Environmental Public Goods and Endogenous Technological Change:

a Game-Theoretical Analysis of Incentives to Invest in Climate Technology in a Non-Cooperative Setting

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Abstract

The thesis investigates the interrelation between environmental public goods and climate-related endogenous technological change. Specifically, we analyze whether the public good property of mitigation (or strategic interaction) hinders or fosters the countries' incentives to invest in four climate-related technologies (abatement, energy efficiency, adaptation and low-carbon technology) in a non-cooperative setting. Our findings have shown that strategic interaction hinders the incentives to invest in abatement technology, fosters the incentives to invest in energy efficiency and adaptation technology, and can both foster and hinder the incentives to invest in low-carbon technology. In the case of symmetrical countries, a country would always prefer to invest in a less efficient abatement technology due to strategic reasons if the number of countries is sufficiently large.

Acknowledgments

I hope this section will be perceived not as a cliché, but as a sincere expression of a deep gratitude to all those who contributed, directly or indirectly, to the completion of this master thesis.

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$for\ Luca^{D^R}$

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Abbreviations

AB	Abatement
AD	Adaptation
BRIC	Brazil, Russia, India and China
CCS	Carbon capture and storage
COP	Conference of the Parties
CO_2	Carbon dioxide
EE	Energy efficiency
GDP	Gross domestic product
GHG	Greenhouse gas
IEA	International environmental agreement
LC	Low-carbon
NE	Nash equilibrium
NI	Numerical illustration
OECD	Organisation for Economic Co-operation and Development
PG	Public good
R&D	Research and development
TC	Technological change
TT	Technology transfer
UNFCCC	United Nations Framework Convention on Climate Change
WTP	Willingness to pay
w.r.t.	with respect to

1 Introduction

International climate agreements have been evolving since 1992 when the UN Framework Convention on Climate Change (UNFCCC) was adopted. The key long-term goal of the latest climate treaty, the Paris Agreement (2015), is to keep the rise in global average temperature well below 2°C above pre-industrial levels and to pursue efforts to reduce it further to 1.5°C (UNFCCC 2016). As the scientific community stresses, substantial reductions in global GHG emissions are necessary to achieve this ambitious goal (IPCC 2014). In other words, the problem of the under-provision of GHG mitigation has to be remedied to ensure stable concentrations of GHGs in the atmosphere at appropriate levels and thus prevent adverse climatic changes.

Extensive research has shown that the under-provision problem is rooted in the public good (PG) property of mitigation (IPCC 2001; Barrett 1990; Stern et al. 1999;). Indeed, the healthy atmosphere with stable concentrations of GHGs is both non-excludable and non-rivalrous: one cannot prevent the use of the atmosphere by other agents, and the use of the atmosphere by one agent does not limit its use by the other agents. As such, the provision of GHG mitigation exerts a positive environmental externality. In the context of international environmental politics this implies that the parties to a climate treaty have an incentive to free ride, which results in a non-cooperative equilibrium and hence inefficiently high global GHG emissions. International climate governance we observe today indeed falls well short of being effective (Barrett 2015; Bulkeley 2015; Keohane 2016).

What could serve as a remedy to the under-provision problem in a non-cooperative setting of international climate governance? Multiple authors in climate economics, for example, Grubb (2002), Grübler (1999), and Stern (2008) claim that the advancement in climate-related technology is a promising solution. Just as the advancement in vaccine research in the 1950s made it possible to prevent poliomyelitis, the development, application and diffusion of climate-friendly technology could enable humanity to prevent the hazardous consequences of climate change (Nordhaus 1999).

The inherent scientific uncertainty about climate change and its impacts on society renders it, however, utterly different from an infections disease. More importantly, environmental PGs and climate-related technological progress are interlinked: the former can actually hinder the advancement in climate-related technology even when emissions are chosen cooperatively. As Buchholz et al. (1994) have shown, countries tend to use abatement technology as an instrument to bargain emission reductions, which means that their choice of technology becomes strategic. When making a strategic technology choice, countries can choose from more efficient (low per unit cost of abatement) or less efficient (high per unit cost of abatement) abatement technologies. One might assume intuitively that a rational player would prefer a more efficient (less expensive) technology at least if it comes at the same cost as the less efficient. Yet, this is not the case given the PG problem. Strategically interacting countries in both non-cooperative and cooperative cases tend to invest in a less efficient (more expensive) abatement technology even when a more efficient technology is available for free. This occurs because a country can shift the burden of mitigation to the other countries if it invests in a less efficient abatement technology. This way the country can credibility commit to lower abatement (or higher emission levels), while inducing *ceteris paribus* the other countries to mitigate more.

The findings by Buchholz et al. (1994) thus demonstrated the importance of strategic interaction for endogenous technological change (TC) and the levels of emission reductions. Yet, they only considered one type of climate-related technology - abatement technology - which apparently gained a special attention after the issue of the first IPCC Assessment Report in 1990 (IPCC). Today with the rapid technological progress and the exacerbation of the climate change problem many new forms of climate-friendly technology have come into play, whereas the PG problem has remained unchanged. Moreover, there is a general consensus that one form of technology can hardly be the 'silver bullet' for the climate change problem, and rather portfolios of technologies have to be considered (IPCC 2007). Yet, the economic research covering the interrelation between environmental PGs and climate-related technological innovation remains very scarce.

We seek to close this gap and provide a novel outlook on endogenous TC in the context of strategic interaction. This said, we build on the research of Buchholz et al. (1994) by scrutinizing the internal structure of countries' economies in greater detail, and namely, by making a distinction between four types of climate-related technologies: abatement technology, energy efficiency technology, adaptation technology and low-carbon technology. Let us briefly explain what we mean by each technology type.

- Abatement (AB) technology is treated as a domestic policy facilitating the development of abatement (end-of-pipe) technologies, such as post-combustion CO_2 capture, pre-combustion carbon capture, or oxyfuel combustion.
- Energy efficiency (EE) technology is analogously treated as a domestic policy facilitating the development of energy efficient technologies, such as more energy efficient coal power plants, more energy efficient vehicles, or more energy efficient heating and cooling devices.
- Adaptation (AD) technology is analogously treated as a domestic policy facilitating the development of adaptation technologies, such as flood safeguards, more resilient crops, or water recycling.
- Low-carbon (LC) technology is analogously treated as a domestic policy facilitating the development of low-carbon technologies, such as gas power plants, solar panels or wind turbines.

Accordingly, we define endogenous TC as a domestic policy facilitating the development of any type of the four technologies specified. In contrast to Buchholz et al. (1994) we are not concerned with optimal technology choices. Rather, we address the topic of endogenous TC in a qualitative way by investigating how the PG problem influences the incentives to invest in a particular technology type.

Our research question can be formulated as follows:

- Does the public good property of mitigation hinder or foster the incentives to invest in four climate-related technologies (AB, EE, AD, LC) in a non-cooperative setting?

In order to answer this question, we use the tools of game theory and mathematical economics. We firstly introduce a general model of investment incentives, where we impose particular assumptions and find the unique Nash equilibrium. Secondly, we conduct a comparative static analysis to determine how individual abatement, total net emissions, and individual gross and net emissions change in the equilibrium state with changing climate technology parameters. Finally, we examine how the total welfare of a country changes in response to the technology parameters' change. To illustrate our findings, we propose and solve a specific model of investment incentives satisfying the conditions of the general model, and provide a numerical example at the end.

Our results show that the PG property of mitigation hinders the incentives to invest in AB technology, fosters the incentives to invest in EE and AD technologies, and can both foster and hinder the incentives to invest in LC technology. Put differently, strategic interaction under Nash conjectures makes emission-increasing technologies more appealing and emission-reducing technologies more repelling for countries, which could be another factor explaining the current low levels of mitigation worldwide.

The thesis is structured as follows. Section 2 provides a literature review focusing on the research context and related studies. Section 3 consists of three parts. The first part solves the general model of investment incentives and conducts a comparative static analysis. The second part solves the model with specific functional forms. The third part presents a numerical illustration (NI) based on the results of the specific model. Section 4 discusses the model assumptions and results, as well as provides glimpses at future research. Finally, Section 5 concludes the thesis.

2 Literature Review

The purpose of this section is to provide a context of the research related to the climate-technology relationship and to examine the studies relevant for our model.

2.1 Research Context

The main scope of the theoretical economic research which investigates the climate-technology relationship is related to the topic of technology transfer (TT). This could be explained by the fact that the issue of TT has been prioritised by the UNFCCC since its establishment in 1992 (Haselip et al. 2015). As a consequence, in 2007 the issue was brought up to the international climate negotiations in Bali and is being addressed at each COP since then (Ockwell 2012). For instance, Kyoto Protocol states that *"The developed country Parties < ... > shall take all practicable steps to promote, facilitate and finance, as appropriate, the transfer of, or access to, environmentally sound technologies..."* (Article 4 Kyoto Protocol 2005).

The theoretical findings of TT research can be summarised as follows. Firstly, the asymmetry in discount rates between technology donors (developed countries or the North) and technology recipients (developing countries or the South) substantially influences *inter alia* the decision to transfer technology (Arrow et al. 1996; Azar and Sterner 1996). Secondly, the North-to-South TT can exert positive effects, such as a global emission reduction and a global welfare increase, only if technology is transferred conditionally, i.e., only if developing countries abide by their mitigation commitments. In the absence of a treaty the positive effects diminish due to carbon leakage and the rebound effect. Thirdly, the order of TT plays an important role: the positive effect of a global emission reduction becomes more pronounced if TT occurs after the South makes its mitigation commitments. Hence a global treaty specifying the commitments and the order of transfers is crucial if we want to ensure the positive effects of TT (Stephan and Müller-Fürstenberger 2014).

The research on TC has attracted considerably less attention in theoretical economics, however, it is well represented in an empirical domain. Numerous empirical studies over the last few decades have been proposing and discussing different specifications of TC in the economic models of climate change (Goulder et al. 2002; Löschel et al. 2012; Nordhaus 2002; Romer 1990). The goal of these studies was to develop and improve the methods for the assessment of climate change mitigation policies. To have a better understanding of the researchers' findings, let us give a brief overview of the economic climate models and explain how TC is specified in them.

As Löschel et al. (2012) outlines, the economic models of climate change can be divided into two groups: 'bottom-up' and 'top-down' models. The first group usually includes partial equilibrium models where TC in the energy sector is specified in great detail, while the rest of the economy remains generally untreated. Examples of such models include MARKAL and POLES that were initially developed by the International Environmental Agency and the Institute of Energy Policy and Economics in France respectively. The second group, on the contrary, provides a detailed description of the economy and abstracts from the detailed representation of TC in the energy sector. The types of such models include macroeconomic models, computable general equilibrium models e.g. MIT-EPPA and famous integrated assessment models e.g. DICE/RICE (W. Nordhaus), WITCH (Fondazione Eni Enrico Mattei), or FUND (R. Tol).

The specification of TC in these models can be either exogenous or endogenous. In the most general sense, exogenous TC implies exogenous advancement in energy efficiency. As Popp (2009) showed, exogenous TC is merely a function of time, i.e., it does not depend on innovation, technological shocks, or climate regulations such as carbon taxes or a cap-and-trade system. Hence, the models of exogenous TC are generally simple and transparent, yet the neglect of innovation, policy measures, and the possibility of rapid TC make them highly unrealistic. For this reason endogenous TC has recently become very popular in economic climate modelling, and is usually specified in the models in four ways: directed TC, price-induced TC, learning-by-doing, and facilitation of R&D. Directed TC, as proposed by Acemogly et al. (2012), assumes that the government facilitates a cleaner long-run growth (at the cost of stunting short-run growth) by influencing the allocation of clean and dirty production and the allocation of R&D in clean and dirty industries. Price-induced TC formalised by Hicks (1932) implies that the increase in relative factor prices fosters TC, because firms will seek to reduce relatively increased factor inputs through technological improvements. The concept of learning-by-doing suggested by Arrow (1962) simply states that although pioneering a new technology could be costly, the costs will decrease over time, as firms gain practical knowledge in technology use. Finally, facilitation of R&D could be seen as the investments of firms in R&D with the aim to decrease production costs in the long-run, whereby the spillover effect (positive externality from R&D) substantially influences the investment decisions of firms (Wing 2006; Popp et al. 2009). Since our theoretical model considers domestic policies which foster TC in the context of strategic interaction (induced by externalities), it can be seen as complementary to the empirical models of directed TC and R&D facilitation.

2.2 Relevant Studies

A sole theoretical study which treats endogenous TC in the context of strategic interaction was conducted by W. Buchholz and K.A. Konrad and published in 1994, as shortly mentioned in Section (1). The authors proposed a model with n countries $i = \{1, ..., n\}$ that make strategic technology and emission reduction choices. The model is represented in form of non-cooperative and cooperative dynamic two-stage games of perfect information with countries being rational players. The choice of abatement technology cost λ_i at stage 1 determines the utility of each country at stage 2, which induces countries to make strategic technology choices at stage 1. In other words, the emission reduction choices are strategic substitutes, and due to this strategic substitutability, each country seeks to shift the burden of mitigation to the other countries. A country does so by choosing a technology with a high per unit cost of abatement, even when a technology with a lower cost of abatement is available for free. This way, it can credibility commit to a lower abatement (or higher emission) levels, while inducing *ceteris paribus* the other countries to abate more.

Let us now consider the analysis of Buchholz et al. (1994) in more detail. The countries are represented by their respective firms whose individual utility is determined by a universal private good and aggregate emission reductions (public good), and is independent of the allocation of the reductions. At stage 2 of the non-cooperative game each country maximises its utility with respect to aggregate abatement subject to its budget constraint and the non-negativity constraints of the endogenous variables. The authors assume normality of the individual demands for the private and public goods; under this assumption for $n \geqslant 2$, the private provision of abatement is too small in comparison to the social optimum. It is shown that at stage 1 country i's marginal benefit of choosing a higher λ_i is larger than its marginal cost of choosing a higher λ_i because the other countries will provide more abatement if country i chooses a higher λ_i. Hence, a country would prefer to choose a technology with a high per unit cost of abatement. Further the authors conduct a comparative static analysis, showing that $\forall i = \{2, ..., n\}$ in the equilibrium 1) aggregate abatement decreases with increasing λ_i; 2) individual abatement of all the other countries increases with increasing λ_i; 3) individual utility decreases with an increasing productivity parameter, and 4) the productivity parameter decreases with increasing λ_i. This reaffirms that choosing a higher λ_i is more beneficial. Another interesting finding is that the incentive to choose a higher λ_i becomes stronger if n is large, and if the cooperation at stage 2 for $n = 2$ is anticipated. The case where countries would choose a lower λ_i (more efficient abatement technology) is feasible though if countries also cooperate at stage 1, however, it is a highly unrealistic assumption. The unfortunate overall conclusion is that in both non-cooperative and cooperative setting countries would prefer a worse abatement technology.

