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Abstract: We develop a simple game-theoretic model to investigate the relationship between greenhouse gas emissions and investments into four broad classes of technologies that are relevant for the mitigation of anthropogenic climate change: (i) carbon efficiency technologies, (ii) low-carbon technologies, (iii) emission abatement technologies, and (iv) climate adaptation technologies. We show that the well-known public good property of emission reductions has repercussions on domestic and global emissions: While better low-carbon and better abatement technologies reduce domestic and global emission, better carbon efficiency and adaptation technologies increase them. In addition, indirect effects propagated by the change in equilibrium emissions due to a marginal technological improvement foster investment incentives in case of carbon efficiency and adaptation technologies and reduce them in case of low-carbon and a abatement technologies. Surprisingly, this result holds for both non-cooperative and cooperative international climate policies.

Keywords: technological change, non-cooperative climate policy, cooperative climate policy, climate relevant technologies

JEL-Classification: C71, C72, H41, O33, Q43, Q54

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1 Introduction

The potential threats of unmitigated climate change are undisputable (IPCC 2014). Thus, it not surprising that a global political consensus forms to contain anthropogenic climate change. The Paris Agreement, signed in December 2015 in Paris, states the central goal 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. While there is a broad consensus on the goal, there is much less consensus on the means to achieve this goal. Emission reductions pledged so far by the signatories of the Paris Agreement fall considerably short of global emission pathways consistent with a 2°C goal. In fact, keeping within 2°C makes a reduction of global greenhouse gas emissions to virtually zero (at least for net emissions) inevitable in the medium to long run. Obviously, such a reduction requires a considerable change in the composition of global production technology, away from fossil fuel based towards renewable technologies.

In this paper, we analyze the relationship between improvements in climate related technologies and domestic and global net emissions. Furthermore, we investigate how strong are the investment incentives to invest into better technologies in the first place. To do so, we identify four different categories of climate relevant technologies, namely carbon efficiency increasing technologies, greenhouse gas emission reducing (low-carbon) technologies, (end-of-pipe) abatement technologies and adaptation technologies, and specify how improvements in theses technologies impact on domestic welfare.

We set up a simple static model with n heterogeneous countries. Taking the technological level in the four categories of technologies as given, we characterize the outcome of four different climate policy regimes. (i) The global social optimum, in which a social planner dictates emission and abatement choices such as to maximize global welfare (which is the sum of domestic welfare of all countries), (ii) the non-cooperative Nash equilibrium, in which all countries set emission and abatement levels such as to maximize own domestic welfare only, (iii) a cooperative climate policy regime, in which all countries cooperate with respect to climate policy and distribute the cooperation gain according to the Nash bargaining solution and (iv) a coalition formation game, in which countries in the first stage choose whether to join an international (environmental) agreement. In the second stage, all countries simultaneously choose emission and abatement levels, non-members maximizing their own welfare, and member countries maximizing the joint welfare of all members and distributing the cooperation gain according to the Nash bargaining solution. We then determine the comparative static effects of a marginal improvement of one of the four categories of technologies in one country on domestic and global emissions, and domestic welfare.

We find two important results. First, both the effect on equilibrium emissions levels and the investment incentives into new technologies (i.e., the change in domestic welfare for a marginal technological improvement) crucially depend on the type of technology. While improvements in carbon efficiency and adaptation technologies *increase*, better emission reducing and abatement technologies *decrease* domestic and global equilibrium emissions. In addition, the direct investment incentive, i.e., the change in domestic welfare for a marginal technological improvement leaving equilibrium emissions unchanged, is *positive* for all technological improvements. The indirect investment incentive, i.e., the change in domestic welfare for a marginal technological improvement propagated by the change in equilibrium emissions, is *positive* for carbon efficiency and adaptation technologies, thus fostering the direct effect, and *negative* for emission reducing and abatement technologies, thus opposing the direct effect. In addition, we can show that the indirect effect outweighs the direct effect if the emission reducing and abatement technologies are already sufficiently advanced. The second, even more intriguing insight is that all these results described above do not – at least *qualitatively* – depend on the climate policy regime.

Our results have important policy implications. First, the indirect investment incentives reinforce the under-provision of greenhouse gas emission abatement, by rendering improvements of climate relevant technologies that increase domestic and global emissions ceteris paribus more attractive than technologies that decrease them. Second, our results pose a warning about the effectiveness of technology transfers in combating anthropogenic climate change. Everything else equal, emission reducing or abatement technologies are preferable for technology transfers to carbon efficiency or adaptation technologies.

Our paper relates on the one hand to the large body of literature on induced technological change, for example, Acemoglu et al. (2012), Goulder and Mathai (2000), Löschel and Schymura (2013). The common feature in all these models is that technological change decreases abatement costs, thereby decreasing global emissions.[1] While this is also true in our model for improvements in abatement technologies, we also find the opposite effect for other climate relevant technologies.

On the other hand, our paper is more closely related to the relatively small literature on strategic investment incentives. For example, Harstad (2012) and Harstad (2016) find in a dynamic setting where countries can contract on emissions but not on technological improvements that countries under-invest in technology both in a non-cooperative as well as in a cooperative (Nash bargaining solution) climate regime. Bayramoglu (2010) studies a set-up where firms in two countries exhibit strategic incentives to invest in environmentally

[1] A notable exception is Smulders and Di Maria (2012), which allow for technological progress to increase marginal abatement costs.

friendly technologies depending on the environmental agreement the countries negotiate. Finally, Buchholz and Konrad (1994) analyze, similar to us, investment incentives in abatement technologies in a non cooperative climate policy regime. All these papers have in common that they focus on what we call abatement technologies and do not consider the three other categories of technologies. In addition, all these papers focus on one or two climate policy regimes (most often the non-cooperative Nash equilibrium).

The remainder of the paper is structured as follows. In Section 2 we introduce the model and define the four categories of climate relevant technologies. In Section 3 we characterize the equilibria of our model with respect to the four climate policy regimes. We analyze the effects of improving technologies on domestic and global emission levels, and on welfare in Section 4. Finally, in Section 5 we discuss the robustness of our results with respect to model assumptions and potential model extension and conclude.

2 The model

We consider a world with n heterogenous countries indexed by $i = 1, \dots, n$. Each country i is characterized by its domestic welfare W_i

$$W_i = B_i(\beta_i, \epsilon_i; g_i) - C_i(\alpha_i; a_i) - D_i(\delta_i; E) \ , \tag{1}$$

which consists of three components: $B_i(g_i)$ denotes the country specific benefits from production, which depend on country i's gross emissions g_i, $C_i(a_i)$ are the country specific costs of emission abatement and depend on county i's amount a_i of abated emissions, and $D_i(E)$ denotes the country specific environmental damages induced by global net emissions E.

Country i's net emissions are given by its gross emissions minus abatement $e_i = g_i - a_i$. Thus, global net emissions sum up to:

$$E = \sum_{i=1}^{n} e_i = \sum_{i=1}^{n} (g_i - a_i) \ . \tag{2}$$

We think of emission abatement as any process that reduces the net emissions of a country. This includes both end-of-pipe technologies such as carbon capture and sequestration, which abate gross emissions directly at their source, and establishing or enhancing carbon sink capacities such as afforestation or other land use changes that increase the absorbtion of carbon dioxide out of the atmosphere.

In addition, we also define global welfare as the sum of domestic welfares over all n countries:

$$V = \sum_{i=i}^{n} W_i = \sum_{i=1}^{n} \left[B_i(\beta_i, \epsilon_i; g_i) - C_i(\alpha_i; a_i) - D_i(\delta_i; E)\right] \ . \tag{3}$$

We consider four categories of technologies that we consider relevant in the context of anthropogenic climate change:

1. Production (or efficiency) increasing technologies increase the amount of output that can be produced by the same amount of inputs. As gross emissions is the only explicitly considered input in production, these technologies increase the carbon efficiency (i.e., the amount of GDP produced per unit of emissions).

2. Emission (or carbon) reducing technologies reduce the amount of gross emissions that is needed for a given amount of production output. We also refer to these technologies as low-carbon technologies.

3. Better abatement technologies reduce the abatement costs for any positive level of abatement.

4. Better adaptation technologies reduce the environmental damage costs for any positive level of global net emissions.

The technological level with respect to these four categories of technologies in country i are given by β_i (carbon efficiency technologies), ϵ_i (low-carbon technologies), α_i (abatement technologies) and δ_i (adaptation technologies). As carbon efficiency and low-carbon technologies impact on the production in country i, B_i depends on β_i and ϵ_i. In addition, the level of abatement technologies affects the abatement costs C_i and the level of adaptation technologies influences the environmental damage costs D_i (see equations (1) and (3)).

For all four categories of technologies we employ the convention that a *lower parameter* β_i, ϵ_i, α_i and δ_i characterizes a *better technological level*. Thus, one might think of the parameters β_i, ϵ_i, α_i and δ_i as cost parameters of the respective technologies.

In our analysis we treat the technology parameters β_i, ϵ_i, α_i and δ_i as exogenous and the emission and abatement levels g_i, a_i and E as endogenous. As a consequence, we denote the derivative of one of the components of domestic welfare with respect to its sole endogenous variable by " $'$ ", for example, $B_i'(\beta_i, \epsilon_i; g_i) \equiv dB_i(\beta_i, \epsilon_i; g_i)/dg_i$.

We assume that the benefits from production B_i are strictly increasing and concave on the feasible interval of gross emissions $g_i \in [g_i^{\min}, g_i^{\max}]$:

$$B_i'(\beta_i, \epsilon_i; g_i) > 0 \ , \quad B_i''(\beta_i, \epsilon_i; g_i) < 0 \ . \tag{4a}$$

It seems reasonable that $g_i^{\min} \geq 0$ and that gross emissions are bounded from above at some gross emission level $g_i^{\max} > g_i^{\min}$, which corresponds to the gross emission level produced when the economy of country i operates at full capacity. Yet, our results do not rely on the nature of the feasible interval of gross emissions. As a consequence, we do not impose any particular assumptions about the lower and upper bound of feasible gross emissions.

We assume further that an increase in carbon efficiency (i.e., a decrease in β_i) shifts the benefits from production upwards (see Figure 1 (a)). Thus, better carbon efficiency increases both production and marginal production at any feasible level of gross emissions g_i:

$$\frac{\partial B_i(\beta_i, \epsilon_i; g_i)}{\partial \beta_i} < 0 \ , \quad \frac{\partial B_i'(\beta_i, \epsilon_i; g_i)}{\partial \beta_i} < 0 \ . \tag{4b}$$

We consider better low-carbon technologies (i.e., a decrease in ϵ_i) to shift B_i to the left (see Figure 1 (b)). This implies that production increases for any feasible level of gross emissions g_i, while marginal production is increasing for low levels of gross emissions and decreasing for high levels of gross emissions.[2] We assume that equilibrium gross emission levels of all countries are sufficiently high for marginal production to be decreasing with improving low-carbon technologies:[3]

$$\frac{\partial B_i(\beta_i, \epsilon_i; g_i)}{\partial \epsilon_i} < 0 \ , \quad \frac{\partial B_i'(\beta_i, \epsilon_i; g_i)}{\partial \epsilon_i} > 0^\star \ , \qquad (^\star \text{ if } g_i \text{ sufficiently high}) \ . \tag{4c}$$

We further assume that both abatement costs and environmental damage costs are strictly increasing and convex for all positive and feasible levels of abatement a_i and global net emissions E, respectively. In addition, we consider better abatement technologies (i.e., a decrease in α_i) to reduce both abatement costs and marginal abatement costs for any positive and feasible level of abatement a_i (see Figure 1 (c)). Analogously, better adaptation technologies (i.e., a decrease in δ_i) reduce both the environmental damage costs and the marginal environmental damage costs for all positive and feasible levels of global net emissions E (see

[2] Note that a change in the emission reducing technology may also change the interval of feasible gross emissions. For example, a better emission reducing technology may reduce the gross emissions g_i^{max} produced when the economy operates at full capacity.

[3] This implicitly assumes that countries do not leave a large fraction of their production capacity idle in equilibrium. We discuss this assumption in Section 5.

