Cooperation of climate clubs

Jan Kersting*

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Abstract

The slow progress of international climate change negotiations under the UNFCCC has led to calls for discussions in other, non-global fora, so-called "climate clubs". While the existence of stable agreements has been extensively studied in a global setting, cooperation of countries in such a club presents a new situation. I account for these specific circumstances by applying the concept of a subgame of a cooperative game to the game of global negotiations. The results are less optimistic than in the case of global negotiations, and the existence of a stable agreement in the climate club crucially depends on damage and abatement cost parameters of club members and outsiders. I also find that heterogeneity of countries negatively affects the chances of cooperation. An example is provided by the application of the model to the case of the Group of Twenty.

Keywords: climate club; cooperative game; core stability; international agreements

JEL: C71, D71, H41, Q20, Q54

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*Fraunhofer Institute for Systems and Innovation Research, Breslauer Str. 48, 76139 Karlsruhe, Germany. E-Mail: jan.kersting@isi.fraunhofer.de

Highlights

- I analyze the stability of climate cooperation in a non-global state club.
- For club members, high damages from climate change lead to stable cooperation.
- For outsiders, high damages hinder cooperation inside the club.
- Heterogeneity of countries negatively affects stability of cooperation.
- The Group of Twenty is used as an application of the theoretical model.

1 Introduction

The international negotiation process about limiting global greenhouse gas (GHG) emissions under the United Nations Framework Convention on Climate Change (UNFCCC) has so far failed to produce an agreement about global GHG emission reductions. The process requires consensus among all countries, leading to lengthy negotiations and slow progress. Also, compromises reached tend to represent the lowest common denominator of all countries. These downsides became apparent when the 2009 Conference of the Parties (COP) in Copenhagen failed to reach a global agreement, despite the presence of over 100 heads of state and government.

As an alternative to the current UNFCCC process, some scholars call for discussions in other, non-global fora (see e.g. Bodansky, 2002; Asheim et al., 2006; Naím, 2009; Victor, 2009; Eckersley, 2012; Weischer et al., 2012; Grasso and Roberts, 2014). The literature suggests that advantages of these so-called *climate clubs* over global negotiations might be faster negotiations, higher ambition from the club members, better participation from private actors and more equitable agreements (Biermann et al., 2009). Simple game-theoretic models indeed imply that negotiations in small groups can aid the coordination between countries, and that global negotiations can be supported by prior agreements of a few countries (Smead et al., 2014). An analysis of UNFCCC high-level segment speeches suggests that climate clubs could reduce negotiation complexity by eliminating secondary demands from country positions (Bagozzi, 2014). Most climate clubs try to ensure that they act complementary to the UNFCCC (Widerberg and Pattberg, 2015) and Widerberg and Stenson (2013) claim that climate clubs could lay the groundwork for a global climate deal at the 2015 COP in Paris.

However, from an empirical perspective, not enough is known about the effectiveness of different forms of climate governance to evaluate the proposed advantages of climate clubs (Jordan et al., 2015). Biermann et al. (2009) point out several problems of climate clubs, such as “forum shopping” by powerful states and the potential for a “race to the bottom” between competing clubs. Biermann et al. (2009) conclude that fragmentation of the global climate governance might do more harm than good.

The number of climate clubs has increased substantially since 2005, as negotiations on a global agreement began under the UNFCCC (Weischer et al., 2012). Many of these clubs focus on specific issues, such as the promotion of renewable energy or energy efficiency, or the reduction of deforestation or short-lived greenhouse gases (Widerberg and Stenson, 2013). In a survey of climate negotiation participants (Hjerpe and Nasiritousi, 2015), the two most frequently mentioned clubs were *state clubs*: the Major Economies Forum On Energy And Climate (MEF), which brings together the 17 largest economies of the world, and the Group of Twenty (G20). The topic of climate change was featured in the final declaration of all G20 leaders’ summits since the introduction of regular summits in 2008[1].

Whenever a prospective climate agreement among a group of countries is discussed, the question arises whether the agreement would be stable, that is whether all participating countries would have an incentive to sign it. Theoretical examinations of the stability of international climate cooperation usually conclude that cooperation is only stable among very few countries (e.g. Barrett, 1994; Carraro and Siniscalco, 1993; Diamantoudi and Sartzetakis, 2006), although modifications of the model allow for more substantial cooperation (see Hovi et al., 2014, for an overview). Some studies use this setup to analyse cooperation among smaller country groups. For exclusive membership games, Finus et al. (2005) find that exclusive membership stabilizes some coalitions, compared with open membership. However, these coalitions only marginally improve emission reductions over the non-cooperative equilibrium. Asheim et al. (2006) examine two parallel regional agreements and find that the two agreements are able to improve participation over a single agreement. Nordhaus (2015) studies clubs with penalty tariffs on non-participants. He finds that the penalty greatly enhances participation in the club and that this structure makes emission reductions near the global optimal level possible. However, such a penalty might not be compatible with WTO rules (see Jaspers and Falkner, 2013, for an overview of the literature).

In all of these studies, the participation of countries in a coalition evolves during the course of the game, that is the membership of the climate club changes. However, some of the clubs that are discussed as potential fora for a climate agreement have a fixed set of members and exist independently of the climate issue. The best example is given by the G20, which is often cited as a potential climate club (Naím, 2009; Hjerpe and Nasiritousi, 2015). It was founded as a forum for international economic cooperation and its membership has not changed since its inception. Consequently, participation in such a club is not the result of a game of climate cooperation, as previous studies assert. Rather, the club and its members are given, and the question becomes whether stable climate cooperation in the club is possible. The analysis of this question requires a different framework, which accounts for a given club with fixed membership.

In this paper, I analyze the stability of climate cooperation in pre-existing state clubs with fixed membership, such as the G20. Countries are divided into two distinct groups: those who are supposed to come to an agreement on legally binding commitments for all countries in this group (the *club members*) and the remaining countries, who benefit from commitments made by the club members, but do not commit to emission reductions themselves (the *outsiders*).

[1]See Shaw (2011) for an overview of G20 decisions on climate change.

As decision making in state clubs like the G20 requires approval of all members, an agreement would have to include all club members. Therefore, I analyse the existence of a stable agreement using the core stability concept by Chander and Tulkens (1997), which incorporates such a unanimity rule. That is, I check whether the given cooperative game has a (non-)empty core. So far, this concept has only been used to study global cooperation. As a result of the unanimity rule, a stable global agreement always exists if the functions describing country behaviour satisfy certain assumptions[2] (Chander and Tulkens, 1997; Helm, 2001). I modify the model of global cooperation for the study of cooperation among state clubs, using the concept of a *subgame*. While this concept has been used to study several types of cooperative games[3], it has so far not been employed in the context of the game of climate cooperation. I provide an analytical solution to the game with quadratic functions and determine the set of parameters for which a stable agreement among club members exists. I first assume that countries inside the club and countries outside the club are symmetric among their respective group. This assumption is later dropped and the impact of heterogeneous countries on the stability of a club agreement is shown. Finally, I apply the model to the case of the G20, using abatement cost estimates from a techno-economic model and damage cost estimates from an integrated assessment model.

The model is presented in Section 2. Section 3 gives theoretical results for the symmetric and the asymmetric case. Section 4 shows the application of the model to the case of the G20. Section 5 concludes and gives an outlook for future work.

2 The model

The setup is based on the model of transfrontier pollution by Chander and Tulkens (1997), hereafter CT model. Let $N = \{1, .., n\}$ be the set of players (countries) involved in the cooperative game. The model by Chander and Tulkens then consists of these components for all countries $i \in N$:

- emissions $E_i \in \mathbb{R}$.
- production function $P_i(E_i) : \mathbb{R} \to \mathbb{R}$, depending on a country's own emissions. It is assumed to be monotonically increasing up to a baseline emission level E_i^0, differentiable and concave.

[2]Monotonicity, differentiability and convexity / concavity. See Section 2 for a detailed description of the model.

[3]The subgame concept was introduced by Shapley and Shubik (1969) to study market games. Inter alia, it has also been used to study partition, packing and covering games (Deng et al., 2000; Bietenhader and Okamoto, 2006)

- damage function $D_i(E_N) : \mathbb{R} \to \mathbb{R}$, depending on global emissions E_N. It describes the damages incurred by environmental pollution, climate change in this case. The function is assumed to be monotonically increasing, differentiable and convex.

Each country's utility is determined by the difference of production and damages, $P_i(E_i) - D_i(E_N)$. Therefore, it depends on the emissions of all other players. In order to determine the value function v of the game, assume that a coalition $S \subseteq N$ forms. Members of the coalition maximize joint utility of all coalition members. Non-members split up into singletons and maximize individual utility[4]. It leads to the following parallel optimization problems:

$$\max_{(E_i)_{i \in S}} \sum_{i \in S} [P_i(E_i) - D_i(E_N)] \tag{2.1a}$$

$$\max_{E_j} P_j(E_j) - D_j(E_N) \quad \forall j \notin S \tag{2.1b}$$

Assigning the result of (2.1a) to $v(S)$ defines the value function of the global game. An *agreement* is a distribution of the value of the grand coalition $v(N)$ among all countries. The *core* of the game is the set of agreements, such that no country or coalition of countries has an incentive to deviate from the agreement. An agreement that lies in the core is called *stable*. Helm (2001) showed that the core of the game is not empty for all functions fulfilling the assumptions mentioned above[5]. This result provides a useful benchmark against which the stability of agreements inside a climate club can be compared.