Another study which is important to some extent for our analysis is Sartzetakis et al. (2013). The authors examine the maximum size of stable and self-enforcing coalitions in the context of negative environmental externalities. Although the topic of the study is not related to strategic incentives or strategic technology choice, the specific functional forms which the authors use are highly relevant for our model. The authors assume a dynamic two-stage game of perfect information with n symmetric countries $i = \{1, ..., n\}$ that choose non-cooperatively their individual levels of abatement and gross emissions at stage 2. The assumed functional forms are the following: each country has a quadratic benefit function which is strictly concave in its gross emissions, a quadratic abatement cost function which is strictly convex in country's abatement, and a quadratic damage function which is strictly convex in aggregate net emissions; all functions are parameterized with positive parameters. The total welfare of each country is the difference between a country's benefit and abatement cost minus its environmental damage. In Section (3.2) we adopt the same welfare function setup and almost the same functional forms with the sole modification of the benefit function such that it better serves our research purposes. Some of the abovementioned functional forms have also appeared, for example, in the papers by e.g. Gengenbach et al. (2010), Athanassoglou et al. (2012), or Habla and Winkler (2017), however, in a less similar manner.

Lastly, there is a number of theoretical studies that indirectly treat endogenous TC in the context of the PG problem. Consider, for instance, Bayramoglu (2009): she shows that two asymmetric countries would prefer to establish an IEA based on a uniform emission standard with transfer payments, because it fosters the investments in abatement technology. Another example is Harstad (2012) where the author solves a dynamic infinite game with n emitting countries that invest in climate-related technologies (namely abatement technology and renewable energy sources). The author finds *inter alia* that technology investments can be characterized as a PG even if countries choose cooperatively emission levels and even in the absence of the spillover effect. Yet, the investments might increase if the negotiated emission quotas are small, a climate treaty is long-lasting, and a renegotiation of the treaty is allowed. As such, the authors focused on different designs of IEAs and their influence on TC, while we do not consider a treaty design.

3 The Model

3.1 The General Model of Investment Incentives

3.1.1 Assumptions

In the following, we introduce a static game of complete information with n identical countries $i = \{1, ..., n\}$ that choose simultaneously and non-cooperatively gross emissions $g_i > 0$ and abatement levels $a_i > 0$. Gross emissions of each country represent its economic activity (production and consumption). The emissions of a country are directly related to its welfare and negatively related to the individual welfare of all the other countries. The countries are autonomous and represented by their respective governments that are able to enact policies facilitating the development of four climate-related technologies (EE, AB, AD and LC). The technology types are directly related to the welfare of each country: EE and LC technologies influence the benefit, AB technology influences the cost, and AD technology influences the damage of a country.

Formally the model is specified as follows.

The **benefit function** of country i is given by $B_i(\beta_i, \epsilon_i; g_i)$. It is determined by g_i, a positive parameter β_i which is directly related to EE, and a positive parameter $\epsilon_i \geqslant g_i$ that denotes the emission level of country i when its economy operates at full capacity. The benefit function is strictly concave in g_i[1]:

$$B_i'(\beta_i, \epsilon_i; g_i) > 0, \quad B_i''(\beta_i, \epsilon_i; g_i) < 0 \tag{1}$$

The parameters β_i and ϵ_i vary in the range $(\beta/\epsilon)_i \in \{(\beta/\epsilon)_{min}, (\beta/\epsilon)_{max}\}$ with $(\beta/\epsilon)_{min} > 0$, such that a lower ϵ would imply a higher share of LC technology in country i's energy mix and a lower β would imply a less efficient EE technology.

[1]We treat the positive technology-related parameters as exogenous, separating them from our endogenous variables with a semicolon. We denote the first and second derivative with respect to the sole endogenous variable by '′' and '′′'.

Accordingly,

$$\frac{\partial B_i(\beta_i,\epsilon_i;g_i)}{\partial \beta_i} > 0 \qquad \frac{\partial B_i'(\beta_i,\epsilon_i;g_i)}{\partial \beta_i} > 0, \qquad \frac{\partial B_i'^{-1}(\beta_i,\epsilon_i;g_i)}{\partial \beta_i} > 0$$
$$\frac{\partial B_i(\beta_i,\epsilon_i;g_i)}{\partial \epsilon_i} < 0 \qquad \frac{\partial B_i'(\beta_i,\epsilon_i;g_i)}{\partial \epsilon_i} > 0^* \qquad \frac{\partial B_i'^{-1}(\beta_i,\epsilon_i;g_i)}{\partial \epsilon_i} > 0^* \tag{2}$$

* if g_i is sufficiently high

where '-1' denotes the inverse function with respect to the relevant endogenous variable (in this case g_i).

Figures 1 and **2** demonstrate that our assumptions are reasonable. To make the visual representation more vivid, we omit the index i in the functions, variables and parameters on the plots, as well as mark the lower (initial) parameter values and the corresponding function in a lighter color. The arrows illustrate the functions' direction of change with the increase in the parameter value.

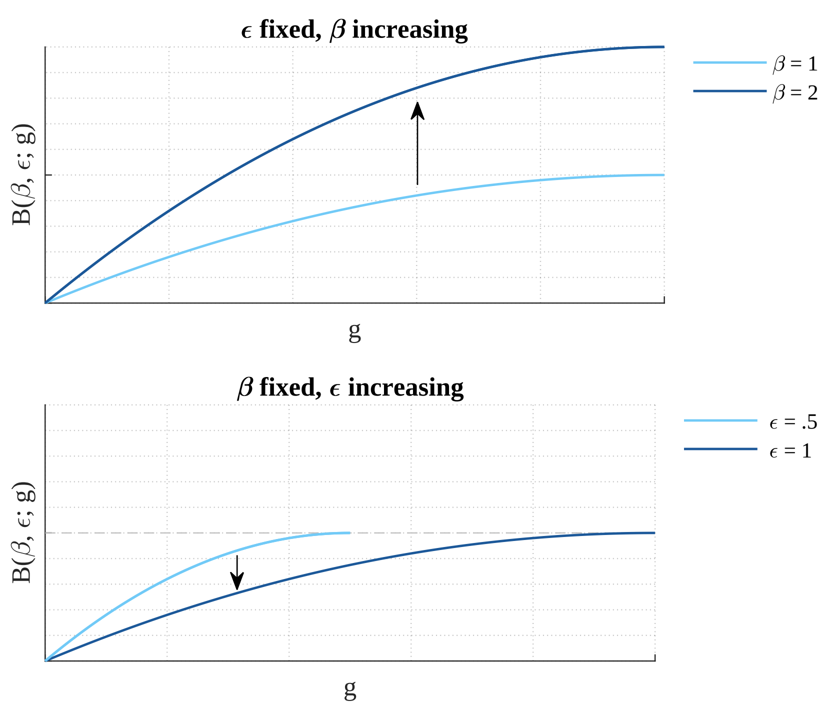

Figure 1: *The direction of change in the benefit function with increasing β_i and ϵ_i.*

As it can be seen from **Figure 1**, the benefit function increases with increasing β_i, however, it decreases with increasing ϵ_i. This shows that the improvements in EE and a larger share of LC technology in country i's energy mix are beneficial for the country.

Consider now the visual representation of (2), i.e., how the derivatives and the inverse derivatives of our functions change with the increasing technology parameters. **Figure 2** shows that the first derivative of the benefit function increases with increasing β_i, which means that the improvements in EE increase the marginal benefit of a country. In contrast, B_i' decreases with a higher ϵ_i, however, only until the intersection point A, and starts increasing thereafter. This implies that a smaller share of LC technology in country i's energy mix increases its marginal benefit if the gross emissions of country i are sufficiently high.

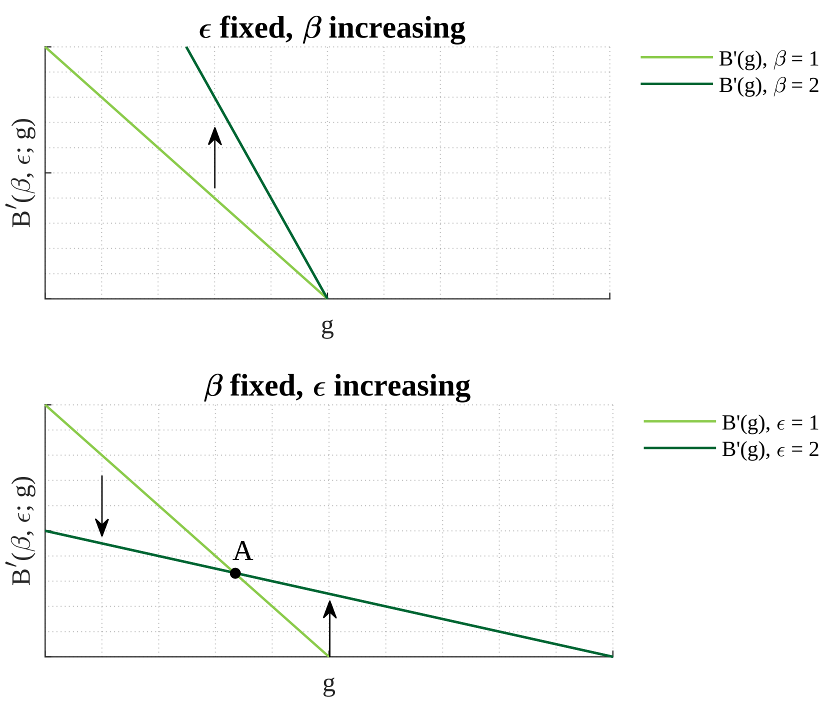

Figure 2: *The direction of change of the marginal benefit function with increasing ϵ_i and β_i.*

The **cost function** of country i is given by $C_i(\alpha_i, a_i)$. It is determined by the level of abatement a_i and a positive parameter α_i which is related to the costs of the AB technology. The cost function is strictly convex in a_i:

$$C_i'(\alpha_i; a_i) > 0, \quad C_i''(\alpha_i; a_i) > 0 \tag{3}$$

The technology parameter α_i varies in the range $\alpha_i \in \{\alpha_{min}, \alpha_{max}\}$ with $\alpha_{min} > 0$ such that a higher level of α_i implies a less efficient (higher per unit cost of abatement) AB technology. Accordingly, the cost and marginal cost functions increase with increasing α_i, implying that a less efficient AB technology is disadvantageous for country i (eq. (4) and **Fig. 3**).

$$\frac{\partial C_i(\alpha_i; a_i)}{\partial \alpha_i} > 0, \quad \frac{\partial C_i'(\alpha_i; a_i)}{\alpha_i} > 0 \qquad \frac{\partial C_i^{'-1}(\alpha_i; a_i)}{\partial \alpha_i} < 0 \tag{4}$$

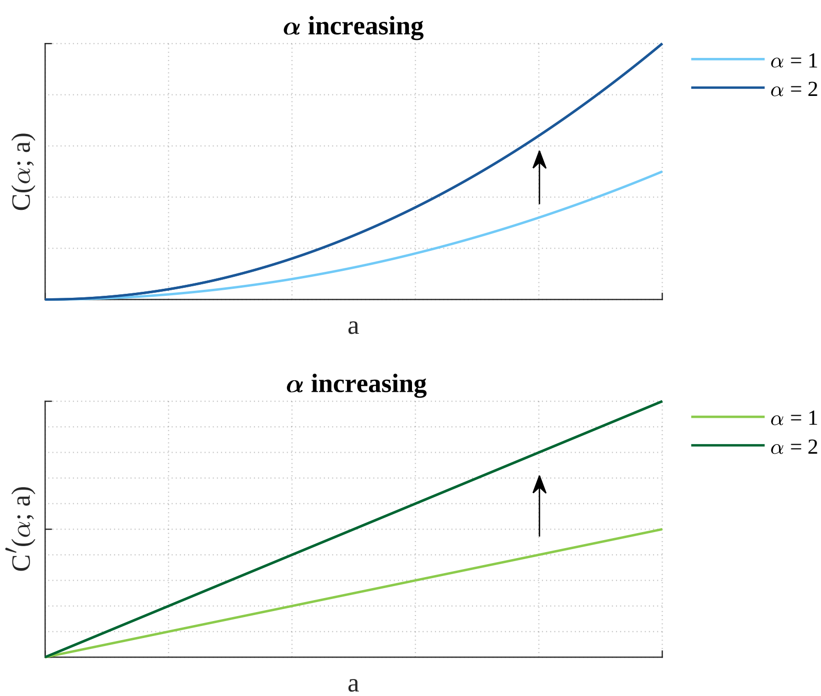

Figure 3: *The direction of change of the cost and marginal cost functions with increasing α_i.*

The **damage function** of country i is given by $D_i(\delta_i; E)$. It is determined by aggregate net emissions $E = \sum_{i=1}^{n} e_i$ and a positive parameter δ_i which is related to the AD technology. The damage function is strictly convex in E.

$$D_i'(\delta_i; E) > 0, \quad D_i''(\delta_i; E) > 0 \tag{5}$$

Analogously to α_i, the technology parameter δ_i varies in the range $\delta_i \in \{\delta_{min}, \delta_{max}\}$ with $\delta_{min} > 0$ such that a higher level of δ_i implies a less efficient (higher per unit damage from total net emissions) AD technology. Hence the damage and marginal damage functions increase with increasing δ_i, implying that a less efficient AD technology is disadvantageous for a country (eq. (6) and **Fig. 4**).

