogenous and a decreasing function of the level of the stock of clean technology. That is, each country can invest in the abatement capital in addition to its control of emissions. The two studies differ in that while [29] assumes that the stock of clean technology is public knowledge, [30] considers the case where the stock of clean technology is country specific. In contrast to these papers, [5], [6] and [31] takes the adoption of a cleaner technology as exogenously given. This captures situations where a cleaner technology is readily available and abstracts from the game of investment in technologies. The game that these papers consider can be viewed as a second stage of a two stage game where, in the first stage, countries invest in their technologies. However, there are some differences between the
settings considered by [31], and [5] and [6]. [31] considers a pollution damage function that is linear in the stock of pollution whereas [5] and [6] have a damage function that is strictly convex in the pollution stock. In addition, for instance, [31] models a cleaner technology as a reduction in the ratio of emission to input of energy into the production process whereas [5] and [6] model a cleaner technology as a reduction in the ratio of emission to output. The main findings are also contrasting: while [31] find that a cleaner technology always increases equilibrium welfare, [5] does not. Moreover, [31] does not model the coalition formation game, which is modeled in [6]. The model and main findings of [5] and [6] are presented in more detail in the following two sections.

1.3 TRANSBOUNDARY POLLUTION AND CLEAN TECHNOLOGIES: THE NON-COOPERATIVE EQUILIBRIUM

Consider \( n \) countries indexed by \( i = 1, \ldots, n \), producing a homogeneous consumption good. Let \( \phi_i \) denote country \( i \)'s level of production and \( \varepsilon_i = \theta \phi_i \), the level of pollution associated with production, where \( \theta \) is an exogenous parameter that represents the ratio of emissions to output. A decrease in \( \theta \) represents the implementation of a cleaner technology in all countries.

Emissions accumulate into a stock of pollution, \( P(t) \), which evolves according to the following transition equation:

\[
\dot{P}(t) = \sum_{i=1}^{n} \varepsilon_i(t) - kP(t) \tag{1}
\]

with

\[
P(0) = P_0 \tag{2}
\]

where \( k > 0 \) represents the rate at which the stock of pollution decays naturally.

For notational convenience, the time argument, \( t \), is generally omitted throughout the paper although it is understood that all variables may be time dependent.

Let

\[
U_i(\phi_i) - D_i(P) \tag{3}
\]

This section presents the main findings of [5].
represent the instantaneous net benefits of country \( i = 1, \ldots, n \), with

\[
U_i(\phi_i) = A\phi_i - \frac{B}{2}\phi_i^2, \quad A, B > 0
\]

and

\[
D_i(P) = \frac{s}{2}P^2, \quad s > 0. \tag{4}
\]

Country \( i \)'s government maximizes the discounted stream of net benefits from consumption by choosing a production strategy, \( Q_i(t) \) (or equivalently a pollution control strategy), as follows:

\[
\max_{Q_i} W = \int_0^\infty e^{-rt} (U_i(\phi_i(t)) - D_i(P(t))) \, dt \tag{5}
\]

subject to the accumulation equation (1) and the initial condition (2). We assume that the discount rate, \( r \), is constant and identical for all countries. Countries are assumed to use Markovian strategies, that is, strategies that are stock dependent. Within this framework, this implies that each country’s emission strategy is decreasing in the global pollution stock, \( P \).

1.3.1 Adoption of a cleaner technology

Within this model setup, we are able to derive several results pertaining to the adoption of a cleaner technology analytically, which we summarize in this section. The formal propositions and a sketch of their proofs are available in the Appendix.

First, we find that a cleaner technology, as represented by a decrease in the emissions to output ratio, \( \theta \), may result in a larger stock of pollution in the long-run (the steady state). This, in turn, implies that the adoption of a cleaner technology may result in an increase in the steady state level of emissions. This is more likely to occur the larger is \( s, k, r \) or \( n \). Since the cleaner technology reduces pollution damage at the margin, countries have an incentive to emit more. This holds for all \( n \geq 1 \), implying that a cleaner technology may result in a larger pollution stock for all \( n \geq 1 \). The greater the damage parameter, \( s \), the greater the impact on countries’ emissions through this channel. Moreover, the greater is the natural rate of decay of the pollution stock, \( k \) or the discount rate, \( r \), the less important the link between current emissions and the stock of pollution. Hence countries emit more under the cleaner technology when either \( k \) or
are greater than a certain threshold. Also, the greater is \( n \), the greater the free-riding incentive of each country and therefore, when faced with the cleaner technology, each country increases its emissions more.