I model negotiations of climate clubs as a *subgame*[6] of the cooperative game in the CT model. The following definition is due to Peleg and Sudhölter (2007).

Definition 1. *Let (N, v) be a game. A* ***subgame*** *of (N, v) is a game (T, v^T) where $\emptyset \neq T \subseteq N$ and $v^T(S) = v(S)$ for all $S \subseteq T$. The subgame (T, v^T) is also denoted by (T, v).*

Let $T \subset N$ be the set of club members and let $R = N \backslash T$ contain the outsiders. Then, the subgame (T, v) assesses the existence of a stable agreement among club members, while outsiders behave as they would in the global

[4]This so-called γ-assumption is further justified in Chander (2007), where it is shown that it corresponds to the behaviour in an equilibrium of the infinitely repeated game, when players are farsighted.

[5]Specifically, these are monotonicity, differentiability and convexity / concavity.

[6]Note that the subgame concept used in this paper is different from the concept of a subgame of a non-cooperative game in extensive form. Therefore, it also bears no relation to the notion of a "subgame-perfect equilibrium".

game. In accordance with the behaviour outlined above, outsiders maximize individual utility, while their payoff depends, inter alia, on the level of emissions of T. Therefore, R benefits from cooperation in T. However, decreasing emissions from T lead to increasing emissions from members of R, as they re-optimize their individual utility, making cooperation among T less beneficial and potentially unstable.

The existence of a stable agreement among the club members is tested by computing the utility of each *subcoalition* $S \subset T$, and comparing it to the utility of the *club coalition* T. This comparison determines the (non-)emptiness of the core of the subgame, which is the focus of the theoretical examination in the next section.

3 Theoretical results

For the theoretical analysis, I use quadratic production and damage functions. This ensures that no country or coalition has a dominant strategy[7], while the game remains analytically solvable. We will see that the (non-)emptiness of the core of the subgame crucially depends on the parameters for emission abatement costs and for damages caused by emissions, which I call μ and π, respectively. The setup is

$$P_i(E_i) = \begin{cases} P_i^0 - \mu_i(E_i^0 - E_i)^2, & E_i < E_i^0 \\ P_i^0, & E_i \geq E_i^0 \end{cases} \quad \forall i \in N \tag{3.1a}$$

$$D_i(E_N) = \pi_i E_N^2 \quad \forall i \in N, \tag{3.1b}$$

with

- baseline production for each country P_i^0 (in monetary units),
- baseline emissions for each country E_i^0,
- abatement cost parameter μ_i (in $\frac{\text{money}}{\text{emissions}^2}$),
- damage cost parameter π_i (in $\frac{\text{money}}{\text{emissions}^2}$),
- global emissions $E_N = \sum_{i=1}^{n} E_i$.

For convenience, define $s := |S|$ and $t := |T|$. The theoretical analysis begins by assuming symmetry of countries inside each of the two groups (T and R). This allows for the computation of conditions for the non-emptiness

[7]In games with linear damage functions, a country's optimal level of emissions is independent of the level of emissions of the other players. Therefore, this optimal level of emissions is a dominant strategy.

of the core of the subgame. In a second step, I allow individual parameters for countries inside a group and show how the core of the game changes with the introduction of heterogeneity.

3.1 Symmetric countries

In this section, I assume symmetry of countries inside each group, meaning that the parameters of all countries inside a group are equal:

$$\mu_l = \mu_i,\ \pi_l = \pi_i,\ P_l^0 = P_i^0 \quad \forall i, l \in T, \tag{3.2a}$$

$$\mu_l = \mu_j,\ \pi_l = \pi_j,\ P_l^0 = P_j^0 \quad \forall j, l \in R. \tag{3.2b}$$

For clarity, the index i represents a country in T, j represents a country in R, with l being an arbitrary third country. In order to determine conditions for the non-emptiness of the core, I first consider the symmetric allocation and later show that no other allocation needs to be considered.

Lemma 1. *Let*

$$y \in \mathbb{R}^t, \quad y_i \equiv \frac{v(T)}{t} \tag{3.3}$$

be the symmetric allocation of the subgame (T, v).

(i) In the setup above, the symmetric allocation lies in the core if and only if

$$a(\mu_i, \mu_j, \pi_i, \pi_j, s, t, n) \leq 0 \quad \forall s = 1, .., t-1, \tag{3.4}$$

where

$$\begin{aligned} &a(\mu_i, \mu_j, \pi_i, \pi_j, s, t, n) \\ =& \left[\frac{t+s}{t^2 \frac{\pi_i}{\mu_i} + 1}(n-t)^2 \left(\frac{\pi_j}{\mu_j}\right)^2 + 2(n-t)\frac{\pi_j}{\mu_j} \right. \\ & \left. +(2-s-t)(s^2\frac{\pi_i}{\mu_i} + 1) + (t-s)\frac{\pi_i}{\mu_i} \right] \frac{(t-s)\frac{\pi_i}{\mu_i}}{s^2 \frac{\pi_i}{\mu_i} + 1}. \end{aligned} \tag{3.5}$$

(ii) $a(\mu_i, \mu_j, \pi_i, \pi_j, s, t, n)$ *is monotonically increasing in* $\frac{\pi_j}{\mu_j}$.

For reasons of readability, all proofs can be found in Appendix A.

As a only depends on the fractions $\frac{\pi_i}{\mu_i}$ and $\frac{\pi_j}{\mu_j}$, set $\mu_i = \mu_j = 1$ without loss of generality and write $a(\pi_i, \pi_j, s, t, n) := a(1, 1, \pi_i, \pi_j, s, t, n)$.

For a set game (i.e. n and t fixed), one can calculate the combinations of π_i and π_j for which the symmetric allocation lies in the core. Let

$$\mathcal{P}_s = \{(\pi_i, \pi_j) \in \mathbb{R}_+^2 \mid a(\pi_i, \pi_j, s, t, n) \leq 0\}. \tag{3.6}$$

Then

$$\mathcal{P} = \bigcap_{s=1}^{t-1} \mathcal{P}_s \tag{3.7}$$

is this set. We will later see that it is the set of parameter combinations that lead to a non-empty core.

Let s, t and n be fixed. As $a(\pi_i, \pi_j, s, t, n)$ is continuous for $\pi_i, \pi_j > 0$, the boundary between $\mathcal{P}_s$ and $\mathbb{R}^2_+ \backslash \mathcal{P}_s$ can be identified. It corresponds to

$$a(\pi_i, \pi_j, s, t, n) = 0$$

and, as Lemma 2 (i) shows, it can be interpreted as a function $\bar{\pi}_j(\pi_i, s, t, n)$. Some useful features of this function are shown in Lemma 2 (ii).

Lemma 2. *(i) The function $\bar{\pi}_j(\pi_i, s, t, n)$ is well defined by*

$$a(\pi_i, \bar{\pi}_j(\pi_i, s, t, n), s, t, n) = 0, \ \pi_i > 0, \bar{\pi}_j(\pi_i, s, t, n) > 0.$$

(ii) $\bar{\pi}_j(\pi_i, s, t, n)$ is monotonically increasing in π_i and s.

As $a(\pi_i, \pi_j, s, t, n)$ is monotonically increasing in π_j, all parameter combinations (π_i, π_j) with $\pi_j > \bar{\pi}_j(\pi_i, s, t, n)$ do not satisfy condition (3.4). For the symmetric allocation to be in the core, this condition has to be satisfied for all s. Together with the fact that $\bar{\pi}_j(\pi_i, s, t, n)$ is monotonically increasing in s, we get the result that $s = 1$ is the only relevant case. In addition, no other allocations have to be considered, as Proposition 1 shows.

Proposition 1.

$$\mathcal{P} = \mathcal{P}_1 \tag{3.8}$$

is the set of parameters that lead to a non-empty core of the game.

I now consider the effect of a change in the parameters π_i and π_j on the stability of cooperation of the club. This is best done by first visualizing the set $\mathcal{P}$. Figure 1 shows $\mathcal{P}$ (blue area) for a game with 3 club members and 2 outsiders.

From the fact that $a(\pi_i, \pi_j, s, t, n)$ is monotonically increasing in π_j, we get the, somewhat counterintuitive, result that a *higher* damage cost parameter of the outsiders R (and thus *lower* emission levels in the uncooperative equilibrium) leads to *less* potential cooperation[8] among the club members T. In contrast, as $\bar{\pi}_j(\pi_i, s, t, n)$ is increasing in π_i, higher damages within the club lead to *more* potential cooperation. The reason lies in the *leakage* effect. Higher damages in R lead to a steeper slope of the best-reply

[8] By "less (more) potential cooperation", I simply mean the fact that, with increasing parameter, the game reaches a point at which the core becomes (non-)empty.