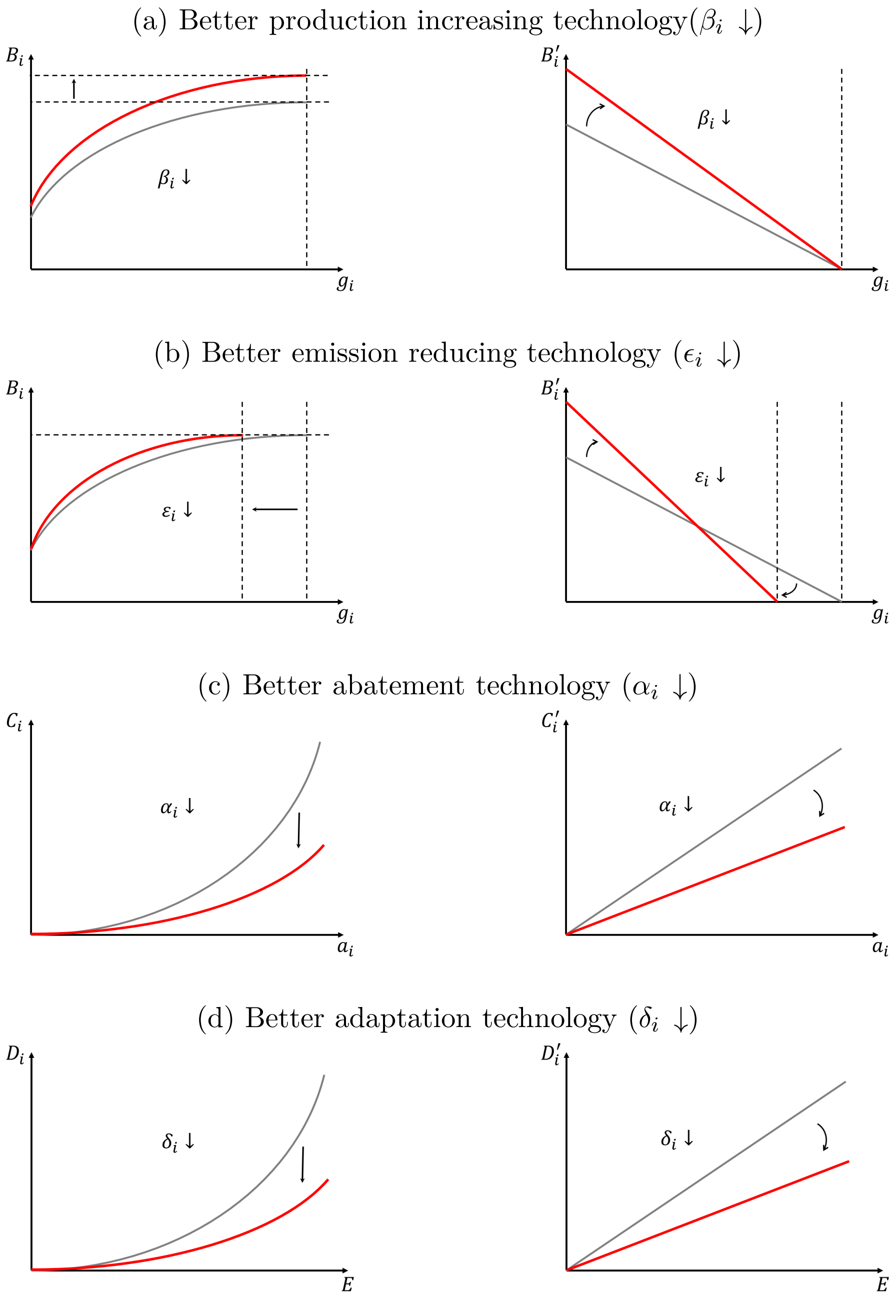

Figure 1: Illustration of the assumptions about better technology on the components of domestic welfare: (a) Impact of better production increasing technology on production and marginal production, (b) impact of better emission reducing technology on production and marginal production, (c) impact of better adaptation technology on abatement costs and marginal abatement costs, and (d) impact of better adaptation technology on environmental damage costs and marginal environmental damage costs.

Figure 1 (d)):

$$C_i'(\alpha_i; a_i) > 0 \ , \quad C_i''(\alpha_i; a_i) > 0 \ , \tag{4d}$$

$$\frac{\partial C_i(\alpha_i; a_i)}{\partial \alpha_i} > 0 \ , \quad \frac{\partial C_i'(\alpha_i; a_i)}{\partial \alpha_i} > 0 \ , \tag{4e}$$

$$D_i'(\delta_i; E) > 0 \ , \quad D_i''(\delta_i; E) > 0 \ , \tag{4f}$$

$$\frac{\partial D_i(\delta_i; E)}{\partial \delta_i} > 0 \ , \quad \frac{\partial D_i''(\delta_i; E)}{\partial \delta_i} > 0 \ . \tag{4g}$$

3 International climate policy regimes

We analyze how a change in the technological level in one of the four categories in country i impacts on the levels of domestic and global net emissions and the level of domestic welfare in country i in four different policy regimes:

1. The global social optimum (GSO), in which a social planer dictates gross emission and abatement levels in all countries to maximize global welfare (see equation (3)).
2. The non-cooperative Nash equilibrium (NE), in which all countries simultaneously choose domestic gross emission and abatement levels to maximize their own domestic welfare (see equation (1)) for given actions of all other countries.
3. The cooperative Nash bargaining solution with transfers (NBS), in which all countries maximize their joint welfare (which results in the GSO) and distribute the cooperation gain (i.e., the difference in global welfare between the GSO and the NE) according to bargaining weights ν_i that sum up to one.
4. The coalition formation game (CFG), in which in the first stage all countries simultaneously decide wether to join a coalition. In the second stage, the members of the coalition maximize their joint welfare and distribute the cooperation gain according to bargaining weights μ_i that sum up to one (as in the NBS), while non-members choose domestic gross emission and abatement levels to maximize their own domestic welfare for given actions of all other countries (as in the NE).

In the following, we characterize the equilibrium levels of gross emissions, abatement and net emissions of these four policy regimes.

3.1 Global social optimum

As a benchmark case, we consider the global social optimum (GSO), in which a social planer dictates gross emission and abatement levels to maximize global welfare:

$$\max_{\{g_i,a_i\}_{i=1}^n} \sum_{i=1}^n W_i \qquad \text{subject to} \quad E = \sum_{i=1}^n (g_i - a_i) \ . \tag{5}$$

As shown in the Appendix, this implies the following necessary and sufficient conditions

$$B_i'(\beta_i, \epsilon_i; g_i) = \sum_{j=1}^n D_j'(\delta_j; E) = C_i'(\alpha_i; a_i) \ , \qquad \forall\ i = 1, \ldots, n \ , \tag{6}$$

which imply that marginal benefits from production have to equal marginal costs of abatement, as net emissions can be reduced by one marginal unit either by reducing gross emissions by one marginal unit or increasing abatement by one marginal unit. In addition, marginal benefits from production (and, thus, also marginal abatement costs) equal the sum of marginal damage costs over all countries, which is the standard Samuelson condition for the global public bad of net emissions.

We indicate the levels of gross emissions, abatement and net emissions in the GSO by a " $\star$ ". They are given by

$$g_i^\star = B_i'^{-1}\left(\sum_{j=1}^n D_j'(\delta_j; E^\star)\right) \ , \quad a_i^\star = C_i'^{-1}\left(\sum_{j=1}^n D_j'(\delta_j; E^\star)\right) \ , \quad e_i^\star = g_i^\star - a_i^\star \ , \tag{7a}$$

where the socially optimal level of global net emissions $E^\star$ is the unique solution of

$$E^\star = \sum_{i=1}^n \left[B_i'^{-1}\left(\sum_{j=1}^n D_j'(\delta_j; E^\star)\right) - C_i'^{-1}\left(\sum_{j=1}^n D_j'(\delta_j; E^\star)\right)\right] \ . \tag{7b}$$

3.2 Non-cooperative Nash equilibrium

In the non-cooperative Nash equilibrium (NE), all countries simultaneously choose gross emission and abatement levels such as to maximize their domestic welfare:

$$\max_{g_i,a_i} W_i \qquad \text{subject to} \quad E = \sum_{i=1}^n (g_i - a_i) \quad \text{and given} \quad g_j, a_j \quad \forall\ j \neq i \ . \tag{8}$$

As shown in the Appendix, the Nash equilibrium is determined by the following necessary and sufficient conditions:

$$B_i'(\beta_i, \epsilon_i; g_i) = D_i'(\delta_i; E) = C_i'(\alpha_i; a_i) \;, \qquad \forall\; i = 1, \ldots, n \tag{9}$$

As in the case of the GSO (and for the same reasons), marginal benefits from production have to equal marginal costs of abatement in equilibrium. Unlike the GSO, however, marginal benefits from production (and, thus, also marginal abatement costs) equal own marginal environmental damage costs only, as individual countries do not take into account the environmental damage costs their net emissions induce on all other countries. This leads to an over-provision of gross emissions and an under-provision of abatement in the NE compared to the corresponding levels of the GSO.

Indicating the levels of gross emissions, abatement and net emissions in the NE by a " ˆ ", we obtain:

$$\hat{g}_i = B_i'^{-1}\big(D_i'(\delta_i; \hat{E})\big) \;, \quad \hat{a}_i = C_i'^{-1}\big(D_i'(\delta_i; \hat{E})\big) \;, \quad \hat{e}_i = \hat{g}_i - \hat{a}_i \;, \tag{10a}$$

where the global level of net emissions $\hat{E}$ in the NE is the unique solution of

$$\hat{E} = \sum_{i=1}^{n} \Big[B_i'^{-1}\big(D_i'(\delta_i; \hat{E})\big) - C_i'^{-1}\big(D_i'(\delta_i; \hat{E})\big) \Big] \;. \tag{10b}$$

3.3 Nash bargaining solution

In the Nash bargaining solution (NBS), we assume that all countries $i = 1, \ldots, n$ cooperate with respect to emissions and abatement levels such as to achieve the GSO, as characterized in Section 3.1, and negotiate about how to distribute the gains from cooperation. We assume that country i's threat point, i.e., the fallback option when negotiation fails, is its level of domestic welfare $\hat{W}_i$ that is achieved in the NE, as characterized in Section 3.2. We consider a transferable utility set-up, i.e., we assume that welfare can be arbitrarily and frictionless re-distributed among countries by a vector of transfers T_i, $i = 1, \ldots, n$ with the property $\sum_{i=1}^{n} T_i = 0$. Then, the after transfer domestic welfare of country i is given by

$$W_i = W_i^\star + T_i \;, \tag{11}$$

where a positive $T_i > 0$ indicates a net transfer to and a negative $T_i < 0$ a net payment from country i.

In the NBS, the levels of domestic welfare after transfers W_i are determined as the solution of

$$\max_{\{W_i\}_{i=1}^n} \Pi_{i=1}^n \left(W_i - \hat{W}_i\right)^{\nu_i} \qquad \text{subject to} \quad \sum_{i=1}^n W_i = V^\star \ , \quad \sum_{i=1}^n \nu_i = 1 \ , \tag{12}$$

where ν_i denotes the relative bargaining power of country i. Indicating the welfare levels in the NBS by a "$\tilde{}$", we obtain (see Appendix):

$$\tilde{W}_i = \hat{W}_i + \nu_i(V^\star - \hat{V}) \ . \tag{13}$$

Thus, in the NBS each country i receives a domestic welfare level that is equal to its outside option (i.e., its doemstic welfare level in the NE, $\hat{W}_i$) plus a fraction ν_i of the cooperation gain (i.e., the difference in global welfare between the GSO and the NE, $V^\star - \hat{V}$). Transfers $\tilde{T}_i$ in the NBS read:

$$\tilde{T}_i = \tilde{W}_i - W_i^\star = \hat{W}_i - W_i^\star + \nu_i(V^\star - \hat{V}) \ . \tag{14}$$

3.4 Coalition formation game

The coalition formation game (CFG) is a two-stage game that resembles the formation of international (environmental) agreements. In the first stage, countries simultaneously decide on whether to join an agreement. In the second stage, all countries simultaneously choose gross emission and abatement levels. Countries that joined the agreement in the first stage (so called member countries) set gross emissions and abatement levels to maximize their joint welfare and distribute the cooperation gain according to the NBS for given bargaining weights μ_i summing up to one. Countries that did not join the agreement in the first stage (so called non-members) set gross emissions and abatement levels to maximize their own domestic welfare only, given the gross emission and abatement choices of all other countries (like in the NE). In the following, we concentrate attention to the second stage. Thus, we assume the membership status of all countries has already been chosen in the first stage and denote the set of member countries by $\mathcal{C} \subseteq \{1, \ldots, n\}$.