Moreover, we find that a decrease in \( \theta \) results in an increase of the emissions throughout the transition phase to the steady state if the stock of pollution is large enough.\(^8\) This is illustrated in Figure 1 for a discrete change of \( \theta \) from \( \theta' \) to \( \theta'' < \theta' \) where, starting from any pollution \( P > \tilde{P}_{\theta'} \), the equilibrium path of emissions, \( E \), given \( \theta = \theta'' \) is, at each moment, above the equilibrium path of emissions given \( \theta = \theta' > \theta'' \).

![Figure 1: Emissions as a function of \( P \) as \( \theta \) changes from \( \theta' \) to \( \theta'' < \theta' \)](image)

For \( n = 1 \) (which corresponds to the globally efficient outcome), although the implementation of a cleaner technology may increase emissions, the resultant change in welfare is positive. We show that this is not necessarily the case when \( n > 1 \) countries set their emission strategies non-cooperatively. More specifically, we find that a marginal reduction in \( \theta \), at a given level of \( P \), decreases welfare if the pollution damage parameter, \( s \), is large enough. Moreover, we find that as long as the cleaner technology increases the steady state pollution stock, it also reduces the steady state welfare level (see [5], Remark 2). This result is more likely to hold when countries use Markovian strategies, as compared to static games or dynamic games where countries would choose emissions paths as opposed to emission strategies that depend on the pollution stock. Since the

\(^8\)This result is related to the “rebound effect” and “backfire effect” in the literature on energy efficiency policies, by which the decrease in energy consumption caused by increased energy efficiency is mitigated or reversed due to behavioural responses (see, for example, [32] and [33], [34], or [35], [36], [37], [38] and [39]).
non-cooperative emission strategies of countries are downward sloping functions of the stock of pollution, an increase in an individual country’s emissions would result in a larger level of pollution stock, which would in turn induce other countries to reduce their emissions. For this reason, each country has an extra incentive, relative to a static setting, to engage in a more “aggressive” or “voracious” behavior when countries use Markovian strategies, such that the increased pollution damage may outweigh the benefits from the additional consumption causing welfare to decrease.\textsuperscript{9} Thus, the dynamic nature of the climate change problem increases the likelihood of this perverse effect of implementing cleaner technologies being realized. Indeed, in the case of two countries, if damage arises from the flow of the sum of pollution (i.e., if the cost of pollution were $\frac{1}{2} s (E_1 + E_2)^2$ instead of $\frac{1}{2} s P^2$), it can be shown that a decrease of the emissions to output ratio is always welfare improving, for any arbitrarily large value of the damage parameter $s$, in sharp contrast with the dynamic case where countries use Markovian strategies.

1.3.2 The case of climate change

We show that the perverse effect of implementing a cleaner technology may occur for values of the parameters based on empirical evidence. We start by describing the benchmark case with the following parameter values, as summarized by Table 1.

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<th>Table 1: Parameter values</th>
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<td>Parameter</td>
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In Table 1, $x$ represents an estimate of the percentage of world GDP lost due to a change in temperature if the stock of pollution doubles relative to the current level. The damage parameter, $s$, is derived from $x$.\textsuperscript{10} We choose the benchmark value of $r$ to lie

\textsuperscript{9}The intuition behind this result is similar to the one behind the `voracity effect’ in [40] and [41], obtained in the context of growth under weak or absent property rights.

\textsuperscript{10}The values used for $x$ in the existing literature range from 30% (see [42]) to about 5% (see [43]). [44] and [26] have used the same approach to derive the numerical value of the pollution damage parameter.
somewhere in between the values typically used in the climate change literature of about 1.4% (as used by the Stern Report, 2006) and about 4%, (as used by [42]). Following [42], [45] among others, we use the natural rate of decay $k = 0.005$. We also present the results for $x = 0.05$ and $x = 0.1$, holding the other parameter values constant at the benchmark levels. We also allow $k$ to vary from 0 to $\infty$, holding the other parameter values constant at the benchmark levels, and allow $r$ to vary from 0 to $\infty$, holding the other parameter values constant at the benchmark levels. For further details about our choice of parameter values, please refer to [5].