$$\frac{\partial D_i(\delta_i; E)}{\partial \delta_i} > 0, \quad \frac{\partial D_i'(\delta_i; E)}{\partial \delta_i} > 0 \quad \frac{\partial D_i'^{-1}(\delta_i; E)}{\partial \delta_i} < 0 \tag{6}$$

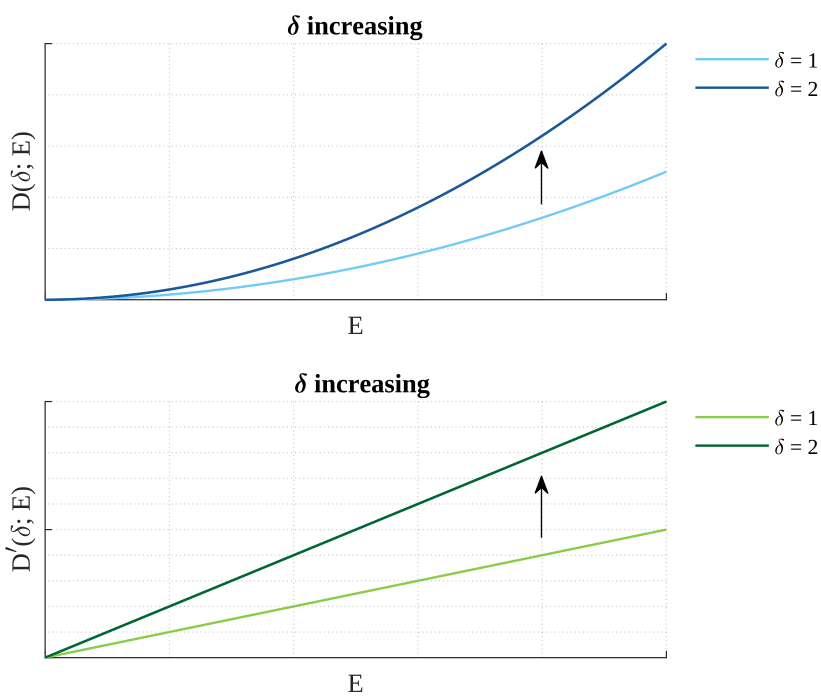

Figure 4: *The direction of change of the damage and marginal damage functions with increasing* δ_i.

Furthermore, we know that an inverse function is a function which negates the action of another function. This said, a function $z(y)$ is an inverse of a function $f(x)$ if it gives x whenever it is applied to y: $f(x) = y \Leftrightarrow z(y) = x$ (Scheinerman 2013). Hence it is probable that the inverse of B_i' can increase with increasing β_i, decrease with increasing ϵ_i prior the intersection point A, and increase thereafter. The inverses of C_i' and D_i' can decrease with increasing α_i and δ_i respectively.

Finally, we impose the standard assumptions that the functions are continuous, twice differentiable, and with a positive decreasing (benefit function) and a positive increasing (cost and damage functions) marginal product (**Table 1**). In addition, we impose the assumptions about how our functions change with the changing technology parameter $\square_i \in \{\alpha, \beta, \delta, \epsilon\}$ (**Table 2**).

Table 1: *Main assumptions of the General Model of Investment Incentives.*

$$
\begin{aligned}
&B_i'(\beta_i, \epsilon_i; g_i) > 0, \quad B_i''(\beta_i, \epsilon_i; g_i) < 0 \\
&C_i'(\alpha_i; a_i) > 0, \qquad C_i''(\alpha_i; a_i) > 0 \\
&D_i'(\delta_i; E) > 0, \qquad D_i''(\delta_i; E) > 0
\end{aligned}
$$

Table 2: *Additional assumptions of the General Model of Investment Incentives.*

$$
\begin{array}{lll}
\dfrac{\partial B_i(\beta_i, \epsilon_i; g_i)}{\partial \beta_i} > 0 & \dfrac{\partial B_i'(\beta_i, \epsilon_i; g_i)}{\partial \beta_i} > 0, & \dfrac{\partial B_i'^{-1}(\beta_i, \epsilon_i; g_i)}{\partial \beta_i} > 0 \\
\dfrac{\partial B_i(\beta_i, \epsilon_i; g_i)}{\partial \epsilon_i} < 0 & \dfrac{\partial B_i'(\beta_i, \epsilon_i; g_i)}{\partial \epsilon_i} > 0^* & \dfrac{\partial B_i'^{-1}(\beta_i, \epsilon_i; g_i)}{\partial \epsilon_i} > 0^* \\
\dfrac{\partial C_i(\alpha_i; a_i)}{\partial \alpha_i} > 0, & \dfrac{\partial C_i'(\alpha_i; a_i)}{\alpha_i} > 0 & \dfrac{\partial C_i'^{-1}(\alpha_i; a_i)}{\partial \alpha_i} < 0 \\
\dfrac{\partial D_i(\delta_i; E)}{\partial \delta_i} > 0, & \dfrac{\partial D_i'(\delta_i; E)}{\partial \delta_i} > 0 & \dfrac{\partial D_i'^{-1}(\delta_i; E)}{\partial \delta_i} < 0
\end{array}
$$

* if g_i is sufficiently high

3.1.2 Nash Equilibrium

The welfare function is strictly concave and is expressed as the difference between the benefit of country i and its abatement cost minus its environmental damage:

$$W_i = B_i(\beta_i, \epsilon_i; g_i) - C_i(\alpha_i; a_i) - D_i(\delta_i; E) \tag{7}$$

Each country i maximizes simultaneously and non-cooperatively their individual welfare with respect to gross emissions and abatement, taking the technology parameters and the emission and abatement levels of the other countries as given.

$$\max_{g_i, a_i} W_i(g_i, a_i, E) \qquad \text{s.t. } E = \sum_{j=1}^{n} g_j - a_j \tag{8}$$

The first-order conditions of the welfare maximization problem result in the optimal levels of gross emissions and abatement (see an expanded version in A.2):

$$\begin{aligned} a_i &= C_i^{\prime -1}\left[D_i^{\prime}(\delta_i; E)\right] \\ g_i &= B_i^{\prime -1}\left[D_i^{\prime}(\delta_i; E)\right] \qquad \forall i = 1, ..., n \end{aligned} \tag{9}$$

Hence the levels of net emissions e_i and aggregate net emissions E are

$$e_i = g_i - a_i = B_i^{\prime -1}\left[D_i^{\prime}(\delta_i; E)\right] - C_i^{\prime -1}\left[D_i^{\prime}(\delta_i; E)\right] \tag{10a}$$

$$\underbrace{E}_{\text{LHS}} = \sum_{i=1}^{n} e_i = \underbrace{\sum_{i=1}^{n}\left(B_i^{\prime -1}\left[D_i^{\prime}(\delta_i; E)\right] - C_i^{\prime -1}\left[D_i^{\prime}(\delta_i; E)\right]\right)}_{\text{RHS}} \tag{10b}$$

The left-hand side (LHS) of the equation (10b) is increasing in E, while the right-hand side (RHS) is decreasing in E. Thus, there exists a unique level of $\hat{E}$ such that $LHS = RHS = 0$ which denotes the aggregate emission level in the Nash equilibrium.

The NE is defined by the vector $(\hat{g}_1, ..., \hat{g}_n; \hat{a}_1, ..., \hat{a}_n; \hat{e}_1, ..., \hat{e}_n)$:

$$
\begin{aligned}
\hat{g}_i &= B_i'^{-1}\left[D_i'(\delta_i, \hat{E})\right] \\
\hat{a}_i &= C_i'^{-1}\left[D_i'(\delta_i, \hat{E})\right] \\
\hat{e}_i &= B_i'^{-1}\left[D_i'(\delta_i, \hat{E})\right] - C_i'^{-1}\left[D_i'(\delta_i, \hat{E})\right]
\end{aligned}
\tag{11}
$$

for given $(\alpha_1, ..., \alpha_n; \beta_1, ..., \beta_n; \delta_1, ..., \delta_n; \epsilon_1, ..., \epsilon_n)$.

3.1.3 Comparative Static Analysis

The comparative *static* analysis is the method to determine how the endogenous variables of a model change in response to a change in the exogenous variables or parameters of a model in an *equilibrium state*. The comparative static analysis can be either qualitative or quantitative. Qualitative comparative statics makes it possible to determine the direction of change (positive, negative or zero), while quantitative comparative statics also gives information about the magnitude of change (how strong a change is) (Chiang, A. C., 1984).

Since we are predominantly concerned with the direction of change, we conduct a qualitative comparative static analysis in the following. Specifically, we seek now to understand how individual net emissions (e_i), the net emissions of all the other countries ($E_{-i} = \sum_{j \neq i}^{n} e_j$) and aggregate net emissions (E) change in the equilibrium state with the marginal change in the technology parameters of a country ($\square_i$). Furthermore, we determine how the abatement and gross emissions of country i (a_i and g_i) change in the equilibrium if technology parameters $\square_{i/j}$ change marginally in country i/j. As a last step, we explore how the welfare of country i (W_i) and the welfare of some other country (W_j) changes with the change in $\square_i$ in the equilibrium state. As such, we treat the variables e_i, E_{-i}, E, a_i and g_i as endogenous, and the technology parameters $\square_{i/j}$ as exogenous.

The results of the comparative static analysis for emissions and abatement are summarized in **Tables 3** and **4**. The detailed derivation of the results is presented in Appendix (A.3 - A.22).

Table 3: *The direction of change in the net emissions of country i, the net emissions of all the other countries, and the total net emissions with the change in* $\square_i$*.*

$\frac{d\hat{e}_i}{d\alpha_i} > 0$	$\frac{d\hat{E}_{-i}}{d\alpha_i} < 0$	$\frac{d\hat{E}}{d\alpha_i} > 0$
$\frac{d\hat{e}_i}{d\beta_i} > 0$	$\frac{d\hat{E}_{-i}}{d\beta_i} < 0$	$\frac{d\hat{E}}{d\beta_i} > 0$
$\frac{d\hat{e}_i}{d\delta_i} < 0$	$\frac{d\hat{E}_{-i}}{d\delta_i} > 0$	$\frac{d\hat{E}}{d\delta_i} < 0$
$\frac{d\hat{e}_i}{d\epsilon_i} > 0^*$	$\frac{d\hat{E}_{-i}}{d\epsilon_i} < 0^*$	$\frac{d\hat{E}}{d\epsilon_i} > 0^*$

* if g_i is sufficiently high

As we can see from **Table 3**, quite intuitively, the net emissions of country i and the total net emissions increase with a worse AB technology and a lower share of LC technology in country i's energy mix. What is less intuitive is that the net emissions and the total net emissions increase with better EE and AD technologies. This could be explained by 1) the presence of the *rebound effect*, i.e., the situation when the improvements in EE result in an increased energy consumption that drives net emissions up (Gillingham 2016); 2) the fact that a better AD technology lowers the damage costs of any given level of global emissions. As a consequence, it is optimal to produce and emit more. The emissions of all the other countries, in their turn, increase if country i has a better AB technology, worse EE and AD technologies, and a higher share of LC technology in its energy mix. The explanation to such result rests on the PG property of mitigation which induces the other countries to free ride on emissions.

Table 4: *The direction of change in the abatement and gross emissions of country i with the change in* $\square_{i/j}$.

$\frac{d\hat{a}_i}{d\alpha_i} \lesseqgtr 0$	$\frac{d\hat{a}_i}{d\alpha_j} > 0$	$\frac{\partial \hat{g}_i}{\partial \alpha_i} < 0$	$\frac{\partial \hat{g}_i}{\partial \alpha_j} < 0$
$\frac{d\hat{a}_i}{d\beta_i} > 0$	$\frac{d\hat{a}_i}{d\beta_j} > 0$	$\frac{\partial \hat{g}_i}{\partial \beta_i} < 0$	$\frac{\partial \hat{g}_i}{\partial \beta_j} < 0$
$\frac{d\hat{a}_i}{d\delta_i} \lesseqgtr 0$	$\frac{d\hat{a}_i}{d\delta_j} < 0$	$\frac{\partial \hat{g}_i}{\partial \delta_i} \lesseqgtr 0$	$\frac{\partial \hat{g}_j}{\partial \delta_j} > 0$
$\frac{d\hat{a}_i}{d\epsilon_i} > 0^*$	$\frac{d\hat{a}_i}{d\epsilon_j} > 0^*$	$\frac{\partial \hat{g}_i}{\partial \epsilon_i} < 0^*$	$\frac{\partial \hat{g}_i}{\partial \epsilon_j} < 0^*$

* if g_i is sufficiently high

The change in the aggregate abatement and gross emissions, as well as the change in the abatement and gross emissions of all the other countries are not in the focus of our analysis. The reason for this is that such estimations do not serve our central purpose of determining how the welfare of country i/j changes with the change in $\square_i$. Yet, it is still interesting to see how the individual abatement and gross emissions of country i respond to the changes in $\square_{i/j}$.

Table 4 shows that the abatement of country i can both increase or decrease with its worse AB and AD technologies. The direction of change would depend in this case on specific functional forms. The abatement of i, however, clearly increases if both countries have better EE and less LC technologies, as well as if country j has a worse AB technology. This is in line with the main findings of Buchholz et al. (1994) that a less efficient AB technology in one country induces the other country to abate more. The results of comparative statics for gross emissions appear to be less intuitive: the gross emissions of country i increase if both countries have a better AB technology or more LC technologies. Put differently, a lower per unit cost of abatement and the wide application of low-carbon technologies give an incentive to produce more gross emissions.

As a next step, we conduct comparative statics for the welfare of country i and j with respect to the changes in $\square_i$.