In the second stage, non-member countries $i \notin \mathcal{C}$ face the same maximization problem (8) as in the NE, leading to the same necessary and sufficient conditions (as shown in the Appendix). Accordingly, the equilibrium levels of gross emissions $\check{g}_i^{NC}$, abatement $\check{a}_i^{NC}$ and net emissions $\check{e}_i^{NC}$ are given by (for all $i \notin \mathcal{C}$):

$$\check{g}_i^{NC} = B_i'^{-1}\big(D_i'(\delta_i; \check{E})\big) \ , \quad \check{a}_i^{NC} = C_i'^{-1}\big(D_i'(\delta_i; \check{E})\big) \ , \quad \check{e}_i^{NC} = \check{g}_i^{NC} - \check{a}_i^{NC} \ , \tag{15}$$

where $\check{E}$ denotes the global net emissions in the Nash equilibrium of the second stage of the CFG for a given set of members $\mathcal{C}$.

Member countries $i \in \mathcal{C}$ choose gross emission and abatement levels such as to maximize their joint welfare $V^C = \sum_{i\in\mathcal{C}} W_i$:

$$\max_{\{g_i,a_i\}_{i\in\mathcal{C}}} \sum_{i\in\mathcal{C}} W_i \qquad \text{subject to} \quad E = \sum_{i=1}^{n}(g_i - a_i) \quad \text{and given} \quad g_j, a_j \quad \forall\, j \notin \mathcal{C}\ . \tag{16}$$

This yields the following necessary and sufficient conditions (see Appendix):

$$B_i'(\beta_i, \epsilon_i; g_i) = \sum_{j\in\mathcal{C}} D_j'(\delta_j; E) = C_i'(\alpha_i; a_i)\ , \tag{17}$$

as member countries take the externalities their net emissions impose on all other member countries into account. We obtain for the equilibrium levels of gross emissions $\check{g}_i^C$, abatement $\check{a}_i^C$ and net emissions $\check{e}_i^C$ (for all $i \in \mathcal{C}$):

$$\check{g}_i^C = B_i'^{-1}\left(\sum_{j\in\mathcal{C}} D_j'(\delta_j; \check{E})\right)\ , \quad \check{a}_i^C = C_i'^{-1}\left(\sum_{j\in\mathcal{C}} D_j'(\delta_j; \check{E})\right)\ , \quad \check{e}_i^C = \check{g}_i^C - \check{a}_i^C\ , \tag{18}$$

where the equilibrium level of global net emissions $\check{E}$ is given by the unique solution of

$$\begin{aligned}
\check{E} &= \sum_{j\notin\mathcal{C}} \check{e}_j^{NC} + \sum_{j\in\mathcal{C}} \check{e}_j^C \\
&= \sum_{j\notin\mathcal{C}} \left[B_j'^{-1}(D_j'(\delta_j; \check{E})) - C_j'^{-1}(D_j'(\delta_j; \check{E}))\right] + \\
&\quad + \sum_{j\in\mathcal{C}} \left[B_j'^{-1}\left(\sum_{k\in\mathcal{C}} D_k'(\delta_k; \check{E})\right) - C_j'^{-1}\left(\sum_{k\in\mathcal{C}} D_k'(\delta_k; \check{E})\right)\right]\ .
\end{aligned} \tag{19}$$

As member countries distribute the cooperation gain according to the NBS, the domestic welfare $\check{W}_i$ of country $i \in \mathcal{C}$ in the equilibrium of the second stage of the CFG is given by:

$$\check{W}_i = \hat{W}_i - \mu_i(\check{V}^C - \hat{V}^C)\ , \tag{20}$$

where μ_i denotes the bargaining power of country i (with $\sum_{i\in\mathcal{C}} \mu_i = 1$), $\check{V}^C$ is the joint welfare of all member countries and $\hat{V}^C$ is the joint welfare of all non-participating countries in the equilibrium of the second stage of the CFG.

4 Impacts of technological change

We now investigate how a marginal improvement in one of the four categories of climate relevant technologies in one country affects the equilibrium levels of net emissions and the levels of domestic welfare in the four international climate policy regimes characterized in Section 3.

4.1 Impacts of technological change on net emission levels

We start with the effects of marginal changes in the technological level, as measured by the cost parameters β_i, ϵ_i, α_i and δ_i of the four different categories of technologies, on net emission levels. More precisely, we analyze the comparative static effect on the equilibrium net emission levels in the four different policy regimes if one of the four technology categories marginally improves in one country i (i.e., the corresponding cost parameter β_i, ϵ_i, α_i or δ_i marginally decreases). As the following proposition shows, the effects depend on which technologies are improved, but (at least qualitatively) not on the climate policy regime:

Proposition 1 (Effects of technological improvements on net emissions)
Given that assumptions (4a)–(4g) *hold, then in all four policy regimes (GSO, NE, NBS and CFG) a marginal* improvement *in the technological level of country* $i \in \{1, \ldots, n\}$

1. *in low-carbon or abatement technologies* decreases *the equilibrium levels of country i's domestic and global net emission,*
2. *in carbon efficiency or adaptation technologies* increases *the equilibrium levels of country i's domestic and global net emission.*

While the proof of Proposition 1 is in the Appendix, the economic intuition is straightforward. A marginal improvement in one of the four categories of technologies in country i has a direct effect on its domestic net emissions. Better low-carbon technologies decrease the marginal productivity at any sufficiently high level of gross emissions, while better abatement technologies reduce the marginal abatement costs for any positive abatement level. Thus, ceteris paribus, the former reduces the level of gross emissions and the latter increases the level of abatement of country i, both leading to a decrease in net emissions in country i in the equilibria of all four policy regimes. A marginal improvement in carbon efficiency increases the marginal productivity at any level of gross emissions, while better adaptation technologies decrease the marginal environmental damage costs at any positive level of global net emissions. Thus, ceteris paribus, the former increases the level of gross emissions and the latter increases the level of net emissions (in general, due to an increase in gross

	$\boldsymbol{\beta_i} \downarrow$	$\boldsymbol{\epsilon_i} \downarrow$	$\boldsymbol{\alpha_i} \downarrow$	$\boldsymbol{\delta_i} \downarrow$
GSO	$e_i^\star \uparrow,\ E_{-i}^\star \downarrow,\ E^\star \uparrow$	$e_i^\star \downarrow,\ E_{-i}^\star \uparrow,\ E^\star \downarrow$	$e_i^\star \downarrow,\ E_{-i}^\star \uparrow,\ E^\star \downarrow$	$e_i^\star \uparrow,\ E_{-i}^\star \uparrow,\ E^\star \uparrow$
NE	$\hat{e}_i \uparrow,\ \hat{E}_{-i} \downarrow,\ \hat{E} \uparrow$	$\hat{e}_i \downarrow,\ \hat{E}_{-i} \uparrow,\ \hat{E} \downarrow$	$\hat{e}_i \downarrow,\ \hat{E}_{-i} \uparrow,\ \hat{E} \downarrow$	$\hat{e}_i \uparrow,\ \hat{E}_{-i} \downarrow,\ \hat{E} \uparrow$
NBS	$\tilde{e}_i \uparrow,\ \tilde{E}_{-i} \downarrow,\ \tilde{E} \uparrow$	$\tilde{e}_i \downarrow,\ \tilde{E}_{-i} \uparrow,\ \tilde{E} \downarrow$	$\tilde{e}_i \downarrow,\ \tilde{E}_{-i} \uparrow,\ \tilde{E} \downarrow$	$\tilde{e}_i \uparrow,\ \tilde{E}_{-i} \uparrow,\ \tilde{E} \uparrow$
CFG	$\check{e}_i^{NC} \uparrow,\ \check{E}_{-i} \downarrow,\ \check{E} \uparrow$ $\check{e}_i^{C} \uparrow,\ \check{E}_{-i} \downarrow,\ \check{E} \uparrow$	$\check{e}_i^{NC} \downarrow,\ \check{E}_{-i} \uparrow,\ \check{E} \downarrow$ $\check{e}_i^{C} \downarrow,\ \check{E}_{-i} \uparrow,\ \check{E} \downarrow$	$\check{e}_i^{NC} \downarrow,\ \check{E}_{-i} \uparrow,\ \check{E} \downarrow$ $\check{e}_i^{C} \downarrow,\ \check{E}_{-i} \uparrow,\ \check{E} \downarrow$	$\check{e}_i^{NC} \uparrow,\ \check{E}_{-i} \downarrow,\ \check{E} \uparrow$ $\check{e}_i^{C} \uparrow,\ \check{E}_{-i} \uparrow\downarrow,\ \check{E} \uparrow$

Table 1: Effects of a marginal technological improvement in country i on the equilibrium net emissions levels of country i (e_i), all other countries (E_{-i}) and global net emissions (E) for the four policy regimes GSO, NE, NBS, CFG.

emissions and a decrease in abatement) in country i, leading to an increase in net emissions of country i in the equilibria of all four policy regimes.

In addition to this direct effect, which – at least qualitatively – is the same in all four policy regimes, there is an indirect effect. All other countries change their equilibrium levels of net emissions as a consequence to the change in net emissions in country i. As Table 1 shows, the indirect effect, measured as the change of the sum of net emissions of all other countries but country i, E_{-i}, is always in the opposite direction of the direct effect in case of a reduction in β_i, ϵ_i and α_i. In case of an improvement in adaptation technologies (i.e., a reduction in δ_i), the indirect effect can go either in the same direction as the direct effect or in the opposite direction. As the direct effect always outweighs the indirect effect, global levels of net emissions move in the same direction as the domestic net emission levels of country i in the equilibria of all four policy regimes.

Proposition 1 conveys two important insights. First, improvements in climate relevant technologies do not necessarily reduce global net emissions. This is particularly important for long-run climate policies, as the stabilization of greenhouse gas concentrations in the atmosphere (for example, in order to contain the increase of average global surface temperature compared to its pre-industrial level below 2°C) mandates to reduce global net emissions of greenhouse gases to virtually zero in the long run. Our results show that improvements in carbon efficiency and adaptation technologies have to be accompanied by sufficiently large improvements in low-carbon and abatement technologies to reduce global net emissions. Second, this result does – at least not qualitatively – depend on the international climate policy regime. No matter to which extent climate policies are cooperative or non-cooperative, the qualitative effect of technological improvements on domestic and global net emissions is always the same.

4.2 Impacts of technological change on domestic welfare levels

We now investigate the effect of technological progress on welfare. More precisely, we calculate the comparative static effects of a marginal decrease of the cost parameters β_i, ϵ_i, α_i and δ_i in country i on welfare (on global welfare in case of the GSO and on country i's domestic welfare in case of all other policy regimes). We interpret the effect of a marginal improvement in one of the four categories of technologies on welfare as a measure of the "incentive to invest" into improvements of the respective technologies, because – everything else equal – the incentive to invest into an improvement of a particular category of technologies is the higher, the higher is the welfare gain of such an improvement. Of course, this investment incentive is a qualitative measure, as it neglects important aspects such as the costs of technological improvements. As a consequence, our measure of investment incentives cannot, in general, guide countries into what kind of technologies, and to which extent, they should invest.

We first, consider the investment incentives in the GSO:

Proposition 2 (Investment incentives in the GSO)
Given that assumptions (4a)–(4g) *hold, a marginal improvement in any of the four categories of technologies in any country* $i \in \{1, \dots, n\}$ *increases global welfare.*

Proposition 2 may seem trivial. However, we shall see that this is not the case, when investigating the innovation incentives in the other policy regimes. While the rigorous proof is relegated to the Appendix, the economic intuition is as follows. A marginal improvement in any of the four categories of technologies in any country i has a direct and an indirect effect on welfare. The direct effect is straightforward and is simply the welfare gain achieved in country i by employing the better technologies keeping all gross emission and abatement levels constant (therefore, the direct effect could also be called a first-order effect). However, employing improved technologies leads to an adjustment of gross emission and abatement levels in the GSO. These adjustments also impact on welfare. However, unlike the direct effect, which is always a welfare gain, the indirect effects may positively or negatively impact on welfare. However, in the GSO the total indirect effect is equal to zero. As a consequence, only the direct effect remains, which is always a welfare gain.[4]

[4] While the indirect effects cancel out on a global level in the GSO, this is, in general, not true on the level of domestic welfare. However, as the global social planer only cares about global welfare, we consider it appropriate to only look at innovative incentives on a global level. Obviously, this is different in case of the other policy regimes, where individual countries decide on gross emission and abatement levels and, therefore, also care primarily on the effect of technological improvements on their own welfare.