We define the function:

$$G(P, \theta, \theta_0) = \frac{W(P; \theta)|_{\theta} - W(P; \theta)|_{\theta=\theta_0}}{W(P; \theta)|_{\theta=\theta_0}}$$

which represents the relative change in welfare as $\theta$ changes from $\theta_0$ to $\theta$ at a given stock of pollution, $P$. We set $\theta_0 = 3.8315 \times 10^{-4}tCO_2/\$, in line with 2008 world GDP and total CO$_2$ emission from fossil fuel combustion and land use, and a short-term decay rate of emissions of 36%, as reported by [46]. Note that in Figure 2, $W(P; \theta)|_{\theta=\theta_0} < 0$ and, therefore, when $G(P, \theta, \theta_0) > 0$ we have $W(P; \theta)|_{\theta} - W(P; \theta)|_{\theta=\theta_0} < 0$.

From Figure 2, it follows that the emissions per output ratio has to decrease below $\tilde{\theta}_0 = 1.722 \times 10^{-4}tCO_2/\$ (i.e., a decrease of 54.33%) for the decrease to be welfare enhancing. The threshold $\tilde{\theta}_0$ falls to $1.0155 \times 10^{-4}tCO_2/\$ (i.e., a decrease of 73.5%)
when we use $x = 5\%$ and to $6.251 \times 10^{-5} tCO_2/\$ (i.e., a decrease of 83.68\%) when $x = 10\%$.

Next, we plot $W_\theta|_{P = P^{SS}(\theta_0)}$ as a function of $x$.

For the benchmark case, for all $x > 0.1\%$ we have $W_\theta|_{P = P^{SS}(\theta_0)} > 0$. A marginal decrease in emissions per output ratio reduces welfare.

Let $Z \equiv \frac{P_0}{P^{SS}(\theta_0)}$, where $P^{SS}(\theta_0)$ represents the steady state pollution stock at $\theta = \theta_0$. That is, $Z$ is a parameter that sets the initial level of the stock of pollution relative to the steady state stock of pollution. Figure 4 shows that $W_\theta|_{P = Z \cdot P^{SS}(\theta_0)}$ is strictly increasing in $Z$.

Figure 4 shows that $W_\theta|_{P = Z \cdot P^{SS}(\theta_0)}$ is positive for $Z > \bar{Z} = 0.263$. That is, the larger the stock of pollution at which we introduce a cleaner technology the more likely this
will result in a welfare loss. The value of $\tilde{Z}$ decreases to 0.237 when $x = 5\%$ and to 0.231 when $x = 10\%$.

Similarly, one can show that $W_{\theta|P=P^{SS}(\theta_0)}$ is a strictly decreasing function of $k$ and is positive for $k < \tilde{k} = 0.025$. The smaller the rate of decay the more likely that the implementation of a clean technology reduces all players’ welfare. The threshold $\tilde{k}$ increases to 0.033 when $x = 5\%$ and to 0.039 when $x = 10\%$.

We also find that the above results may carry over to the case of an asymmetric pollution game where countries differ with respect to their emissions per output ratios. Please refer to Section 6 of [5] for further details.

To sum up, we find that the perverse effect of implementing a cleaner technology is not ruled out when an empirically relevant range of parameters are used. Moreover, it is when the damage is relatively large and/or the initial stock of pollution is relatively large and when the natural rate of decay of pollution is relatively ‘small’, i.e. precisely the situations where the tragedy of the commons is at its worst, that this perverse effect is realized. The main policy implication is that even if more stringent environmental regulations lead to the adoption of cleaner technologies, it may not be enough to mitigate green house gas emissions. It is only when international cooperation on emission strategies brings us to a scenario consistent with $n = 1$, that is, the globally efficient emission strategies are implemented at any given $\theta$, that the adoption of cleaner technologies will necessarily improve welfare.

This leads naturally to our next question. Does the adoption of cleaner technologies affect the ability of countries to cooperate on emission reductions?

1.4 CLEAN TECHNOLOGIES AND THE STABILITY OF INTERNATIONAL ENVIRONMENTAL AGREEMENTS\textsuperscript{11}

In the absence of international cooperation over emission reductions, the non-cooperative equilibrium is identical to that in the previous section, as formalized in the Appendix Part I.A. In this section we present the framework we use to analyze the coalition formation game to control emissions, followed by a summary of our main findings.

\textit{Coalition Formation}

\textsuperscript{11}This section summarizes the main findings of [6].
Let $N$ denote the set of all countries, where each country is indexed by $i = 1, \ldots, n$. Suppose that countries in the set $M \subset N$ sign an agreement while those in $N \setminus M$ each choose to act individually. We denote the size of coalition $M$ by $m$.