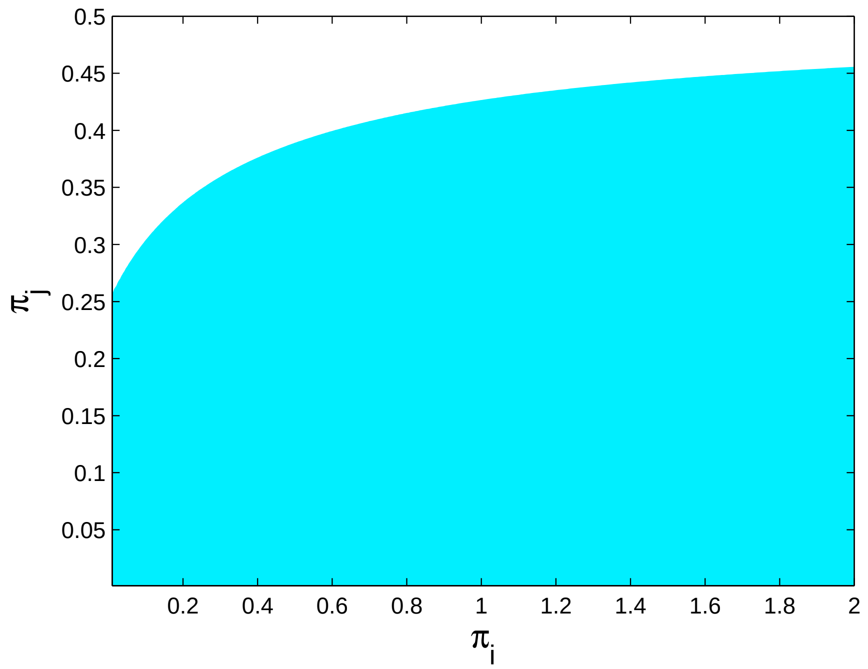

Figure 1: The blue area represents $\mathcal{P}$ for $t = 3, n = 5$.

function for countries in R[9]. This means that countries in R react more strongly to cooperation in T (and the accompanying emission reductions) by increasing emissions themselves. The result is less potential cooperation in T. Increases in π_i do not influence the best-reply function of countries in R and therefore do not cause a stronger leakage effect. Consequently, a different effect determines the result of an increase in π_i: the gains of cooperation for members of T grow and hence lead to games with a non-empty core. These effects are similar to the behaviour of stable coalition size in non-cooperative models, based on the internal and external stability concept (see e.g. Finus, 2003).

Taken together, the results imply that it is especially important to involve those countries with high climate damages and/or low mitigation costs in the club attempting to negotiate a climate agreement, as it enhances the parameter space leading to the existence of a stable agreement. While it is in the self-interest of countries with high climate damages to participate in those negotiations, countries with low mitigation costs might need to be motivated externally, for example by the prospect of transfer payments for emission reductions.

[9] See proof to Lemma 1.

3.1.1 Upper limit of π_j

The shape of $\mathcal{P}$ in Figure 1 suggests that the boundary value might converge to a fixed value for large π_i. Indeed, there exists such an absolute upper limit $\bar{\pi}_j^{ul}$, independent of π_i. To show the existence of $\bar{\pi}_j^{ul}$, consider the shape of the boundary of $\mathcal{P}$ and write $\bar{\pi}_j(\pi_i, t, n)$ for $\bar{\pi}_j(\pi_i, 1, t, n)$. The following Proposition states the main results about this function and its limits.

Proposition 2. *Let $\bar{\pi}_j(\pi_i, t, n)$ be defined by*

$$a(\pi_i, \bar{\pi}_j(\pi_i, t, n), 1, t, n) = 0, \quad \pi_i > 0 \text{ and } \bar{\pi}_j > 0. \tag{3.9}$$

Then

(i) $\bar{\pi}_j(\pi_i, t, n)$ is well defined and

$$\bar{\pi}_j(\pi_i, t, n) = \frac{t\left(\sqrt{t^2\pi_i^2 + (t^2+1)\pi_i + 1} - t\pi_i\right) - 1}{(t+1)(n-t)}. \tag{3.10}$$

(ii)

$$\lim_{\pi_i \to 0} \bar{\pi}_j(\pi_i, t, n) = \frac{t-1}{(t+1)(n-t)} =: \bar{\pi}_j^{ll} \tag{3.11}$$

(iii)

$$\lim_{\pi_i \to \infty} \bar{\pi}_j(\pi_i, t, n) = \frac{t-1}{2(n-t)} =: \bar{\pi}_j^{ul} \tag{3.12}$$

(iv) $\bar{\pi}_j^{ll}$ and $\bar{\pi}_j^{ul}$ are monotonically increasing in t (for $2 \le t < n$) and approach infinity as $t \to n$.

Proposition 2 (ii) and (iii) confirm the existence of upper and lower limits of the boundary function. This means that if $\pi_j > \bar{\pi}_j^{ul}$, the core of the game is always empty, irrespective of π_i. In other words, if damages from climate change are very high outside of the club, the club will not cooperate. In this case the main beneficiaries from emission reductions are not part of the club and cooperation in the club would only be met by corresponding emission increases outside of it, as outlined in the previous section. On the other hand, the existence of the lower limit means that if $\pi_j < \bar{\pi}_j^{ll}$, that is damages outside of the club are very low, cooperation is always possible. In this case, outsiders will not change their behaviour very much if the club cooperates, as they are not heavily affected by climate change. Therefore, the club comprises all relevant countries and the game of club cooperation becomes "global", in the sense that it includes all countries affected by climate change. As a result, the game is similar to the original game of global cooperation by Chander and Tulkens (1997), in which the core is non-empty for all parameters (Helm, 2001).

Proposition 2 (iv) also shows that the results are consistent with the result of the game of global cooperation. As the number of outsiders shrinks and the number of club members approaches all players, the set of parameter combinations that lead to a non-empty core expands towards the whole parameter space. This means that, in the limit of club size, a stable agreement exists for all parameter combinations.

3.2 Asymmetric countries

In this section, I drop the assumption of symmetry of countries and allow for individual parameters for each country. This means that the model is characterized by the number of countries n, the number of club members t and the parameter vector

$$\pi \in \mathbb{R}^n_+. \tag{3.13}$$

I continue to assume $\mu \equiv 1$. Proposition 3 shows results for global emissions E_N in the cases of no cooperation or full cooperation among club members, when heterogeneity is present.

Proposition 3. *Let*

$$\pi_T := \sum_{i \in T} \pi_i, \quad \pi_R := \sum_{j \in R} \pi_j.$$

and $i \in T$. Assume coalition $S \subset T$ forms. Then

$$E_N = \frac{E_N^0}{\pi_T + \pi_R + 1} \text{ if } S = \{i\} \tag{3.14}$$

and

$$E_N = \frac{E_N^0}{t\pi_T + \pi_R + 1} \text{ if } S = T. \tag{3.15}$$

These instances represent the case of no cooperation (formation of singleton coalitions) and the case of full cooperation among club members, respectively.

Proposition 3 shows that global emissions do not depend on the individual values of the damage parameter. Rather, they only depend on the parameter sum of both groups. This means that individual parameters π_i can be varied, while holding π_T and π_R constant, without changing global emissions in the cooperative case. I use this property to study the impact of heterogeneity on the value of coalitions and therefore the existence of a stable allocation.

Due to the increased complexity of the case of asymmetric countries, conditions for a non-empty core cannot easily be calculated. Instead, I draw on Proposition 1 and focus on the set of singleton coalitions. Specifically, I check whether

$$\sum_{i \in T} v(\{i\}) > v(T), \tag{3.16}$$

which is a sufficient condition for an *emtpy* core. The set of parameters for which condition (3.16) is not satisfied is called $\tilde{\mathcal{P}}$. To be clear, this means that, while $\pi \notin \tilde{\mathcal{P}}$ is a sufficient condition for an empty core, $\pi \in \tilde{\mathcal{P}}$ is only a necessary condition for a non-empty core. However, Proposition 1 showed that

$$\tilde{\mathcal{P}} = \mathcal{P} \tag{3.17}$$

in the symmetric case. Similar to Lemma 1, the elements of $\tilde{\mathcal{P}}$ are determined by a quadratic function in π_R:

Lemma 3. *Let $\pi \in \mathbb{R}^n_+$. Then $\pi \in \tilde{\mathcal{P}}$ if and only if*

$$a(\pi) = \sum_{i \in T} a_i(\pi_i, \pi_T, \pi_R) \leq 0, \tag{3.18}$$

where

$$\begin{aligned} a_i(\pi_i, \pi_T, \pi_R) = &\left[\frac{1}{\pi_i^2 + \pi_i} - \frac{1}{\pi_T^2 + \pi_i}\right]\pi_R^2 \\ &+ \left[\frac{\pi_T + 1}{\pi_i^2 + \pi_i} - \frac{t\pi_T + 1}{\pi_T^2 + \pi_i}\right]2\pi_R \\ &+ \frac{(\pi_T + 1)^2}{\pi_i^2 + \pi_i} - \frac{(t\pi_T + 1)^2}{\pi_T^2 + \pi_i}. \end{aligned} \tag{3.19}$$

By design, condition (3.18) is equivalent to condition (3.4) in the symmetric case. Lemma 3 shows that heterogeneity of countries in R does not influence membership in $\tilde{\mathcal{P}}$, as the condition only depends on π_R, the sum of parameters in R. The utility of club members is only influenced by the sum of emissions of outsiders, not their distribution. As the sum of emissions of outsiders does not depend on the distribution of parameters among outsider countries, the cooperation decision is not influenced by this distribution. However, it is clear that heterogeneity of countries in the club influences the core. Proposition 4 investigates this influence.