Turning to the three other policy regimes and following up on the discussion of investment incentives into better technologies in the GSO, we can write the investment incentives of country i to invest into better technologies – independently of the policy regime – as the sum of a direct effect and an indirect effect:

$$\frac{dW_i}{d\square} = \underbrace{\text{direct effect (DE)}}_{<0} + \text{indirect effect (IE)} \ , \qquad \square \in \{\beta_i, \epsilon_i, \alpha_i, \delta_i\} \ . \tag{21}$$

The direct effect is the welfare gain of employing marginally improved technologies keeping all endogenous variables unchanged and is always positive for marginal reductions in the cost parameters β_i, ϵ_i, α_i and δ_i. The indirect effect is conveyed through the change in the endogenous variables in the equilibrium of the respective climate policy regime. Unlike the direct effect, the indirect effect can be positive or negative:

Proposition 3 (Investment incentives in the NE, NBS and CFG)
Given that assumptions (4a)–(4g) *hold, then in the equilibria of the NE, NBS and CFG policy regimes a marginal technological improvement in country* $i \in \{1, \dots, n\}$

1. *has always a positive* direct effect*,*
2. *while the* indirect effect
    a) *is positive for carbon efficiency and adaptation technologies, and*
    b) *is negative for low-carbon and abatement technologies.*

Thus, Proposition 3 states two important results. First, it says that the direct investment incentive is further strengthened by the indirect effect in case of carbon efficiency improving and adaptation technologies and is – at least – weakened by the indirect effect in case of low-carbon and abatement technologies. Combining this insight with the results of Proposition 1, we obtain that the direct investment incentives into technologies leading to *lower* global net emissions are weakened by opposing indirect effects, while the direct investment incentives into technologies leading to *higher* global net emissions are further strengthened by the corresponding indirect effects. Thus, our results show that successful climate change mitigation may be impeded over and above the standard public good property of emissions reductions by the strategic nature of investment incentives into better climate related technologies. Second, and even more intriguing, this result is – at least qualitatively – independent of the climate policy regime, as we proof in the Appendix. More precisely, while the NBS is able to achieve the global social optimal levels of net emissions it still suffers from distorted investment incentives into better climate relevant technologies.

Obviously, an important question is to what extent can the indirect effect weaken the direct effect in case of the low carbon and abatement technologies. To answer this question, we consider the following particular functional forms (quadratic benefit and abatement cost functions and linear environmental damages) for the different components of domestic welfare, which are standard in the literature (see also Sartzetakis and Strantza 2013):

$$B_i(\beta_i, \epsilon_i; g_i) = \frac{2g_i}{\beta_i \epsilon_i^2}\left(\epsilon_i - \frac{g_i}{2}\right) \ , \quad C_i(\alpha_i; a_i) = \frac{\alpha_i}{2} a_i^2 \ , \quad D_i(\delta_i, E) = \frac{\delta_i}{2} E \ . \tag{22}$$

For these functional forms, our assumption that g_i has to be sufficiently high (see equation (4c)) implies:

$$g_i > \frac{\epsilon_i}{2} \ . \tag{23}$$

In the following, we assume that parameter values are such that in the equilibrium of all four climate policy regimes assumption (23) holds for all countries $i = 1, \ldots, n$. Then the following proposition holds:

Proposition 4 (Indirect effects may outweigh direct effects)
Assume that the components of doemstic welfare are given by the functional forms (22) *and that in equilibrium assumption* (23) *holds. Then, in the equilibria of the policy regimes NE, NBS and CFG there exist for all countries $i = 1, \ldots, n$ parameter values*

1. $\bar{\epsilon}_i$ *such that the indirect effect outweighs the direct effect for the investments incentives of low-carbon technologies if $\epsilon_i < \bar{\epsilon}_i$, and*

2. $\bar{\alpha}_i$ *such that the indirect effect outweighs the direct effect for the investments incentives of abatement technologies if $\alpha_i < \bar{\alpha}_i$.*

Proposition 4 says that we cannot rule out that the indirect effect outweighs the direct effect for the investment incentives of low-carbon and abatement technologies. In fact, in all three policy regimes NE, NBS and CFG and for all feasible exogenous parameter combinations that are consistent with assumption (23) we find that investment incentives turn negative for low-carbon and abatement technologies if these technologies are already sufficiently advanced. A negative investment incentive implies that the country would never consider to invest in an improvement of the respective technologies, even if such an investment comes at investment costs of zero. Thus, Proposition 4 implies that there are – in general country and policy regime specific – upper bounds for the technological level of low-carbon and abatement technologies, upon reaching which countries stall any further investments into the respective technologies.

5 Discussion and conclusion

In summary, we find surprisingly robust results across a wide range of climate policy regimes how domestic and global net emissions react to technological progress and on how direct and indirect investment incentives into new technologies depend on the category of technologies. Before we discuss the robustness of both our assumptions and our results with respect to possible model extension, we want to clarify how our four stylized categories of relevant climate technologies translate into real world technological improvements.

The case is straightforward with respect to abatement and adaptation technologies. An improvement in abatement technologies simply allows to abate more gross emissions at a lower cost either directly at the source (e.g., carbon capture and sequestration technologies) or by increasing sink capacities (e.g., afforestation). Similarly, an improvement in adaptation technologies allows to reduce the (expected) impacts from climate change at lower costs (e.g., more resilient infrastructure, more resilient crops, etc.).

With respect to technologies improving carbon efficiency or reducing emissions, which both impact on the aggregate production possibility frontier of an economy matters are less straightforward. For example, how does an improvement in energy efficiency translate into increases (or decreases) of β_i and ϵ_i? If for example, all refrigerators in country i would be replaced by more energy efficient models, what would be the impact on the production function B_i? If energy is at least partly produced by fossil fuels and, thus, produces gross emissions, better refrigerators push the production possibility frontier upwards (i.e., β_i decreases). However, better energy efficiency is known to be prone to a direct and indirect rebound-effect. The direct effect is a substitution effect. As the relative price of "refrigeration" decreases, the equilibrium level of refrigerators increases, which at least partly outweighs the energy reduction due to more efficient refrigerators. The indirect effect is an income effect. The money saved by less energy consumption on refrigeration is spent on other commodities. Depending on whether these other commodities are more or less energy intensive, the total rebound effect can more than outweigh the initial energy saving from replacing all refrigerators by more energy efficient models. In this case the production possibility frontier shifts also to the right (i.e., ϵ_i decreases). In fact, Rausch and Schwerin (forthcoming) show in a CGE model calibrated to U.S. data that for the period from 1960 to 2011 increased energy efficiency has rather increased energy use than reduced it. In the context of our model this implies that increases in energy efficiency have the combined effect of *reducing* β_i and *increasing* ϵ_i which both increase domestic and global net emissions and exhibit an indirect investment incentive that strengthens the direct effect.

Now what about investments in green energy technologies? Consider, for example, a coal power plant is replaced by a renewable power plant with equal capacity. Obviously, this would shift the production possibility frontier to the left (i.e., ϵ_i decreases). As the renewable energy technology reduces ceteris paribus domestic and global gross emissions and, thus, also net emissions, this technology is partly desirable for its decrease in environmental damage. This implies that the new technology may be preferable even if it is more costly than the fossil fuel technology. If this is the case then the replacement of the fossil fuel technology by the renewable energy technology also shifts the production possibility frontier downwards (i.e., β_i increases). Thus, investments in green energy technologies in the context of our model are likely to increase ϵ_i while they decrease β_i, implying that they decrease domestic and global net emissions and exhibit an indirect investment incentive that opposes the direct effect.

Of course, the results of our model depend on the assumptions (4a) to (4g), which we imposed on the different components of domestic welfare B_i, C_i and D_i. Yet, we consider these assumptions as rather uncontroversial and laxer than standard in the literature. The only exception might be assumption (4c) that in equilibrium g_i is sufficiently large, or more precisely, g_i is sufficiently close to ϵ_i. Our defence for this assumption is that otherwise countries would leave in equilibrium a large part of their production capacities idle. We believe that this assumption is innocuous if we investigate the situation under a status quo policy regime. However, an abrupt policy change, for example, from the non-cooperative Nash equilibrium to the global social optimum, may induce a large decrease in the equilibrium gross emission levels and, thereby, violating this assumption. Yet, such an abrupt policy regime change is not a likely scenario to occur.

Another simplification of our model is its static nature, while climate change is clearly a dynamic problem. It is not emissions but accumulated emissions over time that induce the environmental damage. Also technological change requires investments in capital stocks, which is a time consuming process. In fact, one can easily conceive a dynamic version of our model in which in each time step there is a sequence of decisions: first, all countries simultaneously decide on technological investments and, second, all countries simultaneously decide about gross emission and abatement levels. To do so, we would also have to specify costs of technological improvements, implying that actual technological development, emission and abatement paths would depend on the particular assumptions about these costs. Yet, in each stage the qualitative result derived in our simple static model would survive. Improvements in carbon efficiency and adaptation technologies raises, while improvements in low carbon and abatement technologies reduces domestic and global gross emission and abatement levels. In addition, investments incentives exhibit, qualitatively, the same direct and indirect effects as in our static model.

Finally, we want to emphasize that just because our results are *qualitatively* robust across all investigated climate policy regimes, does not mean that the climate policy regime is inconsequential. Obviously, a cooperative climate policy regime, such as the Nash bargaining solution, yields – by construction – lower levels of domestic and global net emissions and higher domestic welfare for all countries than a non-cooperative policy regime like the non-cooperative Nash equilibrium. Moreover, only because the *signs* of the effects are the same in all policy regimes does not mean that the *size* is the same, too (and, in general, it is not). While the discussion of the quantitative impacts is certainly interesting, it is beyond the scope of this paper and constitutes a fruitful avenue for future research.

Yet, the results of our paper have important policy implications. First, we show that the indirect investment incentives reinforce the well-known problem of the under provision of greenhouse gas emission abatement, by rendering climate relevant technologies that *increase* domestic and global emissions ceteris paribus more attractive than technologies that *decrease* domestic and global emissions. Second, our results qualify conventional wisdom about the effectiveness of technology transfers – in particular from developed to less developed countries – in combating anthropogenic climate change. Everything else equal low-carbon or abatement technologies are preferable for technology transfers to carbon efficiency or adaptation technologies.

Appendix

A.1 Policy regimes

A.1.1 Global social optimum

In the global social optimum (GSO) a social planner dictates gross emission and abatement levels such as to maximize global welfare (3). Inserting equation (2) for global net emissions directly into global welfare and taking the derivatives with respect to gross emissions and abatement yields:

$$\frac{dV}{dg_i} = B_i'(\beta_i, \epsilon_i; g_i) - \sum_{j=1}^{n} D_j'(\delta_j; E) = 0 \ , \tag{A.1a}$$

$$\frac{dV}{da_i} = -C_i'(\alpha_i; a_i) + \sum_{j=1}^{n} D_j'(\delta_j; E) = 0 \ . \tag{A.1b}$$

As global welfare is strictly and jointly concave in gross emissions and abatement, the first-order conditions are also sufficient for a global social optimum. Solving equations (A.1a) for gross emissions and abatement, we obtain:

$$g_i^\star = B_i'^{-1}\left(\sum_{j=1}^{n} D_j'(\delta_j; E^\star)\right) \ , \quad a_i^\star = C_i'^{-1}\left(\sum_{j=1}^{n} D_j'(\delta_j; E^\star)\right) \ , \quad e_i^\star = g_i^\star - a_i^\star \ , \tag{A.2}$$

where $E^\star$ denotes the socially optimal level of global net emissions. Summing up domestic net emissions over all countries $i = 1, \ldots, n$, yields the following implicit equation for $E^\star$:

$$E^\star = \sum_{i=1}^{n} \left[B_i'^{-1}\left(\sum_{j=1}^{n} D_j'(\delta_j; E^\star)\right) - C_i'^{-1}\left(\sum_{j=1}^{n} D_j'(\delta_j; E^\star)\right)\right] \ . \tag{A.3}$$

As the left-hand side is strictly increasing and the right-hand side is strictly decreasing in $E^\star$, there exists a unique level $E^\star$ in the global social optimum. Inserting back $E^\star$ into (A.2) yields the domestic endogenous variables in the GSO.