The nonsignatories’ maximization problem is given by (5) subject to the accumulation equation (1) and the initial condition (2). The signatories’ maximization problem is given by:

$$\max_{q_i} W_m(P) = \sum_{i=1}^{m} w_i(\phi_i(t), P(t)), \quad i \in M$$

subject to the accumulation equation (1) and the initial condition (2), where $w_i$ represents an individual signatory’s welfare.

It can be shown that the signatories’ joint value function is

$$W_m(P) = -\frac{1}{2} \alpha_m P^2 - \beta_m P - \mu_m$$

and that each nonsignatory’s value function is

$$W_{nm}(P) = -\frac{1}{2} \alpha_{nm} P^2 - \beta_{nm} P - \mu_{nm}$$

In (6) and (7), $\alpha_m, \beta_m, \mu_m, \alpha_{nm}, \beta_{nm}$ and $\mu_{nm}$ are functions of the parameters of the model. See [6] for the details of the derivation and the expressions of $\alpha_m, \beta_m, \mu_m, \alpha_{nm}, \beta_{nm}$ and $\mu_{nm}$.

Global welfare under a coalition of size $m$, given a total of $n$ countries is denoted by $W_{m,n}$.

$$W_{m,n}(m) = m(w_m(m)) + (n - m)(w_{nm}(m))$$

where $w_m(m)$ represents the equilibrium welfare of each signatory, and $w_{nm}(m)$ represents the equilibrium welfare of each nonsignatory, given that there are $m$ signatories.

We distinguish between two concepts of stability: "myopic" and "farsighted". The former concept refers to the internal and external stability criteria as described by [18]. By this concept, each country believes that its individual decision to participate in the IEA does not affect others’ participation decisions. Let the stability function be given
by:

\[ \Phi_i (m) \equiv w_m (m) - w_{nm} (m - 1). \]  

(8)

Under myopic stability, a coalition of size \( m \) is said to be internally stable iff \( \Phi_i (m) > 0 \) and externally stable iff \( \Phi_i (m + 1) < 0 \).

To continue with the example of climate change, at the UNFCCC COP Meetings at Copenhagen (2009), Cancun (2010) and other international forums of negotiations, only a small number of large countries or blocks of countries (e.g. US, China, and EU) dominate the discussions. Moreover, small coalitions achieve sizable gains in welfare compared to non-cooperation only when the number of players is small (see, for example, [11]). For these reasons, we are interested in analyzing coalition formation within a context where there are a few players.

Given a small number of players, it becomes difficult to justify the assumption underlying "myopic" stability that each player does not take into account the impact of its decision to leave a coalition on the decision of the other coalition members to remain in the coalition. Therefore, we use an alternative set of stability criteria referred to in the literature as "farsightedness" under which a country considering leaving an IEA, does take into account the implications on other countries’ adhesion to the IEA. We analyze the stability of coalitions using the farsighted stability concept as used by [20], [19], [22] and [21] in the context of environmental agreements. Please refer to Definition 1 on page 13 of [19] for the formal definition of farsighted stable coalitions and farsighted stable sets, as applicable to IEAs.

Here we again use the case of climate change to illustrate the main results, using parameter values that lie within the empirically relevant ranges as identified in the previous section, and identical to those used by [44] to illustrate the case of greenhouse gas emissions by US states. We set \( r = 4\% \), \( k = 0.01 \), \( B = \theta^2 = 1 \) and \( s \in \{0.003063, 0.15315, 0.000613\} \).

1.4.1 The effect of clean technologies on IEAs

We begin by describing our results for the case with three countries, followed by a discussion of cases with more than three countries. The grand coalition is internally unstable in this example, which also implies that the two-country coalition is externally
stable since $\Phi_i (3) < 0$. That is, starting with the grand coalition, each country has an incentive to leave the coalition and set its emissions unilaterally. Also, starting with a two-country coalition, the nonsignatory has no incentive to join the coalition.

We find that the adoption of a cleaner technology makes an otherwise (internally) unstable two-country coalition internally stable, if $\theta$ decreases to a level below a certain threshold due to the implementation of a cleaner technology. This is illustrated by Figure 5. This is because each coalition member’s output is more elastic with respect to $\theta$ than the non-member’s output at a given $P$. The implementation of the cleaner technology reduces the damage from production at the margin, giving each country an incentive to increase its output. The magnitude of this increase in emissions is greater for each signatory country than for each non-signatory. Thus, the cleaner technology reduces the cost of being part of a two-country coalition in terms of sacrificed production.