Proposition 4. *Let $\pi \in \mathbb{R}^n_+$, $l, h \in T$ with*

$$\pi_l \leq \frac{\pi_T}{t}, \quad \pi_h \geq \frac{\pi_T}{t}, \tag{3.20}$$

and let $d > 0$ with

$$d \leq \pi_l, \quad d \leq \pi_T - \pi_h. \tag{3.21}$$

Define $\tilde{\pi} \in \mathbb{R}^n_+$ by

$$\begin{aligned} \tilde{\pi}_l &= \pi_l - d, \\ \tilde{\pi}_h &= \pi_h + d, \\ \tilde{\pi}_i &= \pi_i \qquad \forall i \neq l, i \neq h. \end{aligned} \tag{3.22}$$

Then $a(\tilde{\pi}) > a(\pi)$.

$\tilde{\pi}$ is designed such that $\tilde{\pi}_T = \pi_T$ and $\tilde{\pi}_R = \pi_R$, meaning that the transformation "adds" heterogeneity without altering the sum of parameters in each group. The repeated application of Proposition 4 can construct any vector with these total group values. Therefore, the specific definition of $\tilde{\pi}$ represents no loss of generality about the considered parameter vector.

Proposition 4 shows that the "addition" of heterogeneity in the club leads to an increase in $a(\pi)$. The drivers behind this increase can be best visualized with a numeric example. Building on Figure 1, Figure 2 shows the impact of heterogeneity in the case of $t = 3, n = 5$. π_T and π_R are kept constant, while one country's share of π_T is increased. The remaining part of π_T is divided equally between the other two club members. Focusing on the total net value $a(\pi)$, we see that in the symmetric case (share of $\frac{1}{3}$) we have $a(\pi) < 0$, meaning that a stable agreement exists. However, $a(\pi)$ increases with heterogeneity between the countries in T and $a(\pi)$ is positive for shares larger than 0.55, resulting in an empty core of the corresponding game.

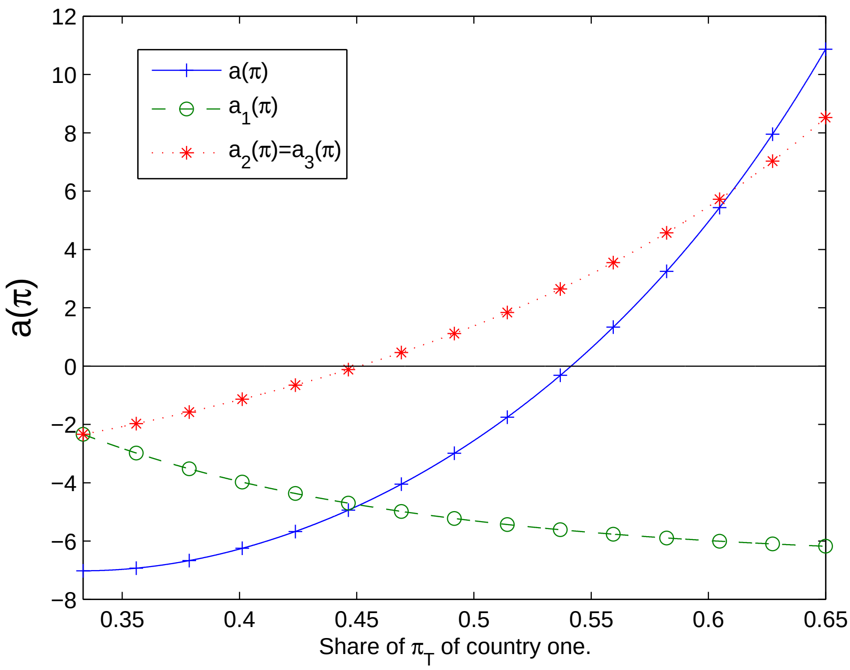

Figure 2: $a(\pi)$ for varying heterogeneity between club members. $\pi_T = 1$, $\pi_R = 0.2$, $t = 3$, $n = 5$.

This increase of $a(\pi)$ is driven by countries two and three, those with a decreasing share of π_T. Note that $a_2(\pi) = a_3(\pi)$ and $a(\pi) = \sum_{i=1}^{3} a_i(\pi)$. As the ratio of damage cost and abatement cost of countries two and three reduces, the gains of cooperation become smaller and $a_2(\pi)$ and $a_3(\pi)$ rise. The opposite is true for country one: its ratio of damage cost and abatement cost increases, leading to higher gains of cooperation and lower $a_1(\pi)$. However, this decrease is not big enough to offset the increases in $a_2(\pi)$ and $a_3(\pi)$. Consequentially, $a(\pi)$ increases with heterogeneity.

As the result of Proposition 4 holds for all π_T and π_R, the non-empty core condition (3.18) is violated for some parameter combinations previously in $\tilde{\mathcal{P}}$ after the execution of transformation (3.22). Therefore, the set $\tilde{\mathcal{P}}$ shrinks with increased heterogeneity, as visualized in Figure 3. It shows $\tilde{\mathcal{P}}$ for different distributions of π_T upon the countries in T. These shares of countries are varied between subfigures only, meaning

$$\hat{\pi}_i = \frac{\pi_i}{\pi_T}, \ i \in T \tag{3.23}$$

is constant for each subfigure.

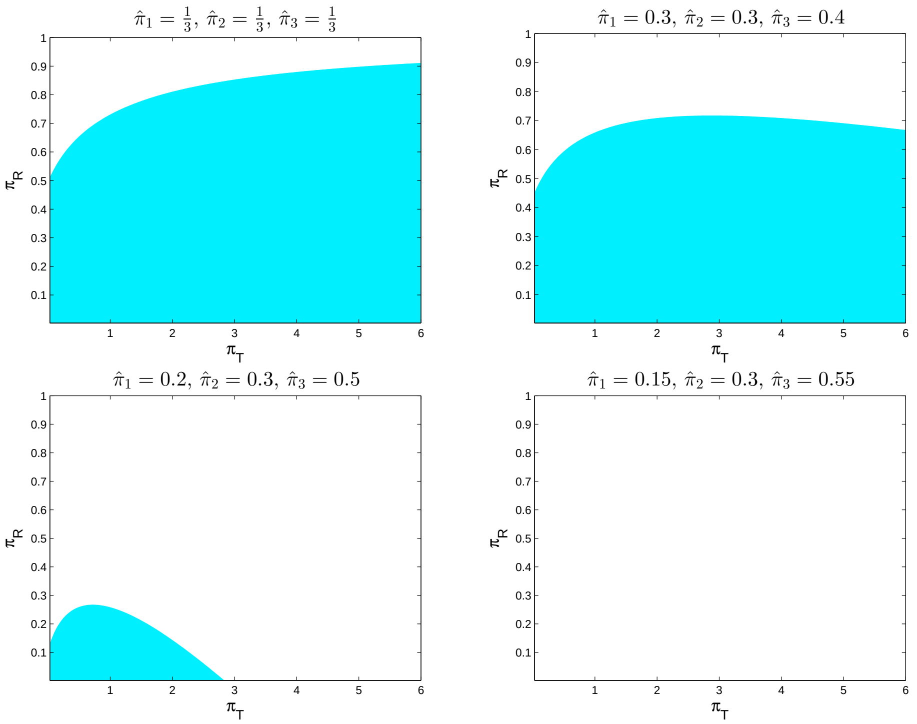

Figure 3: $\tilde{\mathcal{P}}$ for different levels of heterogeneity in T

The shrinking of $\tilde{\mathcal{P}}$ with increased heterogeneity causes a different shape of the boundary of $\tilde{\mathcal{P}}$. While a high π_R still leads to less cooperation in T (as in the symmetric case), the same is true for a high π_T, unlike the symmetric case. An intuitive explanation for this phenomenon is that, for asymmetric countries, the "absolute" differences in the parameters become more pronounced with higher π_T, which reinforces the effect that more heterogeneity causes less cooperation. As the last subfigure shows, high diversity between countries in T can even lead to a game for which the core is empty for all combinations of π_T and π_R.

The results about cooperation of asymmetric countries align with the findings of Driessen et al. (2011), who show that, in a cooperative oligopoly game, higher heterogeneity of marginal costs decreases the size of the core. This is also supported by the non-cooperative model by Na and Shin (1998), who find that coalitions are more likely to form among similar countries. However, Finus and Pintassilgo (2013) show that, in a more general non-cooperative game with transfers, asymmetry can lead to larger stable agreements. The latter view is also backed by Smead et al. (2014), who study a bargaining game of equilibrium selection and find a positive impact of heterogeneity between players on the chances of reaching an agreement.

4 Application of the model to the Group of Twenty

The Group of Twenty (G20) is the most frequently mentioned forum for climate action outside of the UNFCCC in a survey of participants at UNFCCC COPs (Hjerpe and Nasiritousi, 2015). It is also the biggest of the proposed state clubs (Widerberg and Stenson, 2013) and climate change has been a topic of discussion at all of its summits since 2008. Therefore, I use it for an application of the theoretical model. The model could also be applied to all other state clubs.

I start the analysis by estimating abatement cost and damage cost parameters, using the POLES and RICE models. Subsequently, this data is applied to the theoretical model, beginning with the assumption of symmetric countries inside a group. Finally, this assumption is dropped and the impact of heterogeneity is evaluated.