A.1.2 Non-cooperative Nash equilibrium

In the non-cooperative Nash equilibrium (NE) all countries simultaneously choose gross emission and abatement levels such as to maximize their domestic welfare (1). Inserting equation (2) for global net emissions directly into domestic welfare and taking the choices of all other countries $i \neq i$ as given, we obtain the following derivatives with respect to gross emissions and abatement:

$$\frac{dW_i}{dg_i} = B_i'(\beta_i, \epsilon_i; g_i) - D_i'(\delta_i; E) = 0 \ , \tag{A.4a}$$

$$\frac{dW_i}{da_i} = -C_i'(\alpha_i; a_i) + D_i'(\delta_i; E) = 0 \ . \tag{A.4b}$$

As domestic welfare is strictly and jointly concave in domestic gross emissions and abatement levels, the first-order conditions (A.4a) implicitly determine the country i's best responde functions. Solving equations (A.4a) for gross emissions and abatement, we obtain:

$$\hat{g}_i = B_i'^{-1}\big(D_i'(\delta_i;\hat{E})\big) \ , \quad \hat{a}_i = C_i'^{-1}\big(D_i'(\delta_i;\hat{E})\big) \ , \quad \hat{e}_i = \hat{g}_i - \hat{a}_i \ , \tag{A.5}$$

where $\hat{E}$ denotes the level of global net emissions in the Nash equilibrium. Summing up domestic net emissions over all countries $i = 1, \ldots, n$, yields the following implicit equation for $\hat{E}$:

$$\hat{E} = \sum_{i=1}^{n} \Big[B_i'^{-1}\big(D_i'(\delta_i;\hat{E})\big) - C_i'^{-1}\big(D_i'(\delta_i;\hat{E})\big)\Big] \ . \tag{A.6}$$

As the left-hand side is strictly increasing and the right-hand side is strictly decreasing in $\hat{E}$, there exists a unique level $\hat{E}$ in the NE. Inserting back $\hat{E}$ into (A.5) yields the domestic endogenous variables in the NE.

A.1.3 Nash bargaining solution

In the Nash bargaining solution (NBS), we assume that welfare can be arbitrarily and frictionless re-distributed among countries. As a consequence, countries cooperate with respect to emissions and abatement levels to achieve the outcome of the GSO. The outcome of the NE constitutes the threat points. Then, countries distribute the cooperation gain, i.e., the difference in global welfare between the GSO and NE according to the Nash bargaining solution:

$$\max_{\{W_i\}_{i=1}^n} \Pi_{i=1}^n \left(W_i - \hat{W}_i\right)^{\nu_i} \qquad \text{subject to} \quad \sum_{i=1}^{n} W_i = V^\star \ , \quad \sum_{i=1}^{n} \nu_i = 1 \ , \tag{A.7}$$

Thus, the Lagrangian $\mathcal{L}$ reads:

$$\mathcal{L} = \Pi_{i=1}^n \left(W_i - \hat{W}_i\right)^{\nu_i} + \lambda \left[V^\star - \sum_{i=1}^{n} W_i\right] \ . \tag{A.8}$$

Taking the derivative with respect to W_i yields:

$$\frac{d\mathcal{L}}{dW_i} = \nu_i \left(W_i - \hat{W}_i\right)^{v_i - 1} \Pi_{j=1, j\neq i}^n \left(W_j - \hat{W}_j\right)^{\nu_j} - \lambda = 0 \ , \tag{A.9}$$

from which we obtain for the welfare $\tilde{W}_i$ of country i in the NBS:

$$\tilde{W}_i = \hat{W}_i + \nu_i(V^\star - \hat{V}) \ . \tag{A.10}$$

This translates into the following transfers $\tilde{T}_i$ in the NBS:

$$\tilde{T}_i = \tilde{W}_i - W_i^\star = \hat{W}_i - W_i^\star + \nu_i(V^\star - \hat{V}) \ . \tag{A.11}$$

A.1.4 Coalition formation game

We concentrate on the second stage of the coalition formation game (CFG). Thus, the set of member countries has already been chosen in stage one and is given by $\mathcal{C} \subseteq \{1, \ldots, n\}$.

Non-member countries $i \notin \mathcal{C}$ maximization their domestic welfare (1) taking the choices of all other countries $i \neq i$ as given. Thus, for each individual non-member country the maximization problem is identical to the NE and the their levels of emissions and abatement in the Nash equilibrium of the second stage of the CFG for a given set of members $\mathcal{C}$ are given by:

$$\check{g}_i^{NC} = B_i'^{-1}\big(D_i'(\delta_i;\check{E})\big) \ , \quad \check{a}_i^{NC} = C_i'^{-1}\big(D_i'(\delta_i;\check{E})\big) \ , \quad \check{e}_i^{NC} = \check{g}_i^{NC} - \check{a}_i^{NC} \ , \tag{A.12}$$

where $\check{E}$ denotes the global net emissions in the Nash equilibrium of the second stage of the CFG.

Member countries $i \in \mathcal{C}$ cooperate with respect to gross emissions and abatement to maximize their joint welfare $V^C = \sum_{i\in\mathcal{C}} W_i$:

$$\max_{\{g_i,a_i\}_{i\in\mathcal{C}}} \sum_{i\in\mathcal{C}} W_i \qquad \text{subject to} \quad E = \sum_{i=1}^{n}(g_i - a_i) \quad \text{and given} \quad g_j, a_j \quad \forall\ j \notin \mathcal{C} \ . \tag{A.13}$$

Inserting equation (2) for global net emissions directly into the joint welfare V^C and taking the derivatives with respect to gross emissions and abatement yields:

$$\frac{dV^C}{dg_i} = B_i'(\beta_i,\epsilon_i;g_i) - \sum_{j\in\mathcal{C}}^{n} D_j'(\delta_j;E) = 0 \ , \tag{A.14a}$$

$$\frac{dV^C}{da_i} = -C_i'(\alpha_i;a_i) + \sum_{j\in\mathcal{C}}^{n} D_j'(\delta_j;E) = 0 \ . \tag{A.14b}$$

As joint welfare is strictly and jointly concave in gross emissions and abatement, the first-order conditions are also sufficient for a joint welfare maximum. Solving equations (A.14a) for gross emissions and abatement, we obtain:

$$\check{g}_i^{C} = B_i'^{-1}\left(\sum_{j\in\mathcal{C}} D_j'(\delta_j;\check{E})\right) \ , \quad \check{a}_i^{C} = C_i'^{-1}\left(\sum_{j\in\mathcal{C}} D_j'(\delta_j;\check{E})\right) \ , \quad \check{e}_i^{C} = \check{g}_i^{C} - \check{a}_i^{C} \ , \tag{A.15}$$

where $\check{E}$ denotes the global net emissions in the Nash equilibrium of the second stage of the CFG.

Summing up domestic net emissions over all member and non-member countries yields the following implicit equation for $\check{E}$:

$$
\begin{aligned}
\check{E} &= \sum_{j \notin \mathcal{C}} \check{e}_j^{NC} + \sum_{j \in \mathcal{C}} \check{e}_j^{C} \\
&= \sum_{j \notin \mathcal{C}} \Big[B_j'^{-1}\big(D_j'(\delta_j; \check{E})\big) - C_j'^{-1}\big(D_j'(\delta_j; \check{E})\big) \Big] + \\
&\quad + \sum_{j \in \mathcal{C}} \left[B_j'^{-1} \left(\sum_{k \in \mathcal{C}} D_k'(\delta_k; \check{E}) \right) - C_j'^{-1} \left(\sum_{k \in \mathcal{C}} D_k'(\delta_k; \check{E}) \right) \right] \ .
\end{aligned}
\tag{A.16}
$$

As the left-hand side is strictly increasing and the right-hand side is strictly decreasing in $\check{E}$, there exists a unique level $\check{E}$ in the Nash equilibrium of the second stage of the CFG. Inserting back $\check{E}$ into (A.12) and (A.12) yields the domestic endogenous variables in the CFG for non-member and member countries.

A.2 Proof of Proposition 1

To proof Proposition 1, we first observe that by virtue of assumptions (4a) and (4d) the inverse function $B_i'^{-1}$ of marginal production and the inverse function $C_i'^{-1}$ of marginal abatement costs exist. In addition, assumptions (4b), (4c) and (4e) ensure that the following inequalities hold:

$$
\frac{\partial B_i'^{-1}(\beta_i, \epsilon_i; g_i)}{\partial \beta_i} < 0 \ , \quad \underset{(^\star \text{ if } g_i \text{ sufficiently high})}{\frac{\partial B_i'^{-1}(\beta_i, \epsilon_i; g_i)}{\partial \epsilon_i} > 0^\star} \ , \quad \frac{\partial C_i'^{-1}(\alpha_i; a_i)}{\partial \alpha_i} < 0 \ . \tag{A.17}
$$

Second, we derive the comparative static effects for net emissions in the four policy regimes.

A.2.1 Global social optimum and Nash bargaining solution

By construction emissions are identical in the GSO and NBS. We re-write equation (7b) to yield:

$$
F^\star = E^\star - \sum_{i=1}^{n} \left[B_i'^{-1} \left(\sum_{j=1}^{n} D_j'(\delta_j; E^\star) \right) - C_i'^{-1} \left(\sum_{j=1}^{n} D_j'(\delta_j; E^\star) \right) \right] = 0 \ . \tag{A.18}
$$

By virtue of the implicit function theorem, it holds:

$$
\frac{dE^\star}{d\square} = -\frac{\partial F^\star / \partial \square}{\partial F^\star / \partial E} \ , \qquad \square \in \{\beta_i, \epsilon_i, \epsilon_i, \delta_i\} \ . \tag{A.19}
$$

Defining

$$
\phi_i^\star = \frac{\sum_{j=1}^{n} D_j''}{C_i''} - \frac{\sum_{j=1}^{n} D_j''}{B_i''} \ , \quad \Phi^\star = \sum_{i=1}^{n} \phi_i^\star \ , \quad \Phi_{-i}^\star = \Phi^\star - \phi_i^\star \ , \tag{A.20}
$$

we obtain:

$$\begin{aligned}
&\frac{\partial F^\star}{\partial \beta_i} = -\frac{\partial B_i'^{-1}}{\partial \beta_i} > 0 \ , \qquad \frac{\partial F^\star}{\partial \epsilon_i} = -\frac{\partial B_i'^{-1}}{\partial \epsilon_i} < 0 \ , \qquad \frac{\partial F^\star}{\partial \alpha_i} = \frac{\partial C_i'^{-1}}{\partial \alpha_i} < 0 \ , \\
&\frac{\partial F^\star}{\partial \delta_i} = \frac{\partial D_i'}{\partial \delta_i} \sum_{j=1}^{n} \left(\frac{1}{C_j''} - \frac{1}{B_j''} \right) > 0 \ , \qquad \frac{\partial F^\star}{\partial E} = 1 + \Phi^\star > 0 \ ,
\end{aligned} \tag{A.21}$$

and, thus:

$$\begin{aligned}
&\frac{dE^\star}{d\beta_i} = \frac{\partial B_i'^{-1}}{\partial \beta_i} \frac{1}{1+\Phi^\star} < 0 \ , \qquad \frac{dE^\star}{d\epsilon_i} = \frac{\partial B_i'^{-1}}{\partial \epsilon_i} \frac{1}{1+\Phi^\star} > 0 \ , \\
&\frac{dE^\star}{d\alpha_i} = -\frac{\partial C_i'^{-1}}{\partial \alpha_i} \frac{1}{1+\Phi^\star} > 0 \ , \qquad \frac{dE^\star}{d\delta_i} = -\frac{\partial D_i'}{\partial \delta_i} \sum_{i=1}^{n} \left(\frac{1}{C_j''} - \frac{1}{B_j''} \right) \frac{1}{1+\Phi^\star} < 0 \ .
\end{aligned} \tag{A.22}$$

Using the following relationship

$$\frac{de_i^\star}{d\square} = \frac{\partial e_i^\star}{\partial \square} + \frac{de_i^\star}{dE^\star} \frac{dE^\star}{d\square} \ , \qquad \square \in \{\beta_i, \epsilon_i, \alpha_i, \delta_i\} \ , \tag{A.23}$$

we also obtain:

$$\begin{aligned}
&\frac{de_i^\star}{d\beta_i} = \frac{\partial B_i'^{-1}}{\partial \beta_i} \frac{1+\Phi_{-i}^\star}{1+\Phi^\star} < 0 \ , \qquad \frac{de_i^\star}{d\epsilon_i} = \frac{\partial B_i'^{-1}}{\partial \epsilon_i} \frac{1+\Phi_{-i}^\star}{1+\Phi^\star} > 0 \ , \\
&\frac{de_i^\star}{d\alpha_i} = -\frac{\partial C_i'^{-1}}{\partial \alpha_i} \frac{1+\Phi_{-i}^\star}{1+\Phi^\star} > 0 \ , \qquad \frac{de_i^\star}{d\delta_i} = -\frac{\partial D_i'}{\partial \delta_i} \left(\frac{1}{C_i''} - \frac{1}{B_i''} \right) \frac{1}{1+\Phi^\star} < 0 \ .
\end{aligned} \tag{A.24}$$