The welfare of country i in the NE is given by:

$$\hat{W}_i = B_i(\beta_i, \epsilon_i; \hat{g}_i) - C_i(\alpha_i; \hat{a}_i) - D_i(\delta_i; \hat{E}) \tag{12}$$

Differentiating $\hat{W}_i$ w.r.t. α_i yields:

$$\begin{aligned} \frac{\partial \hat{W}_i}{\partial \alpha_i} &= B_i'(\beta_i, \epsilon_i; \hat{g}_i)\frac{d\hat{g}_i}{d\alpha_i} - \frac{\partial C_i(\alpha_i; \hat{a}_i)}{\partial \alpha_i} - C_i'(\alpha_i; \hat{a}_i)\frac{d\hat{a}_i}{d\alpha_i} - D_i'(\delta_i; \hat{E})\frac{d\hat{E}}{d\alpha_i} = \\ &= -\frac{\partial C_i(\alpha_i; \hat{a}_i)}{\partial \alpha_i} - D_i'(\delta_i; \hat{E})\left[\frac{d\hat{E}}{d\alpha_i} - \frac{d\hat{g}_i}{d\alpha_i} + \frac{d\hat{a}_i}{d\alpha_i}\right] = \\ &= \underbrace{-\frac{\partial C_i(\alpha_i; \hat{a}_i)}{\partial \alpha_i}}_{<0} - D_i'(\delta_i; \hat{E})\underbrace{\frac{d\hat{E}_{-i}}{d\alpha_i}}_{<0} \gtreqless 0 \end{aligned} \tag{13}$$

Differentiating $\hat{W}_i$ w.r.t. β_i yields:

$$\begin{aligned} \frac{\partial \hat{W}_i}{\partial \beta_i} &= \frac{\partial B_i(\beta_i, \epsilon_i; \hat{g}_i)}{\partial \beta_i} - B_i'(\beta_i, \epsilon_i; \hat{g}_i)\frac{d\hat{g}_i}{d\beta_i} - C_i'(\alpha_i; \hat{a}_i)\frac{d\hat{a}_i}{d\beta_i} - D_i'(\delta_i; \hat{E})\frac{d\hat{E}}{d\beta_i} = \\ &= \frac{\partial B_i(\beta_i, \epsilon_i; \hat{g}_i)}{\partial \beta_i} - D_i'(\delta_i; \hat{E})\left[\frac{d\hat{E}}{d\beta_i} - \frac{d\hat{g}_i}{d\beta_i} + \frac{d\hat{a}_i}{d\beta_i}\right] = \\ &= \underbrace{\frac{\partial B_i(\beta_i, \epsilon_i; \hat{g}_i)}{\partial \beta_i}}_{>0} - D_i'(\delta_i; \hat{E})\underbrace{\frac{d\hat{E}_{-i}}{d\beta_i}}_{<0} > 0 \end{aligned} \tag{14}$$

Differentiating $\hat{W}_i$ w.r.t. δ_i yields:

$$\begin{aligned} \frac{\partial \hat{W}_i}{\partial \delta_i} &= B_i'(\beta_i, \epsilon_i; \hat{g}_i)\frac{d\hat{g}_i}{d\delta_i} - C_i'(\alpha_i; \hat{a}_i)\frac{d\hat{a}_i}{d\delta_i} - \frac{\partial D_i(\delta_i; \hat{E})}{\partial \delta_i} - D_i'(\delta_i; \hat{E})\frac{d\hat{E}}{d\delta_i} = \\ &= -\frac{\partial D_i(\delta_i; \hat{E})}{\partial \delta_i} - D_i'(\delta_i; \hat{E})\left[\frac{d\hat{E}}{d\delta_i} - \frac{d\hat{g}_i}{d\delta_i} + \frac{d\hat{a}_i}{d\delta_i}\right] = \\ &= \underbrace{-\frac{\partial D_i(\delta_i; \hat{E})}{\partial \delta_i}}_{<0} - D_i'(\delta_i; \hat{E})\underbrace{\frac{d\hat{E}_{-i}}{d\delta_i}}_{>0} < 0 \end{aligned} \tag{15}$$

Differentiating $\hat{W}_i$ w.r.t. ϵ_i yields:

$$\begin{aligned}\frac{\partial \hat{W}_i}{\partial \epsilon_i} &= \frac{\partial B_i(\beta_i, \epsilon_i; \hat{g}_i)}{\partial \epsilon_i} - B_i'(\beta_i, \epsilon_i; \hat{g}_i)\frac{d\hat{g}_i}{d\epsilon_i} - C_i'(\alpha_i; \hat{a}_i)\frac{d\hat{a}_i}{d\epsilon_i} - D_i'(\delta_i; \hat{E})\frac{d\hat{E}}{d\epsilon_i} = \\ &= \frac{\partial B_i(\beta_i, \epsilon_i; \hat{g}_i)}{\partial \epsilon_i} - D_i'(\delta_i; \hat{E})\left[\frac{d\hat{E}}{d\epsilon_i} - \frac{d\hat{g}_i}{d\epsilon_i} + \frac{d\hat{a}_i}{d\epsilon_i}\right] = \\ &= \underbrace{\frac{\partial B_i(\beta_i, \epsilon_i; \hat{g}_i)}{\partial \epsilon_i}}_{<0} - D_i'(\delta_i; \hat{E})\underbrace{\frac{d\hat{E}_{-i}}{d\epsilon_i}}_{<0} \gtreqless 0 \iff \quad g_i \text{ is sufficiently high}\end{aligned} \tag{16}$$

The partial derivatives of W_i with respect to $\square_i$ are decomposed into a direct and indirect effect (or strategic interaction effect). The former implies the partial derivative of a benefit, cost and damage function with respect to $\square_i$, while the latter is the product of the marginal damage and the total derivative of $\hat{E}_{-i}$ with respect to $\square_i$. Note that $\frac{d\hat{E}_{-i}}{d\square_i}$ is the element which accounts for strategic substitutability, as it considers the total net emissions of all the other countries. Accordingly, the sign of the direct and indirect effects determiners whether the PG-property of abatement fosters or hinders the incentives to invest in a particular technology. If both direct and indirect effect exhibit the same sign, i.e., go in the same direction, then the strategic interaction effect fosters the innovation incentives. However, if the effects are of opposite signs (one is negative and the other is positive), then the strategic interaction effect hinders the innovation incentives. In this case the magnitude of the direct and indirect effects will determine the sign of $\frac{d\hat{W}_i}{d\square_i}$: if the indirect effect outweighs the direct one, a country would prefer to have a less efficient technology. The magnitude of the effects depends on the specific parameterized functional forms which could be applied to our general model of investment incentives.

We see that in (13) and (16) the direct effect is positive, while the indirect effect is negative, hence the indirect effect with respect to AB and LC technologies hinders the incentives to invest in these technologies. Accordingly, the welfare of country i can both increase or decrease with increasing α_i and ϵ_i[2]. Hence if the indirect effect

[2] $\frac{d\hat{W}_i}{d\epsilon_i} \lesseqgtr 0$ holds if g_i is high enough; otherwise $\frac{d\hat{W}_i}{d\epsilon_i} < 0$. In the following, we assume that this condition holds.

is stronger than the direct one, a country would prefer to have a less efficient AB technology and less LC technologies in its energy mix. We see further that in (14) and (15) the direct and indirect effects have the same sign (for β_i both are positive, and for δ_i both are negative), which means that the indirect effect fosters the incentives to invest in EE and AD technology. The welfare of country i is unambiguously increasing with a higher β_i and a lower δ_i, showing that better EE and AD technologies are always beneficial for country i.

Let us now analyse how the welfare of some other country j responds to the changes in the exogenous parameters of country i. This will give us a more nuanced understanding of how the adoption of a particular climate technology in one country can influence the welfare of the other country.

The welfare of country j in the NE is given by:

$$\hat{W}_j = B_j(\beta_j, \epsilon_j; \hat{g}_j) - C_j(\alpha_j; \hat{a}_j) - D_j(\delta_j; \hat{E}) \tag{17}$$

Differentiating $\hat{W}_j$ w.r.t. α_i, β_i, δ_i and ϵ_i yields:

$$\begin{aligned}
\frac{\partial \hat{W}_j}{\partial \alpha_i} &= -D_j'(\delta_j, \hat{E})\frac{d\hat{E}}{d\alpha_i} < 0 \\
\frac{\partial \hat{W}_j}{\partial \beta_i} &= -D_j'(\delta_j, \hat{E})\frac{d\hat{E}}{d\beta_i} < 0 \\
\frac{\partial \hat{W}_j}{\partial \delta_i} &= -D_j'(\delta_j, \hat{E})\frac{d\hat{E}}{d\delta_i} > 0 \\
\frac{\partial \hat{W}_j}{\partial \epsilon_i} &= -D_j'(\delta_j, \hat{E})\frac{d\hat{E}}{d\epsilon_i} < 0 \quad \iff \quad g_i \text{ is sufficiently high}
\end{aligned} \tag{18}$$

We see that the welfare of country j decreases if country i has a worse AB, a better EE, and a better AD technology, as well as less LC technology in its energy mix. An intuitive interpretation to this result is that the adoption of emission-increasing technologies in one country is in general disadvantageous for the other country, however, country j is gaining if emissions are dampened in country i. The results of the comparative statics for the welfare of both countries are summarized in **Table 5**.

Table 5: The direction of change of country i/j's welfare with the change in $\Box_i$.

$$\frac{\partial \hat{W}_i}{\partial \alpha_i} \lesseqqgtr 0 \quad \frac{\partial \hat{W}_j}{\partial \alpha_i} < 0$$
$$\frac{\partial \hat{W}_i}{\partial \beta_i} > 0 \quad \frac{\partial \hat{W}_j}{\partial \beta_i} < 0$$
$$\frac{\partial \hat{W}_i}{\partial \delta_i} < 0 \quad \frac{\partial \hat{W}_j}{\partial \delta_i} > 0$$
$$\frac{\partial \hat{W}_i}{\partial \epsilon_i} \gtreqqless 0 \quad \frac{\partial \hat{W}_j}{\partial \epsilon_i} < 0 \quad \Longleftrightarrow \quad \text{if } g_i \text{ is sufficiently high}$$

In summary, the comparative static analysis resulted in three key findings. Firstly, the strategic interaction effect hinders the incentives to invest in AB and LC technologies and fosters the incentives to invest in EE and AD technologies. Secondly, it can happen that a country would prefer to have a worse AB technology and less LC technology in its energy mix due to strategic reasons. Thirdly, a country would always prefer to have better EE and AD technologies. In the next section we show that our results are not purely hypothetical, namely, we show that a country would always prefer to have a worse AB technology if the number of countries is large enough.

3.2 The Specific Model of Investment Incentives

Let us now deploy some specific functional forms that satisfy the assumptions in **Tables 1-2**. We use simple quadratic benefit, cost and damage functions for each country as summarised in (19).

$$\begin{aligned}
&B_i(g_i) = \frac{2\beta_i}{\epsilon_i^2} g_i(\epsilon_i - \frac{1}{2} g_i), && B'(g_i) = \frac{2\beta_i}{\epsilon_i^2}(\epsilon_i - g_i), && B''(g_i) = -\frac{2\beta_i}{\epsilon_i^2} \\
&C_i(a_i) = \frac{1}{2}\alpha_i a_i^2, && C_i'(a_i) = \alpha_i a_i, && C_i''(a_i) = \alpha_i \\
&D_i(E) = \frac{1}{2}\delta_i E^2, && D_i'(E) = \delta_i E, && D_i''(E) = \delta_i
\end{aligned} \tag{19}$$

Recall that the welfare function of country i is given by:

$$W_i = B_i(\beta_i, \epsilon_i; g_i) - C_i(\alpha_i; a_i) - D_i(\delta_i; E) \tag{20}$$

We also define:

$$k = \delta \left(\frac{\alpha\epsilon^2 + 2\beta}{2\beta\alpha} \right) > 0 \tag{21}$$

Assume further that the countries are symmetrical, then we obtain:

$$\begin{aligned}
\frac{\partial W}{\partial \alpha} &= \frac{\delta^2 n^2 \epsilon^2 (k(n-2)-1)}{2(1+nk)^2\alpha^2} > 0 \quad \iff \quad n > 2 + \frac{1}{k} \\
\frac{\partial W}{\partial \beta} &= \frac{4(1+kn)^3\beta^2 + n^2\epsilon^4\delta^2(k(n-2)-1)}{4(1+kn)^3\beta^2} > 0 \\
\frac{\partial W}{\partial \delta} &= -\frac{n^2\epsilon^2\left[((n\beta + \delta\epsilon^2(n-1)) + 2\beta\delta(n-1))k + \alpha\beta\right]}{2(1+kn)^3\beta\alpha} < 0 \\
\frac{\partial W}{\partial \epsilon} &= -\frac{\delta n\epsilon \Big(2(\alpha+\delta)(1+kn)\beta^2 + \delta\big((\epsilon(1+kn) + n\epsilon(kn-1))\alpha\big)\epsilon\beta - 2\delta n\epsilon - n\epsilon^4\alpha\delta^2 \Big)}{2(nk+1)^3\beta^2\alpha} \lesseqqgtr 0
\end{aligned} \tag{22}$$

The detailed derivation of this result is presented in Appendix A.24 - A.32.

The welfare of a country is increasing with a higher α, higher β and lower δ if n is large enough, however, it is not clear how welfare responds to the marginal change in ϵ. Hence in the case of symmetrical countries a country would always prefer to have a worse AB, better EE and better AD technology if the number of countries is sufficiently large. A country might also prefer to have less or more LC technology in its energy mix depending on the value of exogenous parameters.

3.3 Numerical Illustration

In the final part of this chapter we demonstrate how our model can be applied to a real-case example. For this purpose we select five major CO_2-emitting countries and assign particular values to the four technology parameters for each selected country.

As a next step, we provide two NIs to examine the strength of the strategic interaction effect and welfare elasticities for each country.

The top-5 CO_2 emitters in 2017 included China (9.23 Gt CO_2/yr), the United States (5.09 Gt CO_2/yr), the EU (4.15 Gt CO_2/yr), India (2.34 Gt CO_2/yr) and Russian Federation (1.53 Gt CO_2/yr) (from here: Russia). The data are inferred from the BP Statistical Review of World Energy 2018 and are compatible with the rankings provided by the World Bank in 2014 and 2015.

The selection of the values for our exogenous parameters should allow for the realistic calibration of the endogenous parameters g_i, a_i, e_i and E, as well as marginal benefit, cost, and damage of each country. In our model marginal benefit, cost, and damage are equalized in the equilibrium, which does not hold in reality. For this reason we provide two NIs: one calibrates *inter alia* marginal benefit, and the second calibrates marginal damage. The calibration of marginal abatement cost is not feasible due to the absence of data.