4.1 Parameter estimation

4.1.1 Abatement cost estimation

I use scenario runs from the POLES model[10] to generate marginal abatement cost curves (MACCs) for different countries. The employed scenario was produced in 2013. In the baseline, this scenario assumes that dynamic economic growth is restored from 2015 onwards and no global climate agreement is reached, resulting in soaring GHG emissions around the world. From

[10]Prospective Outlook on Long-term Energy Systems (POLES) is a global simulation model for the energy sector, developed by IPTS, LEPII and Enerdata. For a detailed description of the model, see Kitous et al. (2010) or `http://www.enerdata.net/enerdatauk/solutions/energy-models/poles-model.php`.

this baseline, MACCs are produced by the successive introduction of a carbon price.

The POLES scenario runs up to the year 2050. As the largest impacts of climate change are expected to happen in the very long-term, I use a simple procedure to extend the emission paths up to 2300, following Bréchet et al. (2011), Eyckmans and Tulkens (2003) and Nordhaus (2010). Up to 2100, baseline emissions are extrapolated based on the linear trend of per capita emissions for each country. Population values are taken from the scenario of medium fertility from the UN World Population Prospects (UN, 2012). For later years, I follow the extension procedure for Reduced Concentration Pathway 8.5 (Meinshausen et al., 2011; IPCC, 2014). This means constant emissions up to 2150, followed by linear reduction of global emissions to the level that is consistent with stable atmospheric concentrations in 2250. Emissions stay at this level for the rest of the time period.

For each carbon price, I extend the corresponding emission path based on the linear extension of the relative reduction amount below baseline emissions. The reduction stops when net-zero emissions are reached. Abatement costs are calculated as the area under the MACC for each year and country.

Afterwards, emission reductions for each carbon price are accumulated over the whole time period, 2013 to 2300. Abatement costs are also aggregated, using a discount rate of 3%, which is the central rate used by the U.S. Interagency Working Group on Social Cost of Carbon (2013). The result is an abatement cost curve for each country, with each carbon price providing one data point. I then estimate the abatement cost parameter μ as the best fit for a quadratic function to these data points.

For the symmetric case, all G20 countries are assigned the average emission reductions and average abatement costs of G20 countries. Similarly, all non-G20 countries are assigned the average values of non-G20 countries.

4.1.2 Damage cost estimation

I use the integrated assessment model RICE (Nordhaus, 2010) to estimate the damage cost parameter π for each country. RICE provides cumulative emissions and the corresponding temperature increase. It also gives damage functions, depending on temperature increase, for 12 world regions. For each country and cumulative emission level, I use these functions to calculate damages, as percent of output. I then compute absolute damages using GDP projections from the POLES model, which runs up to 2050. The GDP projections are extended up to 2300 based on the trend of per capita values, similar to the procedure for emissions in the abatement cost estimation. Subsequently, they are aggregated over time, again using a 3% discount rate. Finally, absolute damages are given by multiplying the aggregated GDP value with the relative damage amount calculated from RICE.

After this procedure, I estimate the damage cost parameter π as the best fit for a quadratic function to the data points combining cumulative emissions and absolute damages. For the symmetric case, damages are uniformly distributed among all countries in a group, analogue to the abatement cost estimation.

4.2 Existence of a stable agreement

For the application to the model, I consider 130 countries for which there is sufficient data available to perform the parameter estimation. However, the EU is treated as one country and individual EU member states are therefore removed from the list of countries. As a result, the group T includes 16 countries (15 non-EU members of the G20, plus the EU). The remaining 87 countries comprise the set R. For the full list of countries, see Table 2 for G20 countries and Table 3 in Appendix B for non-G20 countries.

4.2.1 Symmetric case

Table 1 shows the results of the parameter estimation in the symmetric case. The large differences in the magnitude of the parameters are a result of the different number of countries in each group and the fact that most big emitters are part of the G20.

	μ	π	Ratio $\frac{\pi}{\mu}$
G20 countries	6,419	88	1.37 E-2
non-G20 countries	113,418	4	3.25 E-5

Table 1: Abatement cost parameter μ and damage cost parameter π in the symmetric case. Values of μ and π in $\frac{EUR}{10^{15} * (tCO_2)^2}$.

In order to determine if the core of the *G20 game* is empty or not, the estimated parameters need to be compared to the set of parameters, which lead to a game with non-empty core, $\mathcal{P}$. Figure 4 shows this set for the G20 configuration, $n = 103, t = 16$. The location of the estimated parameter ratios from Table 1 is shown as a red dot.

I find that the estimated parameter ratios lie squarely in $\mathcal{P}$. Specifically, the ratio of parameters for non-G20 countries is so small that the core of the game is non-empty, irrespective of the ratio of parameters for G20 countries (see Proposition 2). In essence, the collective of G20 countries is large enough, in terms of expected absolute damages from climate change and ability to reduce emissions, that the behaviour of non-G20 countries does not change their incentive to cooperate. Therefore, in the highly stylized scenario of the symmetric case, a stable agreement among G20 countries exists.

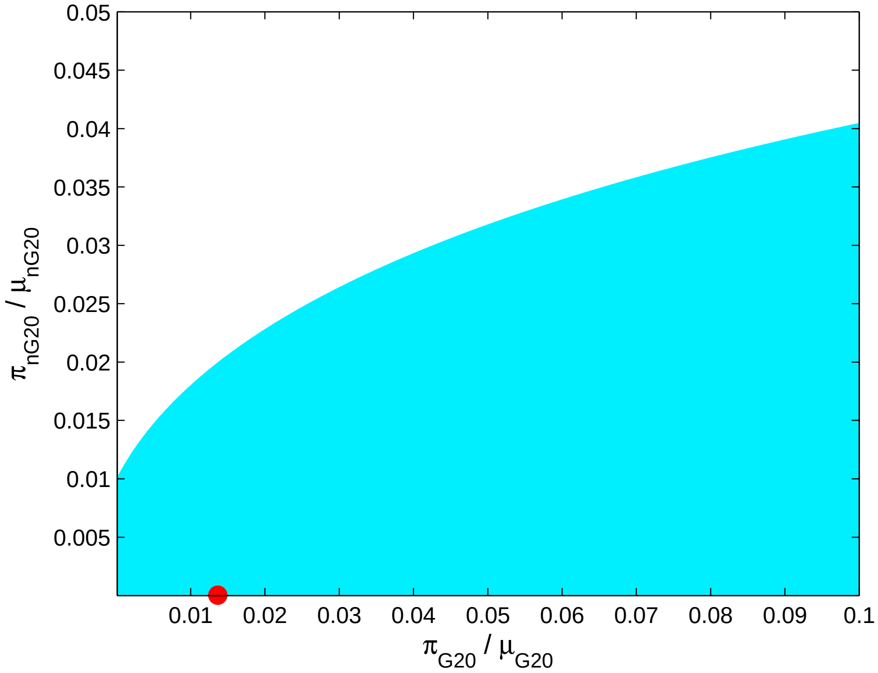

Figure 4: $\mathcal{P}$ for $n = 103, t = 16$ and estimated parameter ratios from Table 1.

4.2.2 Asymmetric case

Table 2 shows the results of the parameter estimation for individual G20 countries. The results for non-G20 countries can be found in Table 3 in Appendix B.

The parameter estimation shows a high degree of heterogeneity between G20 countries. China, the EU, India and the USA especially stand out among the group. These countries have the four highest damage cost parameters, resulting from high GDP and, consequently, high absolute damages. They also have four of the five lowest abatement cost parameters, resulting from high emission levels and the accompanying large abatement opportunities. As a result, the ratio of damage cost and abatement cost in these four countries is one or two orders of magnitude larger than the ratio in other countries.

Consequently, the conclusion about stability of climate cooperation in the case of asymmetric countries differs considerably from the case of symmetric countries. As Proposition 4 showed, "adding" heterogeneity between countries can lead to an empty core of the game. The *G20 game* is such a case. If the estimated parameters from Table 2 are used as the basis of the game, the core of the game is empty. This result is based solely on

Country	μ	π	Ratio $\frac{\pi}{\mu}$
Argentina	36,660	17	4.60E-04
Australia	18,074	17	9.14E-04
Brazil	18,842	29	1.54E-03
Canada	18,941	20	1.07E-03
China	910	483	5.31E-01
EU	8,231	164	1.99E-02
India	1,507	227	1.51E-01
Indonesia	24,546	21	8.74E-04
Japan	26,407	87	3.29E-03
Republic of Korea	55,957	32	5.71E-04
Mexico	61,550	23	3.75E-04
Russian Federation	4,966	19	3.92E-03
Saudi Arabia	53,304	9	1.77E-04
South Africa	44,856	11	2.54E-04
Turkey	20,271	30	1.46E-03
United States of America	8,131	212	2.61E-02

Table 2: Abatement cost parameter μ and damage cost parameter π for G20 countries. Values of μ and π in $\frac{EUR}{10^{15}*(tCO_2)^2}$.

the heterogeneity of countries. If the ratio of abatement cost and damage cost parameters is increased or decreased by an equal percentage for all G20 countries, leaving the heterogeneity between countries constant, the core stays empty. The same is true for a variation of non-G20 parameters. Therefore, I find that heterogeneity among G20 countries makes a potential climate agreement among the club unstable.