Finally,

$$\frac{dE_{-i}^\star}{d\square} = \frac{dE^\star}{d\square} - \frac{de_i^\star}{d\square} \ , \qquad \square \in \{\beta_i, \epsilon_i, \alpha_i, \delta_i\} \ , \tag{A.25}$$

and, thus:

$$\begin{aligned}
&\frac{dE_{-i}^\star}{d\beta_i} = -\frac{\partial B_i'^{-1}}{\partial \beta_i} \frac{\Phi_{-i}^\star}{1+\Phi^\star} > 0 \ , \qquad \frac{dE_{-i}^\star}{d\epsilon_i} = -\frac{\partial B_i'^{-1}}{\partial \epsilon_i} \frac{\Phi_{-i}^\star}{1+\Phi^\star} < 0 \ , \\
&\frac{dE_{-i}^\star}{d\alpha_i} = \frac{\partial C_i'^{-1}}{\partial \alpha_i} \frac{\Phi_{-i}^\star}{1+\Phi^\star} < 0 \ , \qquad \frac{dE_{-i}^\star}{d\delta_i} = -\frac{\partial D_i'}{\partial \delta_i} \sum_{j=1, j\neq i}^{n} \left(\frac{1}{C_j''} - \frac{1}{B_j''} \right) \frac{1}{\Phi^\star} < 0 \ .
\end{aligned} \tag{A.26}$$

A.2.2 Non-cooperative Nash equilibrium

Re-writing equation (10b) yields:

$$\hat{F} = \hat{E} - \sum_{i=1}^{n} \left[B_i'^{-1}\big(D_i'(\delta_i; \hat{E})\big) - C_i'^{-1}\big(D_i'(\delta_i; \hat{E})\big) \right] = 0 \ . \tag{A.27}$$

By virtue of the implicit function theorem, it holds:

$$\frac{d\hat{E}}{d\square} = -\frac{\partial \hat{F}/\partial \square}{\partial \hat{F}/\partial E} \ , \qquad \square \in \{\beta_i, \epsilon_i, \epsilon_i, \delta_i\} \ . \tag{A.28}$$

Defining

$$\hat{\phi}_i = \frac{D_i''}{C_i''} - \frac{D_i''}{B_i''} \ , \quad \hat{\Phi} = \sum_{i=1}^{n} \hat{\phi}_i \ , \quad \hat{\Phi}_{-i} = \hat{\Phi} - \hat{\phi}_i \ , \tag{A.29}$$

we obtain:

$$\begin{aligned}
&\frac{\partial \hat{F}}{\partial \beta_i} = -\frac{\partial B_i'^{-1}}{\partial \beta_i} > 0 \ , \qquad \frac{\partial \hat{F}}{\partial \epsilon_i} = -\frac{\partial B_i'^{-1}}{\partial \epsilon_i} < 0 \ , \qquad \frac{\partial \hat{F}}{\partial \alpha_i} = \frac{\partial C_i'^{-1}}{\partial \alpha_i} < 0 \ , \\
&\frac{\partial \hat{F}}{\partial \delta_i} = \frac{\partial D_i'}{\partial \delta_i}\left(\frac{1}{C_i''} - \frac{1}{B_i''}\right) > 0 \ , \qquad \frac{\partial \hat{F}}{\partial E} = 1 + \hat{\Phi} > 0 \ ,
\end{aligned} \tag{A.30}$$

and, thus:

$$\begin{aligned}
&\frac{d\hat{E}}{d\beta_i} = \frac{\partial B_i'^{-1}}{\partial \beta_i}\frac{1}{1+\hat{\Phi}} < 0 \ , \qquad \frac{d\hat{E}}{d\epsilon_i} = \frac{\partial B_i'^{-1}}{\partial \epsilon_i}\frac{1}{1+\hat{\Phi}} > 0 \ , \\
&\frac{d\hat{E}}{d\alpha_i} = -\frac{\partial C_i'^{-1}}{\partial \alpha_i}\frac{1}{1+\hat{\Phi}} > 0 \ , \qquad \frac{d\hat{E}}{d\delta_i} = -\frac{\partial D_i'}{\partial \delta_i}\left(\frac{1}{C_i''} - \frac{1}{B_i''}\right)\frac{1}{1+\hat{\Phi}} < 0 \ .
\end{aligned} \tag{A.31}$$

Using the following relationship

$$\frac{d\hat{e}_i}{d\square} = \frac{\partial \hat{e}_i}{\partial \square} + \frac{d\hat{e}_i}{d\hat{E}}\frac{d\hat{E}}{d\square} \ , \qquad \square \in \{\beta_i, \epsilon_i, \alpha_i, \delta_i\} \ , \tag{A.32}$$

we also obtain:

$$\begin{aligned}
&\frac{d\hat{e}_i}{d\beta_i} = \frac{\partial B_i'^{-1}}{\partial \beta_i}\frac{1+\hat{\Phi}_{-i}}{1+\hat{\Phi}} < 0 \ , \qquad \frac{d\hat{e}_i}{d\epsilon_i} = \frac{\partial B_i'^{-1}}{\partial \epsilon_i}\frac{1+\hat{\Phi}_{-i}}{1+\hat{\Phi}} > 0 \ , \\
&\frac{d\hat{e}_i}{d\alpha_i} = -\frac{\partial C_i'^{-1}}{\partial \alpha_i}\frac{1+\hat{\Phi}_{-i}}{1+\hat{\Phi}} > 0 \ , \qquad \frac{d\hat{e}_i}{d\delta_i} = -\frac{\partial D_i'}{\partial \delta_i}\left(\frac{1}{C_i''} - \frac{1}{B_i''}\right)\frac{1+\hat{\Phi}_i}{\hat{\Phi}} < 0 \ .
\end{aligned} \tag{A.33}$$

Finally,

$$\frac{d\hat{E}_{-i}}{d\square} = \frac{d\hat{E}}{d\square} - \frac{d\hat{e}_i}{d\square} \ , \qquad \square \in \{\beta_i, \epsilon_i, \alpha_i, \delta_i\} \ , \tag{A.34}$$

and, thus:

$$\begin{aligned}
&\frac{d\hat{E}_{-i}}{d\beta_i} = -\frac{\partial B_i'^{-1}}{\partial \beta_i}\frac{\hat{\Phi}_{-i}}{1+\hat{\Phi}} > 0 \ , \qquad \frac{d\hat{E}_{-i}}{d\epsilon_i} = -\frac{\partial B_i'^{-1}}{\partial \epsilon_i}\frac{\hat{\Phi}_{-i}}{1+\hat{\Phi}} < 0 \ , \\
&\frac{d\hat{E}_{-i}}{d\alpha_i} = \frac{\partial C_i'^{-1}}{\partial \alpha_i}\frac{\hat{\Phi}_{-i}}{1+\hat{\Phi}} < 0 \ , \qquad \frac{d\hat{E}_{-i}}{d\delta_i} = \frac{\partial D_i'}{\partial \delta_i}\left(\frac{1}{C_i''} - \frac{1}{B_i''}\right)\frac{\hat{\Phi}_{-i}}{\hat{\Phi}} > 0 \ .
\end{aligned} \tag{A.35}$$

A.2.3 Coalition formation game

Re-writing equation (19) yields:

$$\begin{aligned}\check{F} = \check{E} - \sum_{j \notin \mathcal{C}} \Big[B_j'^{-1}\big(D_j'(\delta_j; \check{E})\big) - C_j'^{-1}\big(D_j'(\delta_j; \check{E})\big) \Big] - \\ - \sum_{j \in \mathcal{C}} \left[B_j'^{-1} \left(\sum_{k \in \mathcal{C}} D_k'(\delta_k; \check{E}) \right) - C_j'^{-1} \left(\sum_{k \in \mathcal{C}} D_k'(\delta_k; \check{E}) \right) \right] = 0 \ .\end{aligned} \tag{A.36}$$

By virtue of the implicit function theorem, it holds:

$$\frac{d\check{E}}{d\square} = -\frac{\partial \check{F}/\partial \square}{\partial \check{F}/\partial E} \ , \qquad \square \in \{\beta_i, \epsilon_i, \epsilon_i, \delta_i\} \ . \tag{A.37}$$

We now have to distinguish whether country i is a member or non-member country. We define:

$$\begin{aligned}&\check{\phi}_i^{NC} = \frac{D_i''}{C_i''} - \frac{D_i''}{B_i''} \ , && \check{\Phi}^{NC} = \sum_{i \notin \mathcal{C}} \check{\phi}_i^{NC} \ , && \check{\Phi}_{-i}^{NC} = \check{\Phi}^{NC} - \check{\phi}_i^{NC} \ , && \forall\ i \notin \mathcal{C} \ , \\ &\check{\phi}_i^{C} = \frac{\sum_{j \in \mathcal{C}} D_j''}{C_i''} - \frac{\sum_{j \in \mathcal{C}} D_j''}{B_i''} \ , && \check{\Phi}^{C} = \sum_{i \in \mathcal{C}} \check{\phi}_i^{C} \ , && \check{\Phi}_{-i}^{C} = \check{\Phi}^{C} - \check{\phi}_i^{C} \ , && \forall\ i \in \mathcal{C} \ , \\ &\check{\Phi} = \check{\Phi}^{NC} + \check{\Phi}^{C} \ .\end{aligned} \tag{A.38}$$

Country $i \notin \mathcal{C}$:

If country $i \notin \mathcal{C}$, we obtain:

$$\begin{aligned}&\frac{\partial \check{F}}{\partial \beta_i} = -\frac{\partial B_i'^{-1}}{\partial \beta_i} > 0 \ , \qquad \frac{\partial \check{F}}{\partial \epsilon_i} = -\frac{\partial B_i'^{-1}}{\partial \epsilon_i} < 0 \ , \qquad \frac{\partial \check{F}}{\partial \alpha_i} = \frac{\partial C_i'^{-1}}{\partial \alpha_i} < 0 \ , \\ &\frac{\partial \check{F}}{\partial \delta_i} = \frac{\partial D_i'}{\partial \delta_i} \left(\frac{1}{C_i''} - \frac{1}{B_i''} \right) > 0 \ , \qquad \frac{\partial \check{F}}{\partial E} = 1 + \check{\Phi} > 0 \ ,\end{aligned} \tag{A.39}$$

and, thus:

$$\begin{aligned}&\frac{d\check{E}}{d\beta_i} = \frac{\partial B_i'^{-1}}{\partial \beta_i} \frac{1}{1 + \check{\Phi}} < 0 \ , && \frac{d\check{E}}{d\epsilon_i} = \frac{\partial B_i'^{-1}}{\partial \epsilon_i} \frac{1}{1 + \check{\Phi}} > 0 \ , \\ &\frac{d\check{E}}{d\alpha_i} = -\frac{\partial C_i'^{-1}}{\partial \alpha_i} \frac{1}{1 + \check{\Phi}} > 0 \ , && \frac{d\check{E}}{d\delta_i} = -\frac{\partial D_i'}{\partial \delta_i} \left(\frac{1}{C_i''} - \frac{1}{B_i''} \right) \frac{1}{1 + \check{\Phi}} < 0 \ .\end{aligned} \tag{A.40}$$

Using the following relationship

$$\frac{d\check{e}_i^{NC}}{d\square} = \frac{\partial \check{e}_i^{NC}}{\partial \square} + \frac{d\check{e}_i^{NC}}{d\check{E}} \frac{d\check{E}}{d\square} \ , \qquad \square \in \{\beta_i, \epsilon_i, \alpha_i, \delta_i\} \ , \tag{A.41}$$

we also obtain:

$$\begin{aligned}
\frac{d\check{e}_i^{NC}}{d\beta_i} &= \frac{\partial B_i'^{-1}}{\partial \beta_i}\frac{1+\check{\Phi}_{-i}^{NC}+\check{\Phi}^{C}}{1+\check{\Phi}} > 0 \ , \qquad & \frac{d\check{e}_i^{NC}}{d\epsilon_i} &= \frac{\partial B_i'^{-1}}{\partial \epsilon_i}\frac{1+\check{\Phi}_{-i}^{NC}+\check{\Phi}^{C}}{1+\check{\Phi}} < 0 \ , \\
\frac{d\check{e}_i^{NC}}{d\alpha_i} &= -\frac{\partial C_i'^{-1}}{\partial \alpha_i}\frac{1+\check{\Phi}_{-i}^{NC}+\check{\Phi}^{C}}{1+\check{\Phi}} < 0 \ , \qquad & \frac{d\check{e}_i^{NC}}{d\delta_i} &= -\frac{\partial D_i'}{\partial \delta_i}\left(\frac{1}{C_i''}-\frac{1}{B_i''}\right)\frac{1+\check{\Phi}_{-i}^{NC}+\check{\Phi}^{C}}{\check{\Phi}} > 0 \ .
\end{aligned} \tag{A.42}$$