3.3.1 NI-1

Table 6: *Selected technology parameter values by country for NI-1.*

	α	β	δ	ϵ
China	140.0	12270.1	1.00	9.45
US	180.0	19400.0	1.97	5.35
EU	450.0	17270.5	4.68	4.45
India	440.0	2610.0	3.70	2.60
Russia	440.0	1570.0	3.46	1.75

The selected exogenous parameter values summarized in **Table 6** enable us to calibrate the levels of endogenous parameters (**Table 7**) such that they are consistent with empirical values. The comparison of the empirical and calibrated values see in B-Appendix, **Table 13**.

Table 7: *Calibrated levels of endogenous parameters, benefit, cost, damage, and total welfare by country for NI-1.*

	g	**a**	**e**	**E**	**B(g)**	**C(a)**	**D(E)**	**W**
China	9.369	0.15892	9.213	22.249	12269.199	1.768	247.518	12019.913
US	5.318	0.24351	5.350		19399.291	5.337	487.611	18906.343
EU	4.390	0.23139	4.369		17267.392	12.047	1158.386	16096.958
India	2.493	0.18710	2.088		2605.612	7.701	915.818	1682.092
Russia	1.675	0.17496	1.291		1567.110	6.735	856.414	703.962

As a next step, we determine the welfare elasticities and the strength of the strategic interaction effect (indirect effect) for each country.

Recall from the equations 13 - 16 that

$$
\begin{aligned}
& \qquad\qquad \text{direct effect} \qquad\qquad\qquad \text{indirect effect} \\
& \qquad\qquad\qquad \downarrow \qquad\qquad\qquad\qquad\qquad \downarrow \\
\frac{\partial \hat{W}_i}{\partial \alpha_i} &= \underbrace{-\frac{\partial C_i(\alpha_i; \hat{a}_i)}{\partial \alpha_i}}_{<0} \quad - D_i'(\delta_i; \hat{E}) \underbrace{\frac{d\hat{E}_{-i}}{d\alpha_i}}_{<0} \gtreqless 0 \\
\frac{\partial \hat{W}_i}{\partial \beta_i} &= \underbrace{\frac{\partial B_i(\beta_i, \epsilon_i; \hat{g}_i)}{\partial \beta_i}}_{>0} \quad - D_i'(\delta_i; \hat{E}) \underbrace{\frac{d\hat{E}_{-i}}{d\beta_i}}_{<0} > 0 \\
\frac{\partial \hat{W}_i}{\partial \delta_i} &= \underbrace{-\frac{\partial D_i(\delta_i; \hat{E})}{\partial \delta_i}}_{<0} \quad - D_i'(\delta_i; \hat{E}) \underbrace{\frac{d\hat{E}_{-i}}{d\delta_i}}_{>0} < 0 \\
\frac{\partial \hat{W}_i}{\partial \epsilon_i} &= \underbrace{\frac{\partial B_i(\beta_i, \epsilon_i; \hat{g}_i)}{\partial \epsilon_i}}_{<0} \quad - D_i'(\delta_i; \hat{E}) \underbrace{\frac{d\hat{E}_{-i}}{d\epsilon_i}}_{<0} \gtreqless 0 \qquad \Longleftrightarrow \qquad g_i \text{ is sufficiently high}
\end{aligned}
\tag{23}
$$

where the first term of each derivative is the direct effect and the second term is the indirect effect. Such decomposition allows for a simple computation of welfare elasticities and the magnitude of the effects for each country. The welfare elasticities are summarized in **Table 8**.

Table 8: *Welfare elasticity by country and technology type for NI-1, %.*

	AB	**EE**	**AD**	**LC**
China	-0.00013324	1.02074651	-0.02061327	-0.01653339
US	-0.00025656	1.02607657	-0.02582001	-0.01177016
EU	-0.00068122	1.07272881	-0.07204760	-0.02714218
India	-0.00416829	1.54926389	-0.54509561	-0.11679733
Russia	-0.00867438	2.22651299	-1.21783861	-0.17500513

The welfare of each country decreases with 1% deterioration in AB, AD, and LC technologies[3] and increases with 1% improvement in EE technology. This points to the fact that none of the countries would prefer to have a worse AB or less LC technologies in their energy mixes for strategic reasons, while every country would benefit substantially from 1% improvement in EE. Indeed, as **Figure 5** shows, the direct effect (light red and blue) always outweighs the indirect one (dark red and blue) for AB and LC technologies. It also can be seen that the indirect effect hinders the incentives to invest in AB technology by $\approx 10\%$ and in LC technology by $\approx 5\%$ in relation to welfare elasticity for each country. The influence of the indirect effect with respect to EE and AD technologies is much less pronounced (<1%) (see the values in B-Appendix, **Tables 14-15**), i.e., strategic interaction fosters the incentives to invest in EE and AD technologies only marginally. Interesting, that despite the technology parameters vary across the countries, the magnitude of the effects is approximately the same for each country.

[3]By 1% deterioration in LC technology we imply 1% decrease in the share of LC technology in country i's energy mix.

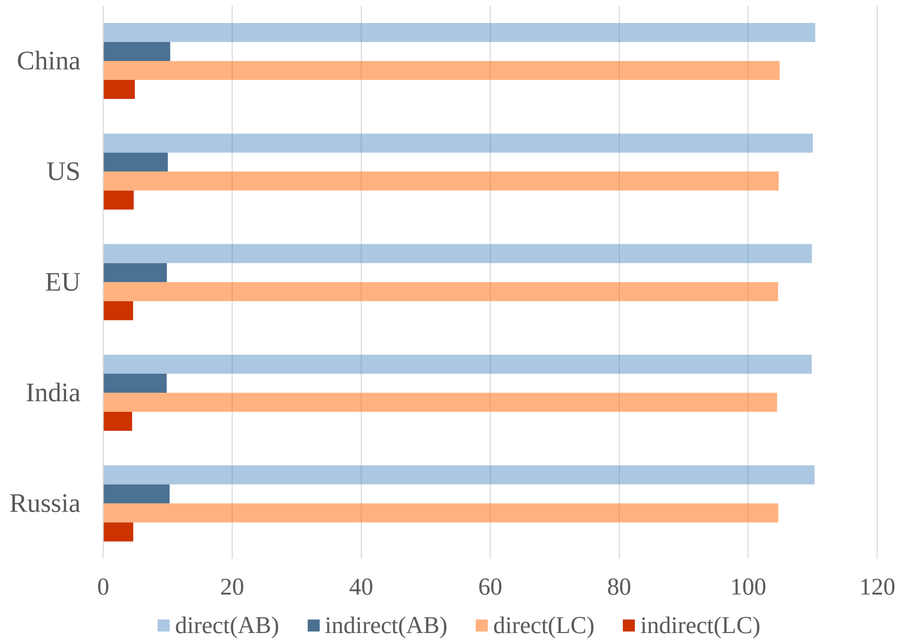

Figure 5: *Relation of the direct and indirect effects to the elasticity w.r.t. AB and LC technology for NI-1,%. See original values in B-Appendix, Tables 14-15.*

3.3.2 NI-2

The robust data on marginal damage is available only for China, the US and the EU, and is therefore less reliable than the data on marginal benefit. For this reason the second NI can be seen as additional rather than alternative to the first one.

Table 9: *Selected technology parameter values by country for NI-2.*

	α	β	δ	ϵ
China	140.0	12270.1	1.25	9.60
US	180.0	19400.0	4.32	5.80
EU	210.0	17270.5	5.43	4.85
India	140.0	2610.0	1.25	2.55
Russia	140.0	1570.0	1.00	1.68

Based on the parameter values from **Table 9** we calibrate the levels of endogenous parameters (**Table 10**) such that they are consistent with empirical values. The comparison of the empirical and calibrated values see in B-Appendix, **Table 16**.

Table 10: *Calibrated levels of endogenous parameters, benefit, cost, damage, and total welfare by country for NI-2.*

	g	a	e	E	B(g)	C(a)	D(E)	W
China	9.495	0.20063	9.294	22.470	12268.548	2.818	315.564	11950.237
US	5.716	0.53928	5.177		19395.549	26.174	1090.590	18279.151
EU	4.767	0.58101	4.186		17264.870	35.445	1370.811	15859.175
India	2.515	0.20063	2.314		2609.461	2.818	315.564	2291.127
Russia	1.660	0.16050	1.499		1569.743	1.803	252.451	1315.519

Respective welfare elasticities are summarized in **Table 11**.

Table 11: *Welfare elasticity by country and technology type for NI-2, %.*

	AB	EE	AD	LC
China	-0.0002030	1.0266595	-0.0264566	-0.0207797
US	-0.0012697	1.0611203	-0.0598506	-0.0260652
EU	-0.0019892	1.0887066	-0.0867173	-0.0314700
India	-0.0010515	1.1389940	-0.1379425	-0.0292416
Russia	-0.0011659	1.1932990	-0.1921331	-0.0270342

Analogously to NI-1, the welfare of each country decreases with 1% deterioration in AB, AD and LC technology and increases with 1% improvement in EE. This reaffirms that none of the countries would prefer to have a worse AB or less LC technologies in their energy mixes in order to shift the burden of mitigation to the other countries, and all countries would benefit substantially from 1% improvement in EE. **Figure 6** demonstrates that the direct effect (light red and blue) always outweighs the indirect one (dark red and blue) for AB and LC technologies, which is in line with the results of NI-1. However, in contrast to NI-1, the strength of the indirect effect for a particular technology is not homogeneous across the countries. We see that the indirect effect with respect to AB technology is weaker for the developed countries (US, EU), constituting ≈ 12%, and stronger for the developing countries (China, India, Russia), constituting ≈ 17%. Regarding LC technology, the reverse is true. The indirect effect is stronger for the developed countries (≈ 16%) and weaker for the developing (≈ 6%). This implies that the strategic interaction effect stronger hinders the incentives of the developed countries to invest in LC technology and the incentives of the developing countries to invest in AB technology. The influence of the indirect effect with respect to EE and AD technologies is in accordance with NI-1, i.e., the indirect effect is <1% (see the values in B-Appendix, **Tables 17-18**).

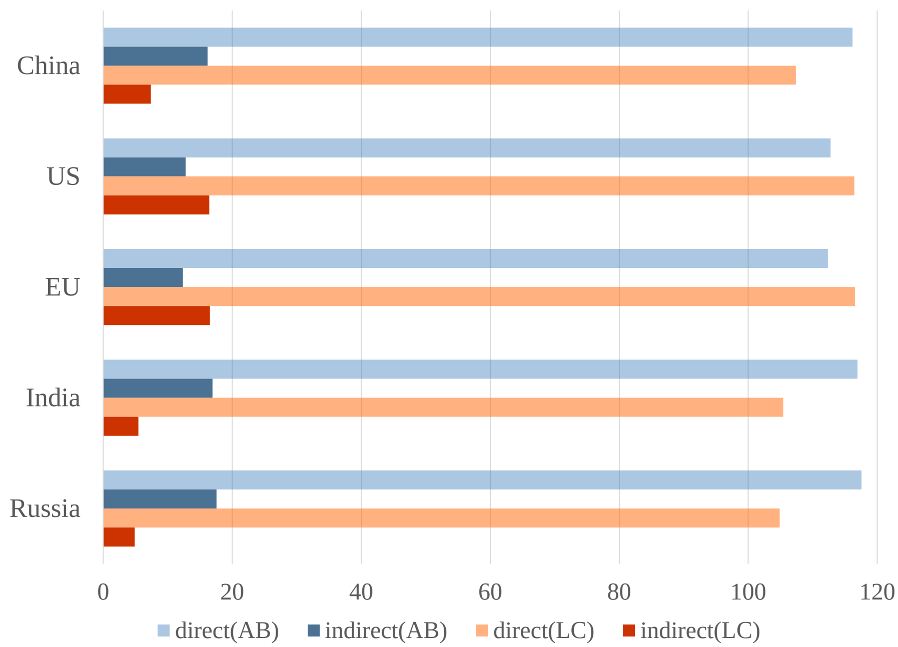

Figure 6: *Relation of the direct and indirect effects to the elasticity w.r.t. AB and LC technology,%. See original values in B-Appendix, Tables 17 - 18.*

4 Discussion

4.1 Assumptions

The results of our model hinge on a few reasonable assumptions about monotonicity and convexity (**Tables 1-2**). The main reason for deploying such assumptions is that they are very general yet they allow to capture the strategic interaction effect, find a unique Nash equilibrium, and to approximate the reality in a sound way. This said, any specific functional forms satisfying our assumptions could be used to conduct a NI and thus make reasonable inferences about real-world situations.

For the sake of simplicity, we used quadratic benefit, cost, and damage functions. It has been shown that the damage is exponential or polynomial in temperature, i.e., a substantial temperature increase may result in dire damage. Although the precise equilibrium climate sensitivity is yet unknown, the climate models generally agree that temperature is increasing logarithmically with atmospheric carbon dioxide concentrations (IPCC 2014). This property coupled with the non-linear damage from temperature change legitimizes a slightly convex in E damage function. Literature also recognizes that an abatement cost curve (and corresponding benefit from gross emissions) can be well approximated with a quadratic form (Winkler 2017). On the other hand, some studies stress that a log-log specification gives a better approximation than simple linear or quadratic functions (Rahman et al. 2009, Bystrom 1998), and, for instance, Buccholz et al. (1994) express their function in a semi-logarithmic way to capture the strategic interaction. Thus, future research could test different forms of benefit, cost and damage functions for different climate technologies.

We approached the PG problem in the framework of a static non-cooperative game. Although such a setup allows to shed light on the incentives, it is yet a substantial simplification because climate politics is a dynamic process: emissions and technologies are being chosen continuously, and the order of emission choices and technological investments is not always straightforward. The underlying assumption of non-cooperation at a global scale is, however, more realistic: the attempts to shape a supranational authority that could enforce the efficient provision of abatement or facilitate the development of climate technology have not been notably successful. Yet, solving the dynamic game and considering a cooperative choice of technologies, rather than emissions, could yield interesting results.