5 Conclusion

In order to account for the special structure of climate negotiations in pre-existing state clubs with fixed membership, I analysed subgames of the cooperative game by Chander and Tulkens (1997). I find that, contrary to the model of global negotiations, a stable agreement does not exist for all parameter combinations. Instead, existence is determined by the ratio of damage and abatement cost parameters. The set of parameters, for which a stable agreement exists, decreases in size as the extent of the club shrinks, due to lower gains of cooperation in the club. Additionally, changes in the cost parameters of both groups (club members and outsiders) lead to vastly different effects. Parameters of non-cooperative outsiders change the result in a counterintuitive way, as higher damage costs lead to less potential cooperation. Parameters of club members influence cooperation in a much more intuitive sense, as higher damages and lower abatement costs enhance the prospect of a stable agreement. However, the parameters of the outsiders play a larger role and can prevent the existence of a stable agreement, when exceeding a certain upper limit.

The introduction of asymmetry in the cost parameters of both groups has a neutral or negative effect on stability of cooperation in the club. While asymmetry in the parameters of outsider countries does not influence cooperation inside the club, asymmetry in the parameters of the club members hurts the chances of cooperation. This can even lead to a situation in which the heterogeneity of countries prevents the existence of a stable agreement, irrespective of all other parameters.

Application of the model to the G20 leads to such a situation: when symmetric countries are assumed, the model predicts cooperation in the group. However, when this assumption is dropped, the core of the subgame is empty and no stable agreement exists.

Overall, the model is a lot less optimistic about the existence of a stable agreement in a climate club than in a global negotiation environment. This was expected as the model mainly considers the impact of potential free-riding of outsiders on an agreement among club members, making cooperation harder. The negative effects as outlined in this paper therefore have to be evaluated against proposed advantages of climate clubs like faster negotiations and better participation from private actors (Biermann et al., 2009), as well as barriers in global negotiations like the blocking power of small countries with special circumstances. In addition, the model could be evaluated for different function shapes and other groups of countries. The model could also be extended in a number of ways. It does not include international macroeconomic effects of emission reduction measures in a country or multiple countries. Also, the model does not include uncertainty about the values of future abatement costs or future damages. These issues are left for further research.

A Proofs

A.1 Proof of Lemma 1

Proof. (i) Calculate the value function of the game. Emissions are given by the first order conditions. Let $S \subseteq T$ and $i \in S$.

$$\begin{aligned}
&\max_{E_i} \sum_{l \in S} [P_l(E_l) - D_l(E_N)] \\
\Rightarrow\ & \frac{\partial P_i(E_i)}{\partial E_i} - \sum_{l \in S} \frac{\partial D_l(E_N)}{\partial E_i} = 0 \\
\Rightarrow\ & 2\mu_i(E_i^0 - E_i) = 2 \underbrace{\sum_{l \in S} \pi_l}_{=:\pi_S} E_N \\
\Rightarrow\ & 2\mu_i(E_i^0 - E_i) = 2s\pi_i E_N \\
\Rightarrow\ & E_i = \frac{\mu_i E_i^0 - s\pi_i E_N}{\mu_i} = E_i^0 - \frac{s\pi_i}{\mu_i} E_N
\end{aligned}$$

For $i \in T$, $i \notin S$ one gets

$$\begin{aligned}
&\max_{E_i} P_i(E_i) - D_i(E_N) \\
\Rightarrow\ & \frac{\partial P_i(E_i)}{\partial E_i} + \frac{\partial D_i(E_N)}{\partial E_i} = 0 \\
\Rightarrow\ & 2\mu_i(E_i^0 - E_i) = 2\pi_i E_N \\
\Rightarrow\ & E_i = \frac{\mu_i E_i^0 - \pi_i E_N}{\mu_i} = E_i^0 - \frac{\pi_i}{\mu_i} E_N.
\end{aligned}$$

And for $j \in R$, the resulting emissions are

$$\begin{aligned}
&\max_{E_j} P_j(E_j) - D_j(E_N) \\
\Rightarrow\ & \frac{\partial P_j(E_j)}{\partial E_j} + \frac{\partial D_j(E_N)}{\partial E_j} = 0 \\
\Rightarrow\ & 2\mu_j(E_j^0 - E_j) = 2\pi_j E_N \\
\Rightarrow\ & E_j = \frac{\mu_j E_j^0 - \pi_j E_N}{\mu_j} = E_j^0 - \frac{\pi_j}{\mu_j} E_N.
\end{aligned}$$

For convenience, define $\lambda_l = \frac{1}{\mu_l}$ and $\lambda_S = \sum_{l \in S} \lambda_l$. Then sum over all players' emissions.

$$\begin{aligned}
\Rightarrow\ & \underbrace{\sum_{k=1}^{n} E_k}_{=E_N} = tE_i^0 + (n-t)E_j^0 - (s^2\lambda_i\pi_i + (t-s)\lambda_i\pi_i + (n-t)\lambda_j\pi_j)E_N \\
\Rightarrow\ & E_N = \frac{tE_i^0 + (n-t)E_j^0}{s^2\lambda_i\pi_i + (t-s)\lambda_i\pi_i + (n-t)\lambda_j\pi_j + 1}.
\end{aligned}$$

With this, the value function can be calculated:

$$
\begin{aligned}
v(S) =& s\left[P_i^0 - \frac{1}{\lambda_i}\left(E_i^0 - (E_i^0 - s\lambda_i\pi_i E_N)\right)^2 - \pi_i E_N^2\right] \\
=& s\left[P_i^0 - \frac{1}{\lambda_i}\left(\frac{s\lambda_i\pi_i(tE_i^0 + (n-t)E_j^0)}{s^2\lambda_i\pi_i + (t-s)\lambda_i\pi_i + (n-t)\lambda_j\pi_j + 1}\right)^2\right. \\
& \left. - \pi_i\left(\frac{tE_i^0 + (n-t)E_j^0}{s^2\lambda_i\pi_i + (t-s)\lambda_i\pi_i + (n-t)\lambda_j\pi_j + 1}\right)^2\right] \\
=& s\left[P_i^0 - \pi_i\frac{(s^2\lambda_i\pi_i + 1)(tE_i^0 + (n-t)E_j^0)^2}{(s^2\lambda_i\pi_i + (t-s)\lambda_i\pi_i + (n-t)\lambda_j\pi_j + 1)^2}\right]
\end{aligned}
$$

and

$$
\begin{aligned}
v(T) =& t\left[P_i^0 - \frac{1}{\lambda_i}\left(\frac{t\lambda_i\pi_i(tE_i^0 + (n-t)E_j^0)}{t^2\lambda_i\pi_i + (n-t)\lambda_j\pi_j + 1}\right)^2\right. \\
& \left. - \pi_i\left(\frac{tE_i^0 + (n-t)E_j^0}{t^2\lambda_i\pi_i + (n-t)\lambda_j\pi_j + 1}\right)^2\right] \\
=& t\left[P_i^0 - \pi_i\frac{(t^2\lambda_i\pi_i + 1)(tE_i^0 + (n-t)E_j^0)^2}{(t^2\lambda_i\pi_i + (n-t)\lambda_j\pi_j + 1)^2}\right].
\end{aligned}
$$

The excess of the symmetric allocation is defined as

$$e(S, y, v) = v(S) - y(S) = v(S) - \frac{s}{t}v(T).$$

Clearly, y lies in the core of (T, v) if and only if

$$e(S, y, v) \leq 0 \; \forall S \subsetneq T.$$

In our case, this is equivalent to

$$
\begin{aligned}
& v(S) \leq \frac{s}{t}v(T) \\
\Leftrightarrow\; & -\frac{s^2\lambda_i\pi_i + 1}{(s^2\lambda_i\pi_i + (t-s)\lambda_i\pi_i + (n-t)\lambda_j\pi_j + 1)^2} \leq -\frac{t^2\lambda_i\pi_i + 1}{(t^2\lambda_i\pi_i + (n-t)\lambda_j\pi_j + 1)^2} \\
\Leftrightarrow\; & \frac{s^2\lambda_i\pi_i + 1}{(s^2\lambda_i\pi_i + (t-s)\lambda_i\pi_i + (n-t)\lambda_j\pi_j + 1)^2} \geq \frac{t^2\lambda_i\pi_i + 1}{(t^2\lambda_i\pi_i + (n-t)\lambda_j\pi_j + 1)^2} \\
\Leftrightarrow\; & \frac{(s^2\lambda_i\pi_i + (t-s)\lambda_i\pi_i + (n-t)\lambda_j\pi_j + 1)^2}{s^2\lambda_i\pi_i + 1} \leq \frac{(t^2\lambda_i\pi_i + (n-t)\lambda_j\pi_j + 1)^2}{t^2\lambda_i\pi_i + 1}
\end{aligned}
$$

$$\Leftrightarrow \frac{((n-t)\lambda_j\pi_j)^2 + 2(n-t)\lambda_j\pi_j(s^2\lambda_i\pi_i + (t-s)\lambda_i\pi_i + 1) + (s^2\lambda_i\pi_i + (t-s)\lambda_i\pi_i + 1)^2}{s^2\lambda_i\pi_i + 1}$$
$$\leq \frac{((n-t)\lambda_j\pi_j)^2 + 2(n-t)\lambda_j\pi_j(t^2\lambda_i\pi_i + 1) + (t^2\lambda_i\pi_i + 1)^2}{t^2\lambda_i\pi_i + 1}$$
$$\Leftrightarrow \underbrace{\left(\frac{1}{s^2\lambda_i\pi_i + 1} - \frac{1}{t^2\lambda_i\pi_i + 1}\right)}_{>0}(n-t)^2(\lambda_j\pi_j)^2$$
$$+ \left(\underbrace{\frac{s^2\lambda_i\pi_i + (t-s)\lambda_i\pi_i + 1}{s^2\lambda_i\pi_i + 1}}_{>1} - \underbrace{\frac{t^2\lambda_i\pi_i + 1}{t^2\lambda_i\pi_i + 1}}_{=1}\right) 2(n-t)\lambda_j\pi_j$$
$$+ \frac{(s^2\lambda_i\pi_i + (t-s)\lambda_i\pi_i + 1)^2}{s^2\lambda_i\pi_i + 1} - (t^2\lambda_i\pi_i + 1)$$
$$\leq 0$$

Define the left hand side of the last inequality as $a(\lambda_i, \lambda_j, \pi_i, \pi_j, s, t, n)$. Due to the rearranging of the formula, it is the excess multiplied with a positive number.