Finally,

$$\frac{d\check{E}_{-i}}{d\Box} = \frac{d\check{E}}{d\Box} - \frac{d\check{e}_i^{NC}}{d\Box} \ , \qquad \Box \in \{\beta_i, \epsilon_i, \alpha_i, \delta_i\} \ , \tag{A.43}$$

and, thus:

$$\begin{aligned}
\frac{d\check{E}_{-i}}{d\beta_i} &= -\frac{\partial B_i'^{-1}}{\partial \beta_i}\frac{\check{\Phi}_{-i}^{NC}+\check{\Phi}^{C}}{1+\check{\Phi}} > 0 \ , \qquad & \frac{d\check{E}_{-i}}{d\epsilon_i} &= -\frac{\partial B_i'^{-1}}{\partial \epsilon_i}\frac{\check{\Phi}_{-i}^{NC}+\check{\Phi}^{C}}{1+\check{\Phi}} < 0 \ , \\
\frac{d\check{E}_{-i}}{d\alpha_i} &= \frac{\partial C_i'^{-1}}{\partial \alpha_i}\frac{\check{\Phi}_{-i}^{NC}+\check{\Phi}^{C}}{1+\check{\Phi}} < 0 \ , \qquad & \frac{d\check{E}_{-i}}{d\delta_i} &= \frac{\partial D_i'}{\partial \delta_i}\left(\frac{1}{C_i''}-\frac{1}{B_i''}\right)\frac{\check{\Phi}_{-i}^{NC}+\check{\Phi}^{C}}{\check{\Phi}} > 0 \ .
\end{aligned} \tag{A.44}$$

Country $i \in \mathcal{C}$:

If country $i \in \mathcal{C}$, we obtain:

$$\begin{aligned}
&\frac{\partial \check{F}}{\partial \beta_i} = -\frac{\partial B_i'^{-1}}{\partial \beta_i} > 0 \ , \qquad \frac{\partial \check{F}}{\partial \epsilon_i} = -\frac{\partial B_i'^{-1}}{\partial \epsilon_i} < 0 \ , \qquad \frac{\partial \check{F}}{\partial \alpha_i} = \frac{\partial C_i'^{-1}}{\partial \alpha_i} < 0 \ , \\
&\frac{\partial \check{F}}{\partial \delta_i} = \frac{\partial D_i'}{\partial \delta_i}\sum_{j\in\mathcal{C}}\left(\frac{1}{C_j''}-\frac{1}{B_j''}\right) > 0 \ , \qquad \frac{\partial \check{F}}{\partial E} = 1+\check{\Phi} > 0 \ ,
\end{aligned} \tag{A.45}$$

and, thus:

$$\begin{aligned}
\frac{d\check{E}}{d\beta_i} &= \frac{\partial B_i'^{-1}}{\partial \beta_i}\frac{1}{1+\check{\Phi}} < 0 \ , \qquad & \frac{d\check{E}}{d\epsilon_i} &= \frac{\partial B_i'^{-1}}{\partial \epsilon_i}\frac{1}{1+\check{\Phi}} > 0 \ , \\
\frac{d\check{E}}{d\alpha_i} &= -\frac{\partial C_i'^{-1}}{\partial \alpha_i}\frac{1}{1+\check{\Phi}} > 0 \ , \qquad & \frac{d\check{E}}{d\delta_i} &= -\frac{\partial D_i'}{\partial \delta_i}\sum_{j\in\mathcal{C}}\left(\frac{1}{C_j''}-\frac{1}{B_j''}\right)\frac{1}{1+\check{\Phi}} < 0 \ .
\end{aligned} \tag{A.46}$$

Using the following relationship

$$\frac{d\check{e}_i^{C}}{d\Box} = \frac{\partial \check{e}_i^{C}}{\partial \Box} + \frac{d\check{e}_i^{C}}{d\check{E}}\frac{d\check{E}}{d\Box} \ , \qquad \Box \in \{\beta_i, \epsilon_i, \alpha_i, \delta_i\} \ , \tag{A.47}$$

we also obtain:

$$\begin{aligned}
\frac{d\check{e}_i^{C}}{d\beta_i} &= \frac{\partial B_i'^{-1}}{\partial \beta_i}\frac{1+\check{\Phi}^{NC}+\check{\Phi}_i^{C}}{1+\check{\Phi}} < 0 \ , \qquad & \frac{d\check{e}_i^{C}}{d\epsilon_i} &= \frac{\partial B_i'^{-1}}{\partial \epsilon_i}\frac{1+\check{\Phi}^{NC}+\check{\Phi}_i^{C}}{1+\check{\Phi}} > 0 \ , \\
\frac{d\check{e}_i^{C}}{d\alpha_i} &= -\frac{\partial C_i'^{-1}}{\partial \alpha_i}\frac{1+\check{\Phi}^{NC}+\check{\Phi}_i^{C}}{1+\check{\Phi}} > 0 \ , \qquad & \frac{d\check{e}_i^{C}}{d\delta_i} &= -\frac{\partial D_i'}{\partial \delta_i}\left(\frac{1}{C_i''}-\frac{1}{B_i''}\right)\frac{1+\check{\Phi}^{NC}}{\check{\Phi}} < 0 \ .
\end{aligned} \tag{A.48}$$

Finally,

$$\frac{d\check{E}_{-i}}{d\square} = \frac{d\check{E}}{d\square} - \frac{d\check{e}_i^C}{d\square} \ , \qquad \square \in \{\beta_i, \epsilon_i, \alpha_i, \delta_i\} \ , \tag{A.49}$$

and, thus:

$$\begin{aligned}
&\frac{d\check{E}_{-i}}{d\beta_i} = -\frac{\partial B_i'^{-1}}{\partial \beta_i}\frac{\check{\Phi}^{NC} + \check{\Phi}^C_{-i}}{1+\check{\Phi}} > 0 \ , \quad \frac{d\check{E}_{-i}}{d\epsilon_i} = -\frac{\partial B_i'^{-1}}{\partial \epsilon_i}\frac{\check{\Phi}^{NC} + \check{\Phi}^C_{-i}}{1+\check{\Phi}} < 0 \ , \\
&\frac{d\check{E}_{-i}}{d\alpha_i} = \frac{\partial C_i'^{-1}}{\partial \alpha_i}\frac{\check{\Phi}^{NC} + \check{\Phi}^C_{-i}}{1+\check{\Phi}} < 0 \ , \\
&\frac{d\check{E}_{-i}}{d\delta_i} = -\frac{\partial D_i'}{\partial \delta_i}\frac{1}{1+\check{\Phi}}\left[\sum_{j\in\mathcal{C}, j\neq i}\left(\frac{1}{C_j''} - \frac{1}{B_ij''}\right) - \left(\frac{1}{C_i''} - \frac{1}{B_i''}\right)\check{\Phi}^{NC}\right] \gtreqless 0 \ .
\end{aligned} \tag{A.50}$$

A.3 Proof of Proposition 2

To proof Proposition 2, we calculate the comparative static effect of a marginal change in the technology parameters β_i, ϵ_i, α_i and δ_i on global welfare V:

$$\begin{aligned}
\frac{dV^\star}{d\square} &= \frac{\partial W_i^\star}{\partial \square} + \sum_{j=1}^n \left[B_j'\frac{dg_j^\star}{d\square} - C_j'\frac{da_j^\star}{d\square} - D_j'\frac{dE^\star}{d\square}\right] \\
&= \frac{\partial W_i^\star}{\partial \square} + \sum_{j=1}^n D_j'\left[\sum_{k=1}^n \frac{dg_k^\star}{d\square} - \sum_{k=1}^n \frac{da_k^\star}{d\square} - \frac{dE^\star}{d\square}\right] \\
&= \frac{\partial W_i^\star}{\partial \square} \ ,
\end{aligned} \tag{A.51}$$

where $\square \in \{\beta_i, \epsilon_i, \alpha_i, \delta_i\}$. We observe that all indirect effects on global welfare, conveyed through changes in emission and abatement levels, sum up to zero and only the direct effect remains. Thus, we obtain:

$$\begin{aligned}
&\frac{dV^\star}{d\beta_i} = \frac{\partial B_i}{\partial \beta_i} < 0 \ , \qquad \frac{dV^\star}{d\epsilon_i} = \frac{\partial B_i}{\partial \epsilon_i} < 0 \ , \\
&\frac{dV^\star}{d\alpha_i} = -\frac{\partial C_i}{\partial \alpha_i} < 0 \ , \qquad \frac{dV^\star}{d\alpha_i} = -\frac{\partial D_i}{\partial \delta_i} < 0 \ .
\end{aligned} \tag{A.52}$$

A marginal improvement in any of the four classes of technologies in any country $i = 1, \ldots, n$ increases global welfare.

A.4 Proof of Proposition 3

To proof Proposition 3, we calculate the comparative static effect of a marginal change in the technology parameters β_i, ϵ_i, α_i and δ_i on domestic welfare W_i in the three policy regimes NE, NSB and CFG:

Non-cooperative Nash equilibrium

In the NE, it holds:

$$
\begin{aligned}
\frac{d\hat{W}_i}{d\Box} &= \frac{d\hat{W}_i}{d\Box} + B_i'\frac{d\hat{g}_i}{d\Box} - C_i'\frac{d\hat{a}_i}{d\Box} - D_i'\frac{d\hat{E}}{d\Box} = \frac{\partial\hat{W}_i}{\partial\Box} - D_i'\left[\frac{d\hat{E}}{d\Box} - \frac{d\hat{e}_i}{d\Box}\right] \\
&= \underbrace{\frac{\partial\hat{W}_i}{\partial\Box}}_{\text{direct effect (DI)}} \qquad \underbrace{-D_i'\frac{d\hat{E}_{-i}}{d\Box}}_{\text{indirect effect (IE)}} \quad ,
\end{aligned}
\tag{A.53}
$$

where $\Box \in \{\beta_i, \epsilon_i, \alpha_i, \delta_i\}$. Thus, we obtain:

$$
\begin{aligned}
\frac{d\hat{W}_i}{d\beta_i} &= \underbrace{\frac{\partial B_i}{\partial\beta_i}}_{<0} \quad \underbrace{-D_i'\frac{d\hat{E}_{-i}}{d\beta_i}}_{<0} < 0 \ , \qquad & \frac{d\hat{W}_i}{d\epsilon_i} &= \underbrace{\frac{\partial B_i}{\partial\epsilon_i}}_{<0} \quad \underbrace{-D_i'\frac{d\hat{E}_{-i}}{d\epsilon_i}}_{>0} \lesseqqgtr 0 \ , \\
\frac{d\hat{W}_i}{d\alpha_i} &= \underbrace{-\frac{\partial C_i}{\partial\alpha_i}}_{<0} \quad \underbrace{-D_i'\frac{d\hat{E}_{-i}}{d\alpha_i}}_{>0} \lesseqqgtr 0 \ , \qquad & \frac{d\hat{W}_i}{d\alpha_i} &= \underbrace{-\frac{\partial D_i}{\partial\delta_i}}_{<0} \quad \underbrace{-D_i'\frac{d\hat{E}_{-i}}{d\delta_i}}_{<0} < 0 \ .
\end{aligned}
\tag{A.54}
$$