![Fig. 5: Internal stability of 2-country IEA as a function of $\theta$ at $P=0$](image)

We can also see from Figure 5 that the threshold in terms of $\theta$ at which the two-country coalition becomes internally stable is decreasing in $s$. Since $s$ represents the degree of increasing marginal damage from pollution, an increase in $s$ effectively increases the free-riding incentive in the case where all countries face identical $s$.

Given a total of three countries, the grand coalition of size 3 is farsighted stable if and only if a coalition of size 2 is internally unstable. If the coalition of size two is internally unstable, when deciding whether to defect, a country compares its welfare under the grand coalition to its welfare under the non-cooperative equilibrium, in this case, the Markov perfect equilibrium. Each country chooses to remain in the grand coalition since it is better off under the grand coalition than under the non-cooperative equilibrium, given identical countries. If the coalition of size two is internally stable, when deciding whether to defect, a country compares its welfare under the grand coalition to its welfare under the coalition structure where it is a singleton facing a subcoalition of two. From
(6) and (7), we have that $w_{nm}(2) > w_m(2)$. That is, due to symmetry, each country is better off free-riding on the two coalition members, which explains why, if the coalition of size two is internally stable, each country has an incentive to defect from the grand coalition.

It follows that the grand coalition of three countries is only farsighted stable if $\theta$ is sufficiently large, that is, the technology is sufficiently dirty. The adoption of a cleaner technology may destabilize an otherwise farsightedly stable grand coalition. The destabilization of the grand coalition raises emissions and decreases global welfare at a given $P$, as shown in Figure 6.

![Figure 6: Global welfare as a function of $\theta$ at $s=0.003063, P=0$](image)

Figure 7 shows $\Phi(2)$ as a function of $P$, at $\theta = 1$ and $\theta = 0.3$. Using Figure 7, we can track the stability function as the pollution stock evolves towards the steady state. Starting at $P = 0$, suppose $\theta$ falls from 1 to 0.3. At $\theta = 1$, the two-country coalition is internally unstable. However, the reduction in $\theta$ makes this coalition stable. Moreover, as the stock rises in transition to the new steady state, the stability function increases, which implies that the higher the stock, the greater the incentive of the two members to remain in the coalition. Due to the fact that $\Phi(2)$ is monotonically increasing in $P$, starting at any $P$ lower than the steady state level, once the grand coalition disintegrates, it cannot become stable again during the transition to the steady state. Moreover, Figure 8 shows that the higher the stock, the greater the range of $\theta$ for which the two-country coalition is stable, and consequently, the grand coalition is farsighted unstable.
It can be shown that an increase in $k$, reflecting a higher rate of absorption of the stock of pollution due to factors such as geo-engineering, has a qualitatively similar effect to a reduction in $\theta$ on the stability of international environmental agreements. Please refer to [6] for further details.

Similar results carry over to the case of a non-accumulative pollutant, where the damage is a function of the flow of emissions at each instant in time rather than the stock of pollution. To analyze such flow pollutants, we set up a static version of the model where the only difference from the model described in the previous section is that the pollution damage faced by country $i$ is given by:

$$D_i \left( \sum_{i=1}^{n} \varepsilon_i \right) = \frac{s}{2} \left( \sum_{i=1}^{n} \varepsilon_i \right)^2, \quad s > 0.$$  \hspace{1cm} (9)

For the three-country case, the results are qualitatively similar to the ones for the
dynamic model, as presented above. For more than three countries, we show that a marginal decrease in the emission per output ratio may result in a discrete jump in the largest stable size of a coalition in either direction and, therefore, may result in a downward or an upward jump in global welfare. This is illustrated using the following example.