The neglect of the scientific uncertainty associated with climate change (i.e., the assumed complete information) is another substantial simplification. However, in the context of the PG problem it does not jeopardize our results because every country has the same level of incomplete information, i.e., no country has a better estimation of the equilibrium climate sensitivity than the other countries (IPCC 2014). It is also safe to depart from the issues of asymmetric information, because the domestic policies and the actions of countries on the international arena are, in general, common knowledge: we are well aware of the energy or climate change policies of, for example, the US or China. Thus, our assumption of a perfect information game is fairly realistic.

Furthermore, we assumed that the government fully controls the firms' incentives to invest in technologies, however, it is only partly realistic. Governments can issue policies aimed at hindering or fostering the investment incentives, however, such policies can hardly have a 100% effect. This said, governmental policies do not fully induce firms to invest more or less in a particular technology, usually they are only partly effective. It would be even more unrealistic to assume that the government can directly impose a technology choice, i.e., fully control the investments *per se*, and not only investment incentives. Whereas for some countries that exert characteristics of an authoritarian regime (e.g., China or Russia) this might be a reasonable assumption, for the other countries under consideration it hardly holds true. For this reason we did not analyze the optimal technology choices, but incentives, assuming 1:1 relationship between governmental signals and the actions of firms. Accordingly, our analysis could be improved by making a distinction between these two notions.

It could also be useful and interesting to consider domestic politics and international emission trading schemes in the analysis. We assumed that the countries are solely represented by their respective governments that make decisions on behalf of domestic firms. However there are also other actors influencing national positions at the international climate negotiations, such as environmental NGOs or green parties (Sprinz 2001). Per capita emission permits can serve in their turn as a criteria for bargaining emission reductions (Callan 2013, Heitzig et al. 2011), and hence they can influence a country's choice of abatement. Thus, future research could 'zoom-in' more on domestic politics, for example, by examining the interaction between firms, government and interest groups, as well as explore the bargaining potential of emission permits on abatement.

4.2 Numerical Illustration

Selection of the technology parameters

The technology parameter values were selected such that they allow for the realistic calibration of the endogenous parameters g_i, a_i, e_i and E, as well as marginal benefit and damage of each country. Whereas the data on net emissions, countries' GDP and marginal benefit is relatively robust, the data on marginal damage is less reliable and hence worth discussing.

For calibrating marginal environmental damage in NI-2 we looked at the perceived damage from climate change, since no robust cross-country data on AD technology deployment is available. The perceived climate damage can be measured based on willingness to pay (WTP) for climate action and public attitudes towards climate change. Since we are mostly concerned with climate politics, we gave more weight to the WTP measure and used public attitudes as an additional indicator.

The survey conducted by the World Bank in 2009 revealed to an extent whether the key emitters are willing to pay more (1% GDP *per capita*) for energy and other products to confront climate change. The results showed that China is most willing to pay (68%), followed by the US (48%), India (44%), and Russia (11%). Among European countries only France (48%) was included in the survey, and therefore we cannot make an inference about the EU-average (Bank 2010). Moreover, in absolute terms China would pay less than, for example, the US. The study by Carlsson et al. (2010) estimated that an average Chinese household would pay $4.99 per month for 30% CO_2 reduction by the year 2050, while the respondents in the US and EU would pay $17.27 and $21.70 respectively, which is comparable with the current price of CO_2 European emission allowance ($25.67). Based on this information we assigned India the same δ_i as for China, since both belong to BRIC, however, we assigned Russia a slightly smaller δ_i (see **Table 9**) because of the notable indifference of Russian population towards climate change. The International Social Survey Programme in 2010 revealed that among 33 countries Russia took the last position in *the perceived dangerousness of climate change* and 25 position in *the importance of climate change* (Smith 2017). In addition, Russia can potentially gain from moderate climate change because of a northward expansion of agricultural activities. As such, Russian population does not perceive climate change neither as dangerous nor as important, whereas the Chinese and Indian population expressed a somewhat larger concern (WB 2009).

Thus, a more robust and comprehensive estimation of marginal environmental damage could improve our numerical results. Further research could also consider additional criteria for selecting technology parameters. In the following, we propose such criteria for AB, LC and EE technologies.

The secondary literature review about the application of end-of-pipe technologies (specifically CCS) can well serve as a measure for **AB** technology parameter. Frondel et al. (2007) showed that in seven OECD countries (Canada, France, Hungary, Japan, Norway and the US) the share of investments in end-of-pipe technologies accounted for only 23.2% of the total climate investments in 2003, while, for example, the investments in EE constituted 76.8% in the same year. The more recent studies by Hammar et.al. (2010) and Wang et.al (2017) reaffirm the low popularity of end-of-pipe technologies in Sweden and the US, and Wennersten et al. (2015) finds further that CCS technology in the major emitting countries (China, the US, the EU, India and Russia) is implemented only on a pilot and demonstration scales. Based on these findings one could assign relatively high and similar values to α_i, displaying thus a high cost of AB technology for each country. While the values of α_i are kept relatively high in our NIs, their variance is yet too large, especially in NI-1.

According to the methodology of the International Energy Agency, energy intensity can serve as an indicator for **EE**. Energy intensity measures the amount of energy needed to produce a unit of output (IEA 2017). Thus, the reductions in energy intensity are associated with the improvements in EE, and vice versa. The World Bank provides cross-country data on energy intensity levels of primary energy (MJ/$2011 PPP GDP) that are presented in **Table 12**.

Table 12: *Energy intensity levels of primary energy (MJ/$2011 PPP GDP) and the share of electricity production from renewable sources (% of total) by country. World Bank Database, last update: 28-08-2018.*

	Energy Intensity (2015)	The share of RES (2014)
China	6.690	4.057
US	5.408	6.900
EU	3.662	16.622
India	4.731	5.184
Russia	8.413	0.070

We know furthermore from Frondel et.al. (2007) that in the OECD countries the investments in EE are much higher compared to those in AB technology. For this reason it makes sense to keep the values for β_i high in comparison to the other parameters, which is satisfied in our NIs.

The values for **LC** technology parameter could be inferred by considering the share of electricity production from renewable energy sources (RES) compared to the total production of electricity. As **Table 12** shows, the share of renewable electricity production is quite low across the countries, with the sole exception of the EU. Therefore, it would be reasonable to choose the parameter values such that the relative difference between g_i and ϵ_i is the greatest for the EU, whereby $\epsilon_i \geqslant g_i$ for all countries. While the latter holds in our NIs, the former property is not captured.

Results of NI-1 and NI-2

In general, both NIs agree on two important points. Firstly, the strategic interaction effect is not strong enough to induce the countries to invest in a worse AB or LC technology, i.e., the welfare of each country does not increase with increasing α_i or ϵ_i. The reason for this is that the condition $K > 1 + 2k_i$ in (A.32) is not satisfied. The condition gets satisfied when the differences in parameter values are minimal, for example, when the values of $\Box_i$ vary in the range of 1-2. Secondly, the strategic interaction effect is much more pronounced with respect to AB and LC technologies (5-17%) than with respect to EE and AD technologies (<1%). This said, the effect hinders the incentives to invest in AB and LC much stronger than it fosters them for EE and AD.

The NIs, however, show different results regarding the homogeneity of the strategic effect magnitude across the countries. In NI-1 the strength of the effect with respect to particular technology did not vary by country, however, NI-2 showed country-specific differences in the magnitude. The effect was more pronounced for the developed countries with respect to LC technology and for the developing countries with respect to AB technology. A third NI, which could be conducted once robust data on marginal AB cost is available, could test for this discrepancy.

5 Conclusions and Policy Implications

This thesis built on the scarce existing research that analyzes the interrelation between environmental PGs and climate-related technological innovation. We proposed a general model (Section 3.1) which investigates the incentives to invest in four different types of climate-related technologies (abatement, energy efficiency, adaptation, and low-carbon technology) in the context of strategic interaction. Specifically, we looked at whether the PG property of mitigation (or strategic interaction) hinders or fosters the incentives to invest in a particular technology type given a non-cooperative setting. We found that strategic interaction hinders the incentives to invest in AB technology, fosters the incentives to invest in EE and AD technologies, and can both foster and hinder the incentives to invest in LC technology. This finding could be another factor explaining the current low levels of mitigation worldwide. We found further that if the strategic interaction effect (indirect effect) with respect to AB and LC technologies is stronger than the direct effect, a country would prefer to invest in a worse AB technology and adopt less LC technology in its energy mix in order to shift the burden of mitigation to the other countries.

The general model was based on a few assumptions about monotonicity and convexity. Accordingly, any specific functional forms satisfying these assumptions could be used to conduct a numerical illustration and make inferences about real-world situations. In the thesis we used quadratic benefit, cost, and damage functions (19) to analyze the influence of the strategic interaction effect on the investment incentives of top-5 global CO_2 emitters: China, the US, the EU, India, and Russia. The results of the two numerical calibrations (NI-1 and NI-2) agreed that strategic interaction hinders the incentives to invest in AB and LC technologies and fosters the incentives to invest in EE and AD technologies. However, the indirect effect is always weaker than the direct one, therefore, no country has an incentive to invest in a worse AB or LC technologies due to strategic reasons. It yet holds true for symmetrical countries with respect to AB technology if the number of countries is sufficiently large (22).

In addition, our analysis gave a qualitative insight into the change of the total net emissions with the change in technology. Quite intuitively, the total net emissions increase with a worse AB technology and a lower share of LC technology in country i's energy mix. What is less intuitive, is that the net emissions and the total net emissions increase with better EE and AD technologies. This could point to the rebound effect and the fact that the damage costs decrease with a better AD technology, hence it is optimal to emit more.

The implications of our analysis for decision-making are threefold. Firstly, it is crucial to distinguish different types of climate-related technologies, because strategic interaction does not exert the same influence on each technology type. Since it hinders the incentives to invest in emission-reducing technologies (AB and LC), the development of the mechanisms that facilitate the investments namely in these technology types should be given a greater priority. Secondly, the distinction between technology types is relevant for technology transfer: it could be more reasonable to transfer emission-reducing (AB, LC) rather than emission-increasing (EE, AD) technologies from the developed to the developing countries. Lastly, the rebound effect should not be overlooked, i.e., the impact of EE technology on environment is not straightforward and hence labeling it as climate-friendly might be misleading.

A Appendix

A.1 The General Model of Investment Incentives

Country i maximises its welfare W_i w.r.t. abatement a_i and gross emissions g_i:

$$\begin{aligned}
\frac{\partial W_i}{\partial a_i} = &\quad - C_i'(\alpha_i; a_i) + D_i'(\delta_i; E) = 0 \\
&\Rightarrow a_i = C_i'^{-1}\left[D_i'(\delta_i; E)\right] \\
\frac{\partial W_i}{\partial g_i} = &\quad B_i'(\beta_i, \epsilon_i; g_i) - D_i'(\delta_i; E) = 0 \\
&\Rightarrow g_i = B_i'^{-1}\left[D_i'(\delta_i; E)\right]
\end{aligned} \tag{A.1}$$

In the equilibrium marginal benefit, cost and damage are equalized:

$$\begin{aligned}
&B_i'(\beta_i, \epsilon_i; g_i) = C_i'(\alpha_i; a_i) = D_i'(\delta_i; E) \\
&\Rightarrow \hat{g}_i = B_i'^{-1}\left[D_i'(\delta_i, \hat{E})\right] \\
&\Rightarrow \hat{a}_i = C_i'^{-1}\left[D_i'(\delta_i, \hat{E})\right] \\
&\Rightarrow \hat{e}_i = B_i'^{-1}\left[D_i'(\delta_i, \hat{E})\right] - C_i'^{-1}\left[D_i'(\delta_i, \hat{E})\right]
\end{aligned} \tag{A.2}$$

Define the sum of the net emissions and the functions F_1 and F_2:

$$\begin{aligned}
&E_{-i} = \sum_{j=1, j\neq i}^{n} e_j \\
&F_1 = e_i - B_i'^{-1}\left[D_i'(\delta_i; e_i + E_{-i})\right] + C_i'^{-1}\left[D_i'(\delta_i; e_i + E_{-i})\right] \\
&F_2 = E_{-i} - \sum_{j=1, j\neq i}^{n} \left(B_j'^{-1}\left[D_j'(\delta_j; e_i + E_{-i})\right] - C_j'^{-1}\left[D_j'(\delta_j; e_i + E_{-i})\right]\right)
\end{aligned} \tag{A.3}$$

Then,

$$\begin{aligned}
&\frac{dE_{-i}}{d\Box_i}, \frac{de_i}{d\Box_i} \\
&\text{where } \Box \in \{\alpha, \beta, \delta, \epsilon\}
\end{aligned} \tag{A.4}$$

can be found by the total differentiation of the equations

$$F_1(e_i, E_{-i}; \Box_i) = 0, \quad F_2(E_{-i}, e_i; \Box_i) = 0 \tag{A.5}$$

Net emissions of all the other countries

Applying the implicit function theorem and solving the system of equations (A.6) results in the expression for $\frac{dE_{-i}}{d\Box_i}$:

$$\begin{cases} dF_1 = \frac{\partial F_1}{\partial e_i} de_i + \frac{\partial F_1}{\partial E_{-i}} dE_{-i} + \frac{\partial F_1}{\partial \Box_i} d\Box_i = 0 \\ dF_2 = \frac{\partial F_2}{\partial e_i} de_i + \frac{\partial F_2}{\partial E_{-i}} dE_{-i} + \frac{\partial F_2}{\partial \Box_i} d\Box_i = 0 \end{cases} \tag{A.6}$$

$$\Rightarrow de_i = -\frac{(\partial F_2/\partial E_{-i}) dE_{-i} + (\partial F_2/\partial \Box_i) d\Box_i}{\partial F_2/\partial e_i}$$

Insert de_i into dF_1 : (A.7)

$$\Rightarrow \frac{dE_{-i}}{d\Box_i} = \frac{\frac{\partial F_1}{\partial e_i} \cdot \frac{\partial F_2}{\partial \Box_i} - \frac{\partial F_1}{\partial \Box_i} \cdot \frac{\partial F_2}{\partial e_i}}{\frac{\partial F_1}{\partial E_{-i}} \cdot \frac{\partial F_2}{\partial e_i} - \frac{\partial F_1}{\partial e_i} \cdot \frac{\partial F_2}{\partial E_{-i}}}$$