The coefficients of the polynomial can be further simplified. One has

$$\frac{1}{s^2\lambda_i\pi_i + 1} - \frac{1}{t^2\lambda_i\pi_i + 1} = \frac{t^2\lambda_i\pi_i + 1 - (s^2\lambda_i\pi_i + 1)}{(s^2\lambda_i\pi_i + 1)(t^2\lambda_i\pi_i + 1)}$$
$$= \frac{(t^2 - s^2)\lambda_i\pi_i}{(s^2\lambda_i\pi_i + 1)(t^2\lambda_i\pi_i + 1)} = \frac{(t+s)(t-s)\lambda_i\pi_i}{(s^2\lambda_i\pi_i + 1)(t^2\lambda_i\pi_i + 1)}$$
$$= \frac{(t-s)\lambda_i\pi_i}{s^2\lambda_i\pi_i + 1}\,\frac{t+s}{t^2\lambda_i\pi_i + 1},$$

$$\frac{s^2\lambda_i\pi_i + (t-s)\lambda_i\pi_i + 1}{s^2\lambda_i\pi_i + 1} - 1 = \frac{s^2\lambda_i\pi_i + (t-s)\lambda_i\pi_i + 1 - s^2\lambda_i\pi_i - 1}{s^2\lambda_i\pi_i + 1}$$
$$= \frac{(t-s)\lambda_i\pi_i}{s^2\lambda_i\pi_i + 1}$$

and

$$\frac{(s^2\lambda_i\pi_i + (t-s)\lambda_i\pi_i + 1)^2}{s^2\lambda_i\pi_i + 1} - (t^2\lambda_i\pi_i + 1)$$
$$= \frac{(t-s)\lambda_i\pi_i}{s^2\lambda_i\pi_i + 1}\left[(2-s-t)(s^2\lambda_i\pi_i + 1) + (t-s)\lambda_i\pi_i\right].$$

This leads to

$$a(\lambda_i, \lambda_j, \pi_i, \pi_j, s, t, n)$$
$$= \Big[\frac{t+s}{t^2\lambda_i\pi_i + 1}(n-t)^2\left(\lambda_j\pi_j\right)^2 + 2(n-t)\lambda_j\pi_j$$
$$+ (2-s-t)(s^2\lambda_i\pi_i + 1) + (t-s)\lambda_i\pi_i\Big]\frac{(t-s)\lambda_i\pi_i}{s^2\lambda_i\pi_i + 1}.$$

(ii) $a(\lambda_i, \lambda_j, \pi_i, \pi_j, s, t, n)$ is a quadratic polynomial of $(\lambda_j \pi_j)$. The coefficients, disregarding the constant term, are positive. Therefore, $a(\lambda_i, \lambda_j, \pi_i, \pi_j, s, t, n)$ is monotonically increasing in $(\lambda_j \pi_j)$. □

A.2 Proof of Lemma 2

Proof. (i) Using the implicit function theorem, $\bar{\pi}_j(\pi_i, s, t, n)$ is well defined if

$$\frac{\partial a(\pi_i, \pi_j, s, t, n)}{\partial \pi_j} \neq 0 \quad \forall \pi_i > 0, \pi_j > 0.$$

Continuing from Lemma 1, one gets

$$\frac{\partial a}{\partial \pi_j} = \underbrace{\frac{(t-s)\pi_i}{s^2\pi_i + 1}}_{>0} \left[\underbrace{2\frac{t+s}{t^2\pi_i + 1}(n-t)^2\pi_j}_{>0} + \underbrace{2(n-t)}_{>0} \right] > 0.$$

(ii) In order to get an analytical solution for $\bar{\pi}_j(\pi_i, s, t, n)$, solve

$$a(\pi_i, \bar{\pi}_j, s, t, n) = 0$$

for $\bar{\pi}_j > 0$.

$$\begin{aligned}
&a(\pi_i, \bar{\pi}_j, s, t, n) = 0 \\
\Leftrightarrow\ &\frac{t+s}{t^2\pi_i + 1}(n-t)^2\bar{\pi}_j^2 + 2(n-t)\bar{\pi}_j + (2-s-t)(s^2\pi_i + 1) + (t-s)\pi_i = 0 \\
\Leftrightarrow\ &\bar{\pi}_j^2 + 2\frac{t^2\pi_i + 1}{(t+s)(n-t)}\bar{\pi}_j + \frac{((2-s-t)(s^2\pi_i + 1) + (t-s)\pi_i)(t^2\pi_i + 1)}{(t+s)(n-t)^2} = 0 \\
\Leftrightarrow\ &\bar{\pi}_j^2 + 2\frac{t^2\pi_i + 1}{(t+s)(n-t)}\bar{\pi}_j + \frac{((t+s)(2-s-t)(s^2\pi_i + 1) + (t^2-s^2)\pi_i)(t^2\pi_i + 1)}{(t+s)^2(n-t)^2} = 0
\end{aligned}$$

$$\begin{aligned}
\Leftrightarrow\ \bar{\pi}_j =& -\frac{t^2\pi_i + 1}{(t+s)(n-t)} \\
&\pm \sqrt{\frac{(t^2\pi_i + 1)^2}{(t+s)^2(n-t)^2} - \frac{((t+s)(2-s-t)(s^2\pi_i + 1) + (t^2-s^2)\pi_i)(t^2\pi_i + 1)}{(t+s)^2(n-t)^2}} \\
=& \frac{-(t^2\pi_i + 1) \pm \sqrt{(t^2\pi_i + 1)(t^2\pi_i + 1 - ((t+s)(2-s-t)(s^2\pi_i + 1) + (t^2-s^2)\pi_i))}}{(t+s)(n-t)}
\end{aligned}$$

As $\bar{\pi}_j > 0$, the term with positive root defines the boundary. With

$$\begin{aligned}
&t^2\pi_i + 1 - ((t+s)(2-s-t)(s^2\pi_i + 1) + (t^2-s^2)\pi_i) \\
=&1 - (t+s)(2-s-t)(s^2\pi_i + 1) + s^2\pi_i \\
=&1 - (t+s-1)(2-s-t)(s^2\pi_i + 1) - (2-s-t)(s^2\pi_i + 1) + s^2\pi_i \\
=&(t+s-1)^2(s^2\pi_i + 1),
\end{aligned}$$

one gets

$$\begin{aligned}\bar{\pi}_j(\pi_i, s, t, n) =& \frac{-(t^2\pi_i + 1) + \sqrt{(t^2\pi_i + 1)(t + s - 1)^2(s^2\pi_i + 1)}}{(t + s)(n - t)} \\ =& \frac{-(t^2\pi_i + 1) + (t + s - 1)\sqrt{(t^2\pi_i + 1)(s^2\pi_i + 1)}}{(t + s)(n - t)}.\end{aligned}$$

One can now show that $\bar{\pi}_j(\pi_i, s, t, n)$ is monotonically increasing in π_i:

$$\begin{aligned}&\frac{\partial \bar{\pi}_j(\pi_i, s, t, n)}{\partial \pi_i} \\ =& \frac{1}{(t + s)(n - t)} \left[-t^2 + (t + s - 1) \frac{2s^2t^2\pi_i + s^2 + t^2}{2\sqrt{(t^2\pi_i + 1)(s^2\pi_i + 1)}} \right] \\ =& \frac{1}{(t + s)(n - t)} \left[-t^2 + \frac{1}{2}(t + s - 1) \left(\frac{(2s^2t^2\pi_i + s^2 + t^2)(2s^2t^2\pi_i + s^2 + t^2)}{(t^2\pi_i + 1)(s^2\pi_i + 1)} \right)^{\frac{1}{2}} \right] \\ =& \frac{1}{(t + s)(n - t)} \left[-t^2 + \frac{1}{2}(t + s - 1) \left(\frac{4s^4t^4\pi_i^2 + 4s^2t^2\pi_i(s^2 + t^2) + (s^2 + t^2)^2}{s^2t^2\pi_i^2 + (s^2 + t^2)\pi_i + 1} \right)^{\frac{1}{2}} \right] \\ \geq& \frac{1}{(t + s)(n - t)} \left[-t^2 + \frac{1}{2}(t + s - 1) \left(\frac{(4t^2)(s^4t^2\pi_i^2 + s^2\pi_i(s^2 + t^2) + 1)}{s^2t^2\pi_i^2 + (s^2 + t^2)\pi_i + 1} \right)^{\frac{1}{2}} \right] \\ \geq& \frac{1}{(t + s)(n - t)} \left[-t^2 + \frac{1}{2}(t + s - 1) \left(4t^2 \right)^{\frac{1}{2}} \right] \\ =& \frac{1}{(t + s)(n - t)} \left[-t^2 + (t + s - 1)t \right] \\ \geq& 0,\end{aligned}$$