Let $A = B = s = 1$ and $n = 8$. The adoption of a cleaner technology represents a decrease in $\theta$ from 0.25 to 0.1. The following table provides the payoffs of insiders and outsiders for each coalition size, $m$, under the dirtier technology at $\theta = 0.25$.

\[
\begin{array}{cccccccc}
1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\
\hline
w_m & -0.444 & -0.448 & -0.389 & -0.290 & -0.178 & -0.071 & 0.025 & 0.100 \\
w_{nm} & -0.444 & -0.305 & -0.104 & 0.0802 & 0.219 & 0.313 & 0.375 \\
\end{array}
\]

As per Table 2, under the dirtier technology, there are no coalitions that are myopically internally stable. The largest farsighted stable coalition that is both internally and externally farsighted stable is $m = 6$, and the complete set of coalition sizes that are farsighted internally stable is given by $\{1, 3, 6\}$. The coalition of size three is farsighted internally stable since if a country chose to defect such that the coalition size became two, it can foresee that the remaining coalition member would also defect since the payoff being a singleton (-0.444) is greater than that of being a coalition member of size two (-0.448). With this foresight, no country would choose to defect from a coalition of size three, since its payoff from being a member of the coalition of size three (-0.389) is greater than that of being a singleton. The coalition of size six is farsighted internally stable since if a country chose to defect, it can foresee that further defections would occur until the coalition size became three, which is farsighted internally stable. With this foresight, no country would choose to defect from a coalition of size six, since the payoff of being a member of a coalition of size six (-0.071) is greater than that of being a non-member of a coalition of size three (-0.104). The coalition of size six is farsighted externally stable since the payoff of a non-member of a coalition of size six (0.313) is higher than that of a member of coalitions of size seven or eight. Table 3 provides the payoffs of insiders and outsiders for each coalition size, $m$, under the cleaner technology.
at $\theta = 0.1$.

Table 3: Payoffs of insiders and outsiders for $\theta=0.1$ and $m \in \{1, \ldots, 8\}$

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w_m$</td>
<td>0.223</td>
<td>0.225</td>
<td>0.232</td>
<td>0.242</td>
<td>0.256</td>
<td>0.271</td>
<td>0.288</td>
<td>0.305</td>
</tr>
<tr>
<td>$w_{nm}$</td>
<td>0.223</td>
<td>0.233</td>
<td>0.251</td>
<td>0.275</td>
<td>0.303</td>
<td>0.330</td>
<td>0.356</td>
<td></td>
</tr>
</tbody>
</table>

As per Table 3, under the cleaner technology at $\theta = 0.1$, there does exist one coalition size that is myopically internally and externally stable, that is, $m = 2$. At the same time, each outsider of a coalition of size 2 would be better off as an insider of a coalition of size 4 and each outsider of a coalition of size 4 would be better off as an insider of a coalition of size 7. The only farsighted stable coalition that is both internally and externally farsighted stable is $m = 7$.

Tables 2 and 3 together imply that going from a dirtier technology ($\theta = 0.25$) to a cleaner technology ($\theta = 0.1$), the size of the largest farsighted stable coalition increases from 6 to 7. Global welfare also increases from 0.203 under $\theta = 0.25$ and farsighted stable coalition of 6, to 2.373 under $\theta = 0.1$ and farsighted stable coalition of 7. Therefore, the perverse result in the case of three countries where the cleaner technology is shown to destabilize the larger coalition and reduce global welfare may be reversed for more than three countries.

In our model, all quantities are strictly positive if and only if $\theta$ is sufficiently small, that is, $\theta \in (0, \theta_{\text{max}}]$. Figure 9 illustrates the largest stable coalition size as a function of $\theta$, and Figure 10 illustrates global welfare under the largest stable coalition as a function of $\theta$, for $\theta \in (0, \theta_{\text{max}}]$. 

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Tables 2 and 3 and Figures 9 and 10, it follows that:
(i) a small change in $\theta$ can alter the size of a stable coalition and therefore result in a jump in the graph of total welfare as a function of $\theta$
(ii) there can be more than one jump as $\theta$ varies
(iii) these jumps can be either upwards or downwards.

Thus, the adoption of cleaner technologies may affect global welfare indirectly by affecting the size of the largest farsighted stable coalition. The relationship between the emission per output ratio and the size of the largest stable coalition and welfare is discontinuous and non-monotonic. The impact of cleaner technologies on the stability of an IEA and on countries’ welfare is thus ambiguous and depends on the regions of parameters where the change in technology occurs.
1.5 CONCLUSIONS AND POLICY IMPLICATIONS

This chapter reviewed the recent literature on the development and adoption of cleaner technologies within an international context where countries emit a transboundary pollutant, and may cooperate on R&D or on mitigation of emissions. Three related streams of the existing literature were reviewed. The main findings of these different streams may be summarized as follows.