Differentiating F_1 and F_2 w.r.t. e_i, E_{-i} and $\Box_i$ yields:

$$
\begin{aligned}
\frac{\partial F_1}{\partial e_i} = & \quad 1 - \frac{D_i''}{B_i''} + \frac{D_i''}{C_i''} = 1 + \frac{\partial F_1}{\partial E_{-i}} > 0 \\
\frac{\partial F_1}{\partial E_{-i}} = & \quad \frac{D_i''}{C_i''} - \frac{D_i''}{B_i''} > 0 \\
\frac{\partial F_1}{\partial \Box_i} : & \quad \frac{\partial F_1}{\partial \alpha_i} = \frac{\partial C_i^{'-1}}{\partial \alpha_i} < 0 \\
& \quad \frac{\partial F_1}{\partial \beta_i} = -\frac{\partial B_i^{'-1}}{\partial \beta_i} < 0 \\
& \quad \frac{\partial F_1}{\partial \delta_i} = \frac{\partial D_i'/\partial \delta_i}{C_i''} - \frac{\partial D_i'/\partial \delta_i}{B_i''} > 0 \\
& \quad \frac{\partial F_1}{\partial \epsilon_i} = -\frac{\partial B_i^{'-1}}{\partial \epsilon_i} < 0 \quad \Longleftrightarrow \quad g_i \text{ is sufficiently high} \\
\frac{\partial F_2}{\partial e_i} = & \quad -\sum_{j=1, j\neq i}^{n} \left(\frac{D_j''}{B_j''} - \frac{D_j''}{C_j''} \right) > 0 \\
\frac{\partial F_2}{\partial E_{-i}} = & \quad 1 - \sum_{j=1, j\neq i}^{n} \left(\frac{D_j''}{B_j''} - \frac{D_j''}{C_j''} \right) = 1 + \frac{\partial F_2}{\partial e_i} > 0 \\
\frac{\partial F_2}{\partial \Box_i} : & \quad \frac{\partial F_2}{\partial \alpha_i} = 0, \frac{\partial F_2}{\partial \beta_i} = 0, \frac{\partial F_2}{\partial \delta_i} = 0, \frac{\partial F_2}{\partial \epsilon_i} = 0 \quad \Rightarrow \frac{\partial F_2}{\partial \Box_i} = 0
\end{aligned}
\tag{A.8}
$$

$$
\Rightarrow \frac{dE_{-i}}{d\Box_i} = \frac{\frac{\partial F_1}{\partial \Box_i} \cdot \frac{\partial F_2}{\partial e_i}}{\frac{\partial F_1}{\partial e_i} \cdot \frac{\partial F_2}{\partial E_{-i}} - \frac{\partial F_1}{\partial E_{-i}} \cdot \frac{\partial F_2}{\partial e_i}} \tag{A.9}
$$

Rewriting (A.9) yields:

$$
\frac{dE_{-i}}{d\Box_i} = \frac{\frac{\partial F_1}{\partial \Box_i} \cdot \frac{\partial F_2}{\partial e_i}}{1 + \sum_{k=1}^{n} \left(\frac{D_k''}{C_k''} - \frac{D_k''}{B_k''} \right)} = \frac{\frac{\partial F_1}{\partial \Box_i} \cdot \left[\sum_{j=1, j\neq i}^{n} \left(\frac{D_j''}{C_j''} - \frac{D_j''}{B_j''} \right) \right]}{1 + \sum_{k=1}^{n} \left(\frac{D_k''}{C_k''} - \frac{D_k''}{B_k''} \right)} \tag{A.10}
$$

Define the functions ϕ and $\triangle$:

$$
\begin{aligned}
&\phi = \sum_{j=1, j\neq i}^{n} \left(\frac{D_j''}{C_j''} - \frac{D_j''}{B_j''} \right) > 0 \\
&\triangle = 1 + \sum_{k=1}^{n} \left(\frac{D_k''}{C_k''} - \frac{D_k''}{B_k''} \right) > 0 \\
&\text{Then,} \quad \frac{dE_{-i}}{d\square_i} = \frac{\partial F_1}{\partial \square_i} \cdot \frac{\phi}{\triangle}
\end{aligned}
\tag{A.11}
$$

Based on the initial assumptions (**??**), in the equilibrium we get:

$$
\begin{aligned}
&\frac{d\hat{E}_{-i}}{d\alpha_i} = \frac{\phi}{\triangle} \frac{\partial C_i'^{-1}}{\partial \alpha_i} < 0 \\
&\frac{d\hat{E}_{-i}}{d\beta_i} = \frac{\phi}{\triangle} \left(-\frac{\partial B_i'^{-1}}{\partial \beta_i} \right) < 0 \\
&\frac{d\hat{E}_{-i}}{d\delta_i} = \frac{\phi}{\triangle} \left(\frac{\partial D_i'/\partial \delta_i}{C_i''} - \frac{\partial D_i'/\partial \delta_i}{B_i''} \right) > 0 \\
&\frac{d\hat{E}_{-i}}{d\epsilon_i} = \frac{\phi}{\triangle} \left(-\frac{\partial B_i'^{-1}}{\partial \epsilon_i} \right) < 0 \quad \iff \quad g_i \text{ is sufficiently high}
\end{aligned}
\tag{A.12}
$$

Net emissions of country i

Applying the implicit function theorem and solving the system of equations (A.6) results in the expression for $\frac{de_i}{d\square_i}$:

$$
\begin{aligned}
&\Rightarrow dE_{-i} = -\frac{(\partial F_2/\partial e_i)de_i + (\partial F_2/\partial \square_i)d\square_i}{\partial F_2/\partial E_{-i}} \\
&\Rightarrow \frac{de_i}{d\square_i} = \frac{\frac{\partial F_1}{\partial E_{-i}} \cdot \frac{\partial F_2}{\partial \square_i} - \frac{\partial F_1}{\partial \square_i} \cdot \frac{\partial F_2}{\partial E_{-i}}}{\frac{\partial F_1}{\partial e_i} \cdot \frac{\partial F_2}{\partial E_{-i}} - \frac{\partial F_1}{\partial E_{-i}} \cdot \frac{\partial F_2}{\partial e_i}}
\end{aligned}
\tag{A.13}
$$

Based on (A.8) we can write the expression for $\frac{de_i}{d\square_i}$:

$$
\frac{de_i}{d\square_i} = -\frac{\partial F_1}{\partial \square_i} \cdot \frac{(1+\phi)}{\triangle}
\tag{A.14}
$$

In the equilibrium:

$$\begin{aligned}
\frac{d\hat{e}_i}{d\alpha_i} &= -\frac{(1+\phi)}{\triangle}\frac{\partial C_i'^{-1}}{\partial \alpha_i} > 0 \\
\frac{d\hat{e}_i}{d\beta_i} &= -\frac{(1+\phi)}{\triangle}\left(-\frac{\partial B_i'^{-1}}{\partial \beta_i}\right) > 0 \\
\frac{d\hat{e}_i}{d\delta_i} &= -\frac{(1+\phi)}{\triangle}\left(\frac{\partial D_i'/\partial \delta_i}{C_i''} - \frac{\partial D_i'/\partial \delta_i}{B_i''}\right) < 0 \\
\frac{d\hat{e}_i}{d\epsilon_i} &= -\frac{(1+\phi)}{\triangle}\left(-\frac{\partial B_i'^{-1}}{\partial \epsilon_i}\right) > 0 \quad \Longleftrightarrow \quad g_i \text{ is sufficiently high}
\end{aligned} \tag{A.15}$$

Total emissions

Applying the implicit function theorem yields:

$$\begin{aligned}
&F = E - \sum_{i=1}^{n}\left(B_i'^{-1}[D_i'(\delta_i; E)] - C_i'^{-1}[D_i'(\delta_i; E)]\right) \\
&FOCs : dF = \frac{\partial F}{\partial E}dE + \frac{\partial F}{\partial \Box_i}d\Box_i = 0 \\
&\Rightarrow \frac{dE}{d\Box_i} = -\frac{\partial F/\partial \Box_i}{\partial F/\partial E}
\end{aligned} \tag{A.16}$$

Differentiating F w.r.t. E and $\Box_i$ yields:

$$\begin{aligned}
\frac{\partial F}{\partial E} &= \quad 1 - \sum_{k=1}^{n}\left(\frac{D_k''}{B_k''} - \frac{D_k''}{C_k''}\right) = \triangle > 0 \\
\frac{\partial F}{\partial \Box_i} &: \quad \frac{\partial F}{\partial \alpha_i} = \frac{\partial C_i'^{-1}}{\partial \alpha_i} < 0 \\
& \quad\quad \frac{\partial F}{\partial \beta_i} = \left(-\frac{\partial B_i'^{-1}}{\partial \beta_i}\right) < 0 \\
& \quad\quad \frac{\partial F}{\partial \delta_i} = \left(\frac{\partial D_i'/\partial \delta_i}{C_i''} - \frac{\partial D_i'/\partial \delta_i}{B_i''}\right) > 0 \\
& \quad\quad \frac{\partial F}{\partial \epsilon_i} = \left(-\frac{\partial B_i'^{-1}}{\partial \epsilon_i}\right) > 0 \quad \Longleftrightarrow \quad g_i \text{ is sufficiently high}
\end{aligned} \tag{A.17}$$

In the equilibrium:

$$\begin{aligned}
\frac{d\hat{E}}{d\alpha_i} &= -\frac{1}{\triangle}\frac{\partial C_i'^{-1}}{\partial \alpha_i} > 0 \\
\frac{d\hat{E}}{d\beta_i} &= -\frac{1}{\triangle}\left(-\frac{\partial B_i'^{-1}}{\partial \beta_i}\right) > 0 \\
\frac{d\hat{E}}{d\delta_i} &= -\frac{1}{\triangle}\left(\frac{\partial D_i'/\partial \delta_i}{C_i''} - \frac{\partial D_i'/\partial \delta_i}{B_i''}\right) < 0 \\
\frac{d\hat{E}}{d\epsilon_i} &= -\frac{1}{\triangle}\left(-\frac{\partial B_i'^{-1}}{\partial \epsilon_i}\right) > 0 \quad \Longleftrightarrow \quad g_i \text{ is sufficiently high}
\end{aligned} \tag{A.18}$$

Abatement of country i

From (A.2) we know that $a_i = C_i'^{-1}[D_i'(\delta_i; E)]$. Hence we can find based on (A.18) the total derivative of a_i w.r.t. $\square_{i/j}$ in the equilibrium:

$$\begin{aligned}
\frac{d\hat{a}_i}{d\alpha_i} &= \frac{\partial C_i''^{-1}}{\partial \alpha_i} + \frac{D_i''}{C_i''}\frac{d\hat{E}}{d\alpha_i} \lesseqgtr 0 \\
\frac{d\hat{a}_i}{d\beta_i} &= \frac{D_i''}{C_i''}\frac{d\hat{E}}{d\beta_i} > 0 \\
\frac{d\hat{a}_i}{d\delta_i} &= \frac{\partial D_i'/\partial \delta_i}{C_i''} + \frac{D_i''}{C_i''}\frac{d\hat{E}}{d\delta_i} \lesseqgtr 0 \\
\frac{d\hat{a}_i}{d\epsilon_i} &= \frac{D_i''}{C_i''}\frac{d\hat{E}}{d\epsilon_i} > 0 \quad \Longleftrightarrow \quad g_i \text{ is sufficiently high}
\end{aligned} \tag{A.19}$$

$$\begin{aligned}
\frac{d\hat{a}_i}{d\alpha_j} &= \frac{D_i''}{C_i''}\frac{d\hat{E}}{d\alpha_j} > 0 \text{ as } \frac{d\hat{E}}{d\square_j} = \frac{d\hat{E}}{d\square_i} \\
\frac{d\hat{a}_i}{d\beta_j} &= \frac{D_i''}{C_i''}\frac{d\hat{E}}{d\beta_j} > 0 \\
\frac{d\hat{a}_i}{d\delta_j} &= \frac{D_i''}{C_i''}\frac{d\hat{E}}{d\delta_j} < 0 \\
\frac{d\hat{a}_i}{d\epsilon_j} &= \frac{D_i''}{C_i''}\frac{d\hat{E}}{d\epsilon_j} > 0 \quad \Longleftrightarrow \quad g_i \text{ is sufficiently high}
\end{aligned} \tag{A.20}$$

Gross emissions of country i

Analogously, we know from (A.2) that $g_i = B_i'^{-1}[D_i'(\delta_i; E)]$. Hence we can find based on (A.18) the total derivative of g_i w.r.t. $\square_{i/j}$ in the equilibrium:

$$\begin{aligned}
\frac{d\hat{g}_i}{d\alpha_i} &= \frac{D_i''}{B_i''}\frac{d\hat{E}}{d\alpha_i} < 0 \\
\frac{d\hat{g}_i}{d\beta_i} &= \frac{\partial B_i'^{-1}}{\partial \beta_i}\frac{D_i''}{B_i''}\frac{d\hat{E}}{d\beta_i} < 0 \\
\frac{d\hat{g}_i}{d\delta_i} &= \frac{\partial D_i'/\partial \delta_i}{B_i''} + \frac{D_i''}{B_i''}\frac{d\hat{E}}{d\delta_i} \lesseqgtr 0 \\
\frac{d\hat{g}_i}{d\epsilon_i} &= \frac{\partial B_i'^{-1}}{\partial \epsilon_i}\frac{D_i''}{B_i''}\frac{d\hat{E}}{d\epsilon_i} < 0 \quad \Longleftrightarrow \quad g_i \text{ is sufficiently high}
\end{aligned} \tag{A.21}$$

$$\begin{aligned}
\frac{d\hat{g}_i}{d\alpha_j} &= \frac{D_i''}{B_i''}\frac{d\hat{E}}{d\alpha_j} < 0 \\
\frac{d\hat{g}_i}{d\beta_j} &= \frac{D_i''}{B_i''}\frac{d\hat{E}}{d\beta_j} < 0 \\
\frac{d\hat{g}_i}{d\delta_j} &= \frac{D_i''}{B_i''}\frac{d\hat{E}}{d\delta_j} > 0 \\
\frac{d\hat{g}_i}{d\epsilon_j} &= \frac{D_i''}{B_i''}\frac{d\hat{E}}{d\epsilon_j} < 0 \quad \Longleftrightarrow \quad g_i \text{ is sufficiently high}
\end{aligned} \tag{A.22}$$