Nash bargaining solution

In the NBS, it holds:

$$
\frac{d\tilde{W}_i}{d\Box} = \frac{\partial\hat{W}_i}{\partial\Box} + \nu_i\left(\frac{dV^\star}{d\Box} - \frac{d\hat{V}}{d\Box}\right) \ ,
\tag{A.55}
$$

where $\Box \in \{\beta_i, \epsilon_i, \alpha_i, \delta_i\}$. We first calculate $d\hat{V}/d\Box$:

$$
\begin{aligned}
\frac{d\hat{V}}{d\Box} &= \frac{d\hat{W}_i}{d\Box} + \sum_{j=1,j\neq i}^{n}\left[B_j'\frac{d\hat{g}_j}{d\Box} - C_j'\frac{d\hat{a}_j}{d\Box} - D_j'\frac{d\hat{E}}{d\Box}\right] = \frac{d\hat{W}_i}{d\Box} - \sum_{j=1,j\neq i}^{n} D_j'\left(\frac{d\hat{E}}{d\Box} - \frac{d\hat{e}_j}{d\Box}\right) \\
&= \frac{\partial\hat{W}_i}{\partial\Box} - D_i'\frac{d\hat{E}_{-i}}{d\Box} - \sum_{j=1,j\neq i}^{n} D_j'\frac{d\hat{E}_{-j}}{d\Box} \ ,
\end{aligned}
\tag{A.56}
$$

with

$$
\frac{d\hat{E}_{-j}}{d\Box} = \frac{d\hat{E}}{d\Box} - \frac{d\hat{e}_j}{d\Box} = 1 + \left(\frac{D_j''}{C_j''} - \frac{D_j''}{B_j''}\right)\frac{d\hat{E}}{d\Box} \ .
\tag{A.57}
$$

Inserting yields:

$$
\begin{aligned}
\frac{d\tilde{W}_i}{d\square} &= \frac{\partial \hat{W}_i}{\partial \square} + \nu_i \left(\frac{dV^\star}{d\square} - \frac{d\hat{V}}{d\square} \right) \\
&= \frac{\partial \hat{W}_i}{\partial \square} - D_i' \frac{d\hat{E}_{-i}}{d\square} + \nu_i \left[\frac{\partial W_i^\star}{\partial \square} - \frac{\partial \hat{W}_i}{\partial \square} + D_i' \frac{d\hat{E}_{-i}}{d\square} + \sum_{j=1, j\neq i}^{n} D_j' \frac{d\hat{E}_{-j}}{d\square} \right] \\
&= \underbrace{(1-\nu_i)\frac{\partial \hat{W}_i}{\partial \square} + \nu_i \frac{\partial W_i^\star}{\partial \square}}_{\text{direct effect (DE)}} \quad \underbrace{-(1-\nu_i) D_i' \frac{d\hat{E}_{-i}}{d\square} + \nu_i \sum_{j=1, j\neq i}^{n} D_j' \frac{d\hat{E}_{-j}}{d\square}}_{\text{indirect effect (IE)}}
\end{aligned} \tag{A.58}
$$

Thus, we obtain:

$$
\begin{aligned}
\frac{d\tilde{W}_i}{d\beta_i} &= \underbrace{(1-\nu_i)\frac{\partial \hat{B}_i}{\partial \beta_i} + \nu_i \frac{\partial B_i^\star}{\partial \beta_i}}_{<0} \quad \underbrace{-(1-\nu_i) D_i' \frac{d\hat{E}_{-i}}{d\beta_i} + \nu_i \sum_{j=1, j\neq i}^{n} D_j' \frac{d\hat{E}_{-j}}{d\beta_i}}_{<0} < 0 \ , \\
\frac{d\tilde{W}_i}{d\epsilon_i} &= \underbrace{(1-\nu_i)\frac{\partial \hat{B}_i}{\partial \epsilon_i} + \nu_i \frac{\partial B_i^\star}{\partial \epsilon_i}}_{<0} \quad \underbrace{-(1-\nu_i) D_i' \frac{d\hat{E}_{-i}}{d\epsilon_i} + \nu_i \sum_{j=1, j\neq i}^{n} D_j' \frac{d\hat{E}_{-j}}{d\epsilon_i}}_{>0} \lesseqqgtr 0 \ , \\
\frac{d\tilde{W}_i}{d\alpha_i} &= \underbrace{-(1-\nu_i)\frac{\partial \hat{C}_i}{\partial \alpha_i} - \nu_i \frac{\partial C_i^\star}{\partial \alpha_i}}_{<0} \quad \underbrace{-(1-\nu_i) D_i' \frac{d\hat{E}_{-i}}{d\alpha_i} + \nu_i \sum_{j=1, j\neq i}^{n} D_j' \frac{d\hat{E}_{-j}}{d\alpha_i}}_{>0} \lesseqqgtr 0 \ , \\
\frac{d\tilde{W}_i}{d\delta_i} &= \underbrace{-(1-\nu_i)\frac{\partial \hat{D}_i}{\partial \delta_i} - \nu_i \frac{\partial D_i^\star}{\partial \delta_i}}_{<0} \quad \underbrace{-(1-\nu_i) D_i' \frac{d\hat{E}_{-i}}{d\delta_i} + \nu_i \sum_{j=1, j\neq i}^{n} D_j' \frac{d\hat{E}_{-j}}{d\delta_i}}_{<0} < 0 \ .
\end{aligned} \tag{A.59}
$$

Coalition formation game

In the CFG, we have to distinguish whether country i is a member or non-member country.

Country $i \notin \mathcal{C}$

For $i \notin \mathcal{C}$, it holds:

$$
\begin{aligned}
\frac{d\check{W}_i}{d\square} &= \frac{\partial \check{W}_i}{\partial \square} + B_i' \frac{d\check{g}_i^{NC}}{d\square} - C_i' \frac{d\check{a}_i^{NC}}{d\square} - D_i' \frac{d\check{E}}{d\square} = \frac{\partial \check{W}_i}{\partial \square} - D_i' \left[\frac{d\check{E}}{d\square} - \frac{d\check{e}_i^{NC}}{d\square} \right] \\
&= \underbrace{\frac{\partial \check{W}_i}{\partial \square}}_{\text{direct effect (DI)}} \qquad \underbrace{-D_i' \frac{d\check{E}_{-i}}{d\square}}_{\text{indirect effect (IE)}} \quad ,
\end{aligned} \tag{A.60}
$$

where $\square \in \{\beta_i, \epsilon_i, \alpha_i, \delta_i\}$. Thus, we obtain:

$$\frac{d\check{W}_i}{d\beta_i} = \underbrace{\frac{\partial B_i}{\partial \beta_i}}_{<0} \underbrace{-D_i' \frac{d\check{E}_{-i}}{d\beta_i}}_{<0} < 0 \ , \qquad \frac{d\check{W}_i}{d\epsilon_i} = \underbrace{\frac{\partial B_i}{\partial \epsilon_i}}_{<0} \underbrace{-D_i' \frac{d\check{E}_{-i}}{d\epsilon_i}}_{>0} \lesseqgtr 0 \ ,$$
$$\frac{d\check{W}_i}{d\alpha_i} = \underbrace{-\frac{\partial C_i}{\partial \alpha_i}}_{<0} \underbrace{-D_i' \frac{d\check{E}_{-i}}{d\alpha_i}}_{>0} \lesseqgtr 0 \ , \qquad \frac{d\check{W}_i}{d\alpha_i} = \underbrace{-\frac{\partial D_i}{\partial \delta_i}}_{<0} \underbrace{-D_i' \frac{d\check{E}_{-i}}{d\delta_i}}_{<0} < 0 \ . \tag{A.61}$$

Country $i \in \mathcal{C}$

For $i \in \mathcal{C}$, it holds:

$$\frac{d\check{W}_i}{d\square} = \frac{d\hat{W}_i}{d\square} + \nu_i \left(\frac{d\check{V}^C}{d\square} - \frac{d\hat{V}}{d\square} \right) \ , \tag{A.62}$$

where $\square \in \{\beta_i, \epsilon_i, \alpha_i, \delta_i\}$. We first calculate $d\check{V}^C / d\square$:

$$\begin{aligned}\frac{d\check{V}^C}{d\square} &= \frac{\partial \hat{W}_i}{\partial \square} + \sum_{j \in \mathcal{C}} \left[B_j' \frac{d\check{g}_j^C}{d\square} - C_j' \frac{d\check{a}_j^C}{d\square} - D_j' \frac{d\check{E}}{d\square} \right] = \frac{\partial \hat{W}_i}{\partial \square} - \sum_{j \in \mathcal{C}} D_j' \left[\sum_{k \in \mathcal{C}} \frac{d\check{g}_k^C}{d\square} - \sum_{k \in \mathcal{C}} \frac{d\check{a}_k^C}{d\square} - \frac{d\check{E}}{d\square} \right] \\ &= \frac{\partial \hat{W}_i}{\partial \square} - \sum_{j \in \mathcal{C}} D_j' \sum_{j \notin \mathcal{C}} \frac{d\check{e}_j^{NC}}{d\square} \ ,\end{aligned} \tag{A.63}$$

with

$$\frac{d\check{e}_j^{NC}}{d\square} = - \left(\frac{D_j''}{C_j''} - \frac{D_j''}{B_j''} \right) \frac{d\check{E}}{d\square} \ . \tag{A.64}$$

Inserting yields:

$$\frac{d\check{W}_i}{d\square} = \underbrace{(1-\nu_i) \frac{\partial \hat{W}_i}{\partial \square} + \nu_i \frac{\partial \check{W}_i}{\partial \square}}_{\text{direct effect (DE)}} \underbrace{-(1-\nu_i) D_i' \frac{d\hat{E}_{-i}}{d\square} + \nu_i \left(\sum_{j=1, j \neq i}^{n} D_j' \frac{d\hat{E}_{-j}}{d\square} - \sum_{j \in \mathcal{C}} D_j' \sum_{j \notin \mathcal{C}} \frac{d\check{e}_j^{NC}}{d\square} \right)}_{\text{indirect effect (IE)}} \tag{A.65}$$

Thus, we obtain:

$$
\begin{aligned}
\frac{d\check{W}_i}{d\beta_i} &= \underbrace{(1-\nu_i)\frac{\partial \hat{B}_i}{\partial \beta_i} + \nu_i \frac{\partial \check{B}_i}{\partial \beta_i}}_{<0} \quad \underbrace{-(1-\nu_i)D_i' \frac{d\hat{E}_{-i}}{d\beta_i} + \nu_i \left(\sum_{j=1, j\neq i}^{n} D_j' \frac{d\hat{E}_{-j}}{d\beta_i} - \sum_{j\in\mathcal{C}} D_j' \sum_{j\notin\mathcal{C}} \frac{d\check{e}_j^{NC}}{d\beta_i} \right)}_{<0} < 0 \ , \\
\frac{d\check{W}_i}{d\epsilon_i} &= \underbrace{(1-\nu_i)\frac{\partial \hat{B}_i}{\partial \epsilon_i} + \nu_i \frac{\partial \check{B}_i}{\partial \epsilon_i}}_{<0} \quad \underbrace{-(1-\nu_i)D_i' \frac{d\hat{E}_{-i}}{d\epsilon_i} + \nu_i \left(\sum_{j=1, j\neq i}^{n} D_j' \frac{d\hat{E}_{-j}}{d\epsilon_i} - \sum_{j\in\mathcal{C}} D_j' \sum_{j\notin\mathcal{C}} \frac{d\check{e}_j^{NC}}{d\epsilon_i} \right)}_{>0} \lesseqgtr 0 \ , \\
\frac{d\check{W}_i}{d\alpha_i} &= \underbrace{-(1-\nu_i)\frac{\partial \hat{C}_i}{\partial \alpha_i} - \nu_i \frac{\partial \check{C}_i}{\partial \alpha_i}}_{<0} \quad \underbrace{-(1-\nu_i)D_i' \frac{d\hat{E}_{-i}}{d\alpha_i} + \nu_i \left(\sum_{j=1, j\neq i}^{n} D_j' \frac{d\hat{E}_{-j}}{d\alpha_i} - \sum_{j\in\mathcal{C}} D_j' \sum_{j\notin\mathcal{C}} \frac{d\check{e}_j^{NC}}{d\alpha_i} \right)}_{>0} \lesseqgtr 0 \ , \\
\frac{d\check{W}_i}{d\delta_i} &= \underbrace{-(1-\nu_i)\frac{\partial \hat{D}_i}{\partial \delta_i} - \nu_i \frac{\partial \check{D}_i}{\partial \delta_i}}_{<0} \quad \underbrace{-(1-\nu_i)D_i' \frac{d\hat{E}_{-i}}{d\delta_i} + \nu_i \left(\sum_{j=1, j\neq i}^{n} D_j' \frac{d\hat{E}_{-j}}{d\delta_i} - \sum_{j\in\mathcal{C}} D_j' \sum_{j\notin\mathcal{C}} \frac{d\check{e}_j^{NC}}{d\delta_i} \right)}_{<0} < 0 \ .
\end{aligned}
\tag{A.66}
$$

Comparing (A.54), (A.59), (A.61) and (A.66), we observe that the signs of the direct and indirect effect are the same in all three policy regimes.

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