The first set of papers examine the conditions under which international cooperation on sharing costs of developing clean technologies is likely to result in stable environmental agreements involving a large number of countries, leading to the globally efficient level of R&D. Large coalitions are generally only stable if the gains from cooperation are low, as concluded by [7], unless the adoption of cleaner technology has increasing returns due to network externalities, or if the cost of adoption declines in the level of R&D, as pointed out by [9]. [10] conclude that if countries are asymmetric, those facing higher marginal damage from the pollutant have more incentive to cooperate on R&D, which reduces cost of adoption of the cleaner technology for all countries leading to an increase in global welfare.

The second set of papers examine how international environmental agreements on mitigation of emissions affect the non-cooperative level of R&D and clean technology adoption across countries. In this literature, the main concern is that the signing of such an IEA may result in a hold up problem with under-investment in R&D. As [3] point out, when IEA signatories commit to emission mitigation, this makes the demand for R&D on clean technologies less elastic. This allows innovators holding patents to charge higher licence fees for the use of cleaner technologies. Anticipating this, countries either do not join IEAs or do not commit to much mitigation, reducing the demand for and hence the profitability of engaging in R&D.

The third set of papers examine how the adoption of cleaner mitigation and adaptation technologies affect (i) the non-cooperative level of pollution stock and welfare, and (ii) the stability of IEAs on emission mitigation. The adoption of cleaner technologies may result in countries raising their emissions emitting more, similar to a "rebound effect", even to the extent that global welfare falls. Using empirically relevant parameter values for the case of climate change, this effect is shown to be more likely to occur for an
accumulative pollutant, such as greenhouse gases, when countries use stock dependent emission strategies, and when the pollution is most damaging, that is, at high levels of pollution stock and low rates of natural decay. Under such conditions it is shown, in the case of three countries, that cleaner technologies may destabilize the grand coalition. This pessimistic result is mitigated when there are more than three countries, in which case, the adoption of cleaner technologies may result in an increase of the size of the largest stable coalition and welfare. However, the relationship between the emission per output ratio and the size of a stable coalition and welfare is in general complex: it exhibits discontinuities, with both upward and downward jumps in the largest stable size of a coalition as the technology used becomes cleaner.

The main policy implication of the above studies is that, while it seems sensible to seek cleaner technologies to deal with severe transboundary pollution problems, the ultimate outcome of such technologies is not straightforward and policies towards such technologies should be designed on a case by case basis. These studies can shed light on the arbitrage between seeking marginal but presumably low cost improvements of an existing technology or seeking breakthrough but presumably high cost technology improvements.

In Sections 3-4 of this chapter, we have made a few simplifying assumptions in order to illustrate the main insights as clearly as possible. Relaxing these may generate further insights, which is left for future work. For example, we have analyzed the case of identical countries. In reality, different regions are vulnerable to different degrees to the effects of climate change and will therefore undertake different amounts/types of adaptation. For instance, Southern Europe is expected to be affected more than Northern Europe by climate change. Therefore, allowing for asymmetries across countries would be a relevant extension. Also, Sections 3-4 analyze the effect of exogenously given reductions in the emission per output ratio. An interesting extension would be to endogenize countries’ investment in developing cleaner technologies. Further policy relevant insights may be generated by examining whether local (instead of global) investments to develop and adopt cleaner technologies may be used strategically to induce participation in IEAs.
References


Appendix

Part I

Appendix to Section 3: Transboundary pollution and clean technologies: the non-cooperative equilibrium

This part of the Appendix presents the formal results we derive for the non-cooperative transboundary pollution game. We include sketches of the proofs of each proposition. For further details, please refer to [5].

I.A: The Markov perfect equilibrium:

Countries are assumed to use Markovian strategies: \( \phi_i(\cdot) = Q_i(P, \cdot) \) with \( i = 1, \ldots, n \). The \( n \)-tuple \( (Q_1^*, \ldots, Q_n^*) \) is a Markov Perfect Nash equilibrium, MPNE, if for each \( i \in \{1, \ldots, n\} \), \( \{\phi_i(t)\} = \{Q_i^*(P(t), t)\} \) is an optimal control path of the problem (5) given that \( \phi_j(\cdot) = Q_j^*(P, \cdot) \) for \( j \in \{1, \ldots, n\}, j \neq i \). As shown by [47], such a game admits a unique Markov perfect equilibrium in linear strategies, given by the following.