A.2 The Specific Model of Investment Incentives

Functional forms for the benefit, cost and damage functions:

$$\begin{aligned}
B_i(g_i) &= \frac{2\beta_i}{\epsilon_i^2} g_i(\epsilon_i - \frac{1}{2}g_i), & B'(g_i) &= \frac{2\beta_i}{\epsilon_i^2}(\epsilon_i - g_i), & B''(g_i) &= -\frac{2\beta_i}{\epsilon_i^2} \\
C_i(a_i) &= \frac{1}{2}\alpha_i a_i^2, & C_i'(a_i) &= \alpha_i a_i, & C_i''(a_i) &= \alpha_i \\
D_i(E) &= \frac{1}{2}\delta_i E^2, & D_i'(E) &= \delta_i E, & D_i''(E) &= \delta_i
\end{aligned} \tag{A.23}$$

The partial derivatives of the functions:

$$\begin{aligned}
&\frac{\partial B_i}{\partial \beta_i} = \frac{2g_i}{\epsilon_i^2}(\epsilon_i - \frac{1}{2}g_i) > 0 && \frac{\partial B_i'}{\partial \beta_i} = \frac{2}{\epsilon_i^2}(\epsilon_i - g_i) > 0, && \frac{\partial B_i^{'-1}}{\partial \beta_i} = \frac{\delta_i \epsilon_i^2 E}{2\beta_i} > 0 \\
&\frac{\partial B_i}{\partial \epsilon_i} = -\frac{2\beta_i g_i}{\epsilon_i^3}(\epsilon_i - g_i) < 0 && \frac{\partial B_i'}{\partial \epsilon_i} = \frac{2\beta_i}{\epsilon_i^3}(2g_i - \epsilon_i) > 0^* && \frac{\partial B_i^{'-1}}{\partial \epsilon_i} = 1 - \frac{\delta_i \epsilon_i E}{\beta_i} > 0^* \\
&\frac{\partial C_i}{\partial \alpha_i} = \frac{a_i^2}{2} > 0, && \frac{\partial C_i'}{\partial \alpha_i} = a_i > 0 && \frac{\partial C_i^{'-1}}{\partial \alpha_i} = -\frac{\delta_i E}{\alpha_i^2} < 0 \\
&\frac{\partial D_i}{\partial \delta_i} = \frac{E^2}{2} > 0, && \frac{\partial D_i'}{\partial \delta_i} = E > 0 && \frac{\partial D_i^{'-1}}{\partial \delta_i} = -\frac{\alpha_i a_i}{\delta_i^2} < 0 \\
&{}^* \text{ if } g_i > \frac{\epsilon_i}{2}
\end{aligned} \tag{A.24}$$

where $g_i = e_i + a_i$ and $E = \sum_{i=1}^{n} e_i = \sum_{i=1}^{n}(g_i - a_i)$

The welfare function of country i:

$$W_i = B_i(\beta_i, \epsilon_i; g_i) - C_i(\alpha_i; a_i) - D_i(\delta_i; E) \tag{A.25}$$

Country i maximises its welfare w.r.t. g_i and a_i

$$\begin{aligned}
&\frac{\partial W_i}{\partial g_i} = B_i'(g_i) - D_i'(E) = 0 \\
&\Rightarrow g_i = \epsilon_i - \frac{\delta_i \epsilon_i^2}{2\beta_i} E \\
&\frac{\partial W_i}{\partial a_i} = -C_i'(a_i) + D_i'(E) = 0 \\
&\Rightarrow a_i = \frac{\delta_i E}{\alpha_i} \\
&\Rightarrow e_i = g_i - a_i = \epsilon_i - \delta_i \left(\frac{\alpha_i \epsilon_i^2 + 2\beta_i}{2\beta_i \alpha_i} \right) E
\end{aligned} \tag{A.26}$$

Define the total emissions

$$\sum_{i=1}^{n} e_i = E = \sum_{i=1}^{n} \epsilon_i - E \sum_{i=1}^{n} \delta_i \left(\frac{\alpha_i \epsilon_i^2 + 2\beta_i}{2\beta_i \alpha_i} \right) \tag{A.27}$$

Define

$$k_i = \delta_i \left(\frac{\alpha_i \epsilon_i^2 + 2\beta_i}{2\beta_i \alpha_i} \right) > 0, \qquad K = \sum_{i=1}^{n} k_i, \qquad \xi = \sum_{i=1}^{n} \epsilon_i \tag{A.28}$$

then we get in the equilibrium:

$$\begin{aligned}
&\Rightarrow \hat{E} = \frac{\xi}{1+K} \\
&\Rightarrow \hat{g}_i = \epsilon_i - \frac{\delta_i \epsilon_i^2}{2\beta_i} \cdot \frac{\xi}{1+K} \\
&\Rightarrow \hat{a}_i = \frac{\delta_i}{\alpha_i} \cdot \frac{\xi}{1+K} \\
&\Rightarrow \hat{e}_i = \epsilon_i - k_i \cdot \frac{\xi}{1+K}
\end{aligned} \tag{A.29}$$

From (13), (14), (15) and (16) we know:

$$\begin{aligned}
\frac{\partial W_i}{\partial \alpha_i} &= -\frac{\partial C_i(\alpha_i; \hat{a}_i)}{\partial \alpha_i} - D_i'(\delta_i; \hat{E}) \frac{d\hat{E}_{-i}}{d\alpha_i} = -\frac{1}{2}\hat{a}_i^2 - \delta_i \hat{E} \frac{d\hat{E}_{-i}}{d\alpha_i} \\
\frac{\partial W_i}{\partial \beta_i} &= \frac{\partial B_i(\beta_i, \epsilon_i; \hat{g}_i)}{\partial \beta_i} - D_i'(\delta_i; \hat{E}) \frac{d\hat{E}_{-i}}{d\beta_i} = \frac{\hat{g}_i}{\epsilon_i^2}(2\epsilon_i - \hat{g}_i) - \delta_i \hat{E} \frac{d\hat{E}_{-i}}{d\beta_i} \\
\frac{\partial W_i}{\partial \delta_i} &= -\frac{\partial D_i(\delta_i; \hat{E})}{\partial \delta_i} - D_i'(\delta_i; \hat{E}) \frac{d\hat{E}_{-i}}{d\delta_i} = -\frac{1}{2}\hat{E}^2 - \delta_i \hat{E} \frac{d\hat{E}_{-i}}{d\delta_i} \\
\frac{\partial W_i}{\partial \epsilon_i} &= \frac{\partial B_i(\beta_i, \epsilon_i; \hat{g}_i)}{\partial \epsilon_i} - D_i'(\delta_i; \hat{E}) \frac{d\hat{E}_{-i}}{d\epsilon_i} = -\frac{2\beta_i \hat{g}_i}{\epsilon_i^3}(\epsilon_i - \hat{g}_i) - \delta_i \hat{E} \frac{d\hat{E}_{-i}}{d\epsilon_i}
\end{aligned} \tag{A.30}$$

We find now the total derivative of E_{-i} w.r.t. $\square_i$:

$$\begin{aligned}
\frac{d\hat{E}_{-i}}{d\alpha_i} &= -\frac{\xi \delta_i (K - k_i)}{\alpha_i^2 (1+K)^2} < 0 \\
\frac{d\hat{E}_{-i}}{d\beta_i} &= -\frac{\xi \delta_i \epsilon_i^2 (K - k_i)}{2\beta_i^2 (1+K)^2} < 0 \\
\frac{d\hat{E}_{-i}}{d\delta_i} &= \frac{\xi (\alpha_i \epsilon_i^2 + 2\beta_i)(K - k_i)}{2\beta_i \alpha_i (1+K)^2} > 0 \\
\frac{d\hat{E}_{-i}}{d\epsilon_i} &= -\frac{\big((K\alpha_i - \delta_i)\beta_i - \frac{1}{2}\alpha_i \delta_i \epsilon_i^2\big)\big((1+K)\beta_i - \epsilon_i \xi \delta_i\big)}{\beta_i^2 \alpha_i (1+K)^2} \lesseqqgtr 0
\end{aligned} \tag{A.31}$$

This yields the partial derivatives of country i's welfare w.r.t. $\square_i$:

$$\begin{aligned}
\frac{\partial W_i}{\partial \alpha_i} &= \frac{\delta_i^2 \xi^2 (K - 2k_i - 1)}{2(1+K)^3 \alpha_i} > 0 \quad \iff \quad K > 1 + 2k_i \\
\frac{\partial W_i}{\partial \beta_i} &= \frac{4(1+K)^3 \beta_i^2 + \xi^2 \delta_i^2 \epsilon_i^2 (K - 2k_i - 1)}{4(1+K)^3 \beta_i^2} > 0 \\
\frac{\partial W_i}{\partial \delta_i} &= -\frac{\xi^2 \left[((1+K)\beta_i + \delta_i \epsilon_i^2 (K - k_i))\alpha_i + 2\beta_i \delta_i (K - k_i) \right]}{2(1+K)^3 \beta_i \alpha_i} < 0 \\
\frac{\partial W_i}{\partial \epsilon_i} &= -\frac{\delta_i \xi \left(2(\alpha_i + \delta_i)(1+K)\beta_i^2 + \delta_i \big(-2\delta_i \xi + (\epsilon_i (1+K) + \xi (K-1))\alpha_i \big) \epsilon_i \beta_i - \xi \alpha_i \delta_i^2 \epsilon_i^3 \right)}{2(1+K)^3 \beta_i^2 \alpha_i} \lesseqgtr 0
\end{aligned} \tag{A.32}$$

B Appendix

Table 13: *The comparison of the empirical and calibrated values (highlighted in blue) for numerical illustration-1. The empirical values are retrieved from the World Bank database, BP Statistical Review (2018), Liu et al. (2018), Smith et al. (2017), and Stern et al. (2012).*

	GDP, 2017 (crnt \$US bn)	B(g)-C(a)	e, 2017 (Gt CO_2)	e	B′(a),%	B′(a), %	D′(E), %	D′(E),%
China	12237.700	12246.950	9.2326	9.210	21.416	21.368	22.727	21.368
US	19390.604	19355.460	5.0877	5.074	42.201	42.094	77.273	42.094
EU	17277.698	17163.265	4.1522	4.159	100.000	100.000	100.000	100.000
India	2597.491	2523.289	2.3442	2.306	79.188	79.060	22.727	79.060
Russia	1577.524	1490.127	1.5253	1.500	73.934	73.932	18.182	73.932

Table 14: *Relation of the direct effect to the welfare elasticity by each country and technology type for numerical illustration-1, %.*

	AB	EE	AD	LC
China	110.39059769	99.99930899	99.89861758	104.89394902
US	110.02057006	99.99966730	99.88721027	104.74084584
EU	109.86436741	99.99838392	99.88266922	104.63347972
India	109.83760991	99.98491829	99.88190784	104.47877056
Russia	110.28583933	99.98280302	99.89529600	104.66186963

Table 15: *Relation of the indirect effect to the welfare elasticity by each country and technology type for numerical illustration-1, %.*

	AB	EE	AD	LC
China	10.39059769	0.00069101	0.10138242	4.89394902
US	10.02057006	0.00033270	0.11278973	4.74084584
EU	9.864367409	0.00161608	0.11733078	4.63347972
India	9.837609907	0.01508171	0.11809216	4.47877056
Russia	10.28583933	0.01719698	0.10470400	4.66186963

Table 16: *The comparison of the empirical and calibrated values (highlighted in blue) for numerical illustration-2. The empirical values are retrieved from the World Bank database, BP Statistical Review (2018), Carlsson et al. (2012), Smith et al. (2017), and Stern et al. (2012).*

	GDP, 2017 (crnt $US bn)	B(g)-C(a)	e, 2017 (Gt CO_2)	e	B′(a),%	B′(a), %	D′(E), %	D′(E),%
China	12237.700	12240.531	9.230	9.294	21.416	23.020	22.727	23.020
US	19390.604	19298.845	5.090	5.177	42.201	79.558	77.273	79.558
EU	17277.698	17143.419	4.150	4.186	100.000	100.000	100.000	100.000
India	2597.491	2581.421	2.340	2.314	79.188	23.020	22.727	23.020
Russia	1577.524	1547.303	1.530	1.499	73.934	18.416	18.182	18.416

Table 17: *Relation of the direct effect to the welfare elasticity by each country and technology type for numerical illustration-2, %.*

	AB	EE	AD	LC
China	116.17152153	99.99831922	99.81072281	107.39162104
US	112.77489062	99.99761442	99.68668999	116.45304101
EU	112.35398757	99.99677185	99.67607806	116.53666873
India	116.95401921	99.99727043	99.84822696	105.43938549
Russia	117.57094642	99.99783969	99.87996112	104.86944437

Table 18: *Relation of the indirect effect to the welfare elasticity by each country and technology type for numerical illustration-2, %.*

	AB	EE	AD	LC
China	16.17152153	0.00168078	0.18927719	7.39162104
US	12.77489062	0.00238558	0.31331001	16.45304101
EU	12.35398757	0.00322815	0.32392194	16.53666873
India	16.95401921	0.00272957	0.15177304	5.43938549
Russia	17.57094642	0.00216031	0.12003888	4.86944437

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Declaration

under Art. 28 Para. 2 RSL 05

Last, first name: Kulakovskaya, Anna

Matriculation number: 16-117-459

Programme: Master of Science in Climate Sciences

Bachelor ☐ Master ☒ Dissertation ☐

Thesis title: Environmental public goods and endogenous technological change: a game-theoretical analysis of incentives to invest in climate technology in a non-cooperative setting

Thesis supervisor: Prof. Dr. Ralph Winkler

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person, except where due acknowledgement has been made in the text. In accordance with academic rules and ethical conduct, I have fully cited and referenced all material and results that are not original to this work. I am well aware of the fact that, on the basis of Article 36 Paragraph 1 Letter o of the University Law of 5 September 1996, the Senate is entitled to deny the title awarded on the basis of this work if proven otherwise. I grant insprection of my thesis.

Bern, 19.10.2018

Signature