**Proposition 1:** For \( P < \bar{P}(\theta) \equiv \frac{1}{B} \left( A - \theta \beta \right), \) the vector \( (Q, \ldots, Q) \)

\[
Q_i^*(P; \theta) = Q(P; \theta) = \frac{1}{B} (A - \theta \beta - \alpha \theta P), \quad i = 1, \ldots, n
\]

constitutes a Markov perfect linear equilibrium and discounted net welfare is given by

\[
W_i(P; \theta) = -\frac{1}{2} \alpha P^2 - \beta P - \mu, \quad i = 1, \ldots, n
\]

where

\[
\alpha \equiv \sqrt{B \left( B (2k + r)^2 + (2n - 1) 4s\theta^2 \right) - (2k + r) B} \left( 2n - 1 \right) \theta^2
\]

\[
\beta \equiv \frac{An \alpha \theta}{B (k + r) + (2n - 1) \alpha \theta^2}
\]

\[
\mu \equiv -\frac{(A - \beta \theta) (A - (2n - 1) \beta \theta)}{2Br}
\]

The steady state level of pollution

\[
P^{SS}(\theta) \equiv \frac{n \theta (A - \theta \beta)}{Bk + n \alpha \theta^2} > 0
\]
is globally asymptoticall y stable.

We note that \( Q_i > 0 \) if \( P < \bar{P}(\theta) \). It is straightforward to show that \( \bar{P}(\theta) > P^{SS}(\theta) \) for all \( \theta \geq 0 \).

I.B: Impact of a cleaner technology

The impact of a cleaner technology on equilibrium steady state pollution stock and equilibrium emissions turns out to be ambiguous. Henceforth, in this section, without loss of generality, we normalize \( B \) to 1. More precisely, we find the following:

**Proposition 2:** For any \( \theta > 0 \), there exists \( \bar{s} > 0 \), \( \bar{k} > 0 \), \( \bar{r} > 0 \) and \( \bar{n} \geq 1 \) such that we have

\[
\frac{dP^{SS}}{d\theta} < 0
\]

if either \( s > \bar{s} \), \( k > \bar{k} \), \( r > \bar{r} \) or \( n > \bar{n} \). That is, a decrease in the emissions to output ratio results in a larger stock of pollution at the steady state.

Let \( E(P; \theta) \equiv \theta Q(P; \theta) \) denote the emissions that are associated with the equilibrium production strategy \( Q(P; \theta) \). Since \( nE(P^{SS}(\theta); \theta) = kP^{SS}(\theta) \), it follows that \( \frac{dE(P^{SS}(\theta); \theta)}{d\theta} \) and \( \frac{dP^{SS}(\theta)}{d\theta} \) have the same sign. This, together with Proposition 2, implies that the adoption of a cleaner technology may result in an increase of the long-run (the steady state) level of emissions. Moreover, we show that a decrease in \( \theta \) results in an increase of the emissions throughout the transition phase to the steady state if the stock of pollution is large enough.

**Proposition 3:** There exists \( \bar{P} \) such that

\[
E_\theta(P; \theta) \leq (>) 0 \text{ for all } P \geq (<) \bar{P}
\]

Moreover \( \bar{P} < \bar{P} \) and \( \bar{P} > 0 \).

From the optimality condition of a best response of a single player we have the Hamilton Jacobi Bellman equation associated to a player’s problem, given by:

\[
rW(P; \theta) = U(Q) - D(P) + W_P(P; \theta)(n\theta Q - kP)
\]  \hspace{1cm} (13)

Differentiating (13) with respect to \( \theta \) and evaluating \( W_\theta \) at \( P = P^{SS}(\theta) \), we derive the
following:

\[ r \left. W_\theta \right|_{P = P^{SS}(\theta)} = (n - 1) E_\theta W_P + QW_P \]  

(14)

A reduction in \( \theta \) causes emissions to decrease as long as production remains un-
changed, implying that \( W_P < 0 \). As per the earlier discussion, \( E_\theta \) may be positive if \( P \)
is sufficiently large. In this case, \( W_\theta \), at a given value of \( P \), may be positive, implying
that the implementation of a cleaner technology results in a lower welfare throughout
the transition phase from an initial stock \( P \) to the steady state. This leads to our main
proposition.

**Main Proposition:** For any \( n > 1 \), there exists \( \bar{s} > 0 \) such that \( W_\theta \big|_{P = P^{SS}(\theta)} > 0 \) for
all \( s > \bar{s} \).