where the first inequality holds as $(s^2 + t^2)^2 \geq 4t^2$ for $t \geq 2, s \geq 1$. Finally, $\bar{\pi}_j(\pi_i, s, t, n)$ is monotonically increasing in s:

$$\begin{aligned}&\frac{\partial \bar{\pi}_j(\pi_i, s, t, n)}{\partial s} \\ =& \Bigg[\left(\sqrt{(t^2\pi_i + 1)(s^2\pi_i + 1)} + (t + s - 1) \frac{1}{2\sqrt{(t^2\pi_i + 1)(s^2\pi_i + 1)}} 2s\pi_i(t^2\pi_i + 1) \right) \\ &* (t + s)(n - t) \\ &- \left((t + s - 1)\sqrt{(t^2\pi_i + 1)(s^2\pi_i + 1)} - (t^2\pi_i + 1) \right) (n - t) \Bigg] \Big/ ((t + s)^2(n - t)^2) \\ =& \Bigg[(t + s)\sqrt{(t^2\pi_i + 1)(s^2\pi_i + 1)} + \frac{(t + s)(t + s - 1)s\pi_i(t^2\pi_i + 1)}{\sqrt{(t^2\pi_i + 1)(s^2\pi_i + 1)}} \\ &-(t + s - 1)\sqrt{(t^2\pi_i + 1)(s^2\pi_i + 1)} + (t^2\pi_i + 1) \Bigg] \Big/ ((t + s)^2(n - t)) \\ =& \left[\sqrt{(t^2\pi_i + 1)(s^2\pi_i + 1)} + \frac{(t + s)(t + s - 1)s\pi_i(t^2\pi_i + 1)}{\sqrt{(t^2\pi_i + 1)(s^2\pi_i + 1)}} + (t^2\pi_i + 1) \right] \Bigg/ ((t + s)^2(n - t)) \\ \geq& 0.\end{aligned}$$

□

A.3 Proof of Proposition 1

Proof.

$$\mathcal{P} = \mathcal{P}_1$$

follows directly from Lemma 1 and the fact that a is increasing in π_j. It remains to be shown that no other allocation has to be considered.

For this, assume that the symmetric allocation does not belong to the core of the game, so $(\pi_i, \pi_j) \notin \mathcal{P} = \mathcal{P}_1$. Let $i \in T$. Then

$$\begin{aligned} 0 &< a(\pi_i, \pi_j, 1, t, n) \\ &= v(\{i\}) - \frac{v(T)}{t} \end{aligned}$$

$$\begin{aligned} &\Leftrightarrow v(\{i\}) > \frac{v(T)}{t} \\ &\Rightarrow \sum_{i \in T} v(\{i\}) > v(T). \end{aligned}$$

Therefore, no allocation can satisfy all singletons simultaneously. The core is empty. □

A.4 Proof of Proposition 2

Proof. (i) From the proof of Lemma 2, one has

$$\bar{\pi}_j(\pi_i, s, t, n) = \frac{-(t^2\pi_i + 1) + (t + s - 1)\sqrt{(t^2\pi_i + 1)(s^2\pi_i + 1)}}{(t + s)(n - t)}.$$

In the case of $s = 1$, this simplifies to

$$\begin{aligned} &\bar{\pi}_j(\pi_i, 1, t, n) \\ =&\frac{-(t^2\pi_i + 1) + t\sqrt{(t^2\pi_i + 1)(\pi_i + 1)}}{(t + 1)(n - t)} \\ =&\frac{t\left(\sqrt{(t^2\pi_i + 1)(\pi_i + 1)} - t\pi_i\right) - 1}{(t + 1)(n - t)} \\ =&\frac{t\left(\sqrt{t^2\pi_i^2 + (t^2 + 1)\pi_i + 1} - t\pi_i\right) - 1}{(t + 1)(n - t)}. \end{aligned}$$

(ii) Follows directly from (i).

(iii) In order to calculate the upper limit, first simplify the inner term

$$\begin{aligned}
&\sqrt{t^2\pi_i^2+(t^2+1)\pi_i+1}-t\pi_i \\
&=\left(\sqrt{t^2\pi_i^2+(t^2+1)\pi_i+1}-t\pi_i\right)\frac{\sqrt{t^2\pi_i^2+(t^2+1)\pi_i+1}+t\pi_i}{\sqrt{t^2\pi_i^2+(t^2+1)\pi_i+1}+t\pi_i} \\
&=\left(t^2\pi_i^2+(t^2+1)\pi_i+1-t^2\pi_i^2\right)\frac{1}{\sqrt{t^2\pi_i^2+(t^2+1)\pi_i+1}+t\pi_i} \\
&=\frac{(t^2+1)\pi_i+1}{\sqrt{t^2\pi_i^2+(t^2+1)\pi_i+1}+t\pi_i} \\
&=\frac{(t^2+1)+\frac{1}{\pi_i}}{\sqrt{t^2\pi_i^2+(t^2+1)\frac{1}{\pi_i}+\frac{1}{\pi_i^2}}+t} \\
&\overset{\pi_i\to\infty}{\to}\frac{t^2+1}{\sqrt{t^2}+t}=\frac{t^2+1}{2t}.
\end{aligned}$$

This leads to

$$\begin{aligned}
\lim_{\pi_i\to\infty}\bar{\pi}_j(\pi_i,t,n)&=\frac{t\frac{t^2+1}{2t}-1}{(t+1)(n-t)}=\frac{\frac{t^2+1}{2}-1}{(t+1)(n-t)} \\
&=\frac{t^2+1-2}{2(t+1)(n-t)}=\frac{(t^2-1)(t-1)}{2(t^2-1)(n-t)} \\
&=\frac{t-1}{2(n-t)} \\
&=:\bar{\pi}_j^{ul}.
\end{aligned}$$

(iv) $\bar{\pi}_j^{ul}$ is obviously monotonically increasing in t. This is also true for $\bar{\pi}_j^{ll}$, as

$$\begin{aligned}
\frac{\partial\bar{\pi}_j^{ll}}{\partial t}&=\frac{(-t^2+(n-1)t+n)-(t-1)(-2t+(n-1))}{(-t^2+(n-1)t+n)^2} \\
&=\frac{-t^2+(n-1)t+n+2t^2-(n-1)t-2t+(n-1)}{(-t^2+(n-1)t+n)^2} \\
&=\frac{t^2-2t+2n-1}{(-t^2+(n-1)t+n)^2} \\
&>0 \quad \forall t\geq 2, n\geq 2.
\end{aligned}$$

□

A.5 Proof of Proposition 3

Proof. Let $S\subset T, \lambda\equiv 1$. Similar to the proof of Lemma 1, one gets

$$\begin{aligned}
E_i&=E_i^0-\pi_S E_N \quad \forall i\in S \\
E_i&=E_i^0-\pi_i E_N \quad \forall i\in T, i\notin S \\
E_j&=E_j^0-\pi_j E_N \quad \forall j\in R
\end{aligned}$$

and

$$E_N = \frac{E_N^0}{s\pi_S + \pi_{T\setminus S} + \pi_R + 1}.$$

In the cases of $S = \{i\}$ and $S = T$, the proposition follows directly. □

A.6 Proof of Lemma 3

Proof. Following Proposition 3, calculate the individual utility of $i \in S$:

$$\begin{aligned}
v_i(S) =& P_i(E_i) - D_i(E_N) \\
=& P_i^0 - \left(E_i^0 - \left(E_i^0 - \pi_S \frac{E_N^0}{s\pi_S + \pi_{T\setminus S} + \pi_R + 1}\right)\right)^2 - \pi_i \left(\frac{E_N^0}{s\pi_S + \pi_{T\setminus S} + \pi_R + 1}\right)^2 \\
=& P_i^0 - (\pi_S^2 + \pi_i) \left(\frac{E_N^0}{s\pi_S + \pi_{T\setminus S} + \pi_R + 1}\right)^2
\end{aligned}$$

Therefore one gets

$$\begin{aligned}
v_i(\{i\}) &= P_i^0 - (\pi_i^2 + \pi_i) \left(\frac{E_N^0}{\pi_i + \pi_{T\setminus i} + \pi_R + 1}\right)^2 \\
&= P_i^0 - (\pi_i^2 + \pi_i) \left(\frac{E_N^0}{\pi_T + \pi_R + 1}\right)^2, \\
v_i(T) &= P_i^0 - (\pi_T^2 + \pi_i) \left(\frac{E_N^0}{t\pi_T + \pi_R + 1}\right)^2
\end{aligned}$$

and

$$\begin{aligned}
& v_i(\{i\}) > v_i(T) \\
\Leftrightarrow & \frac{\pi_T^2 + \pi_i}{(t\pi_T + \pi_R + 1)^2} > \frac{\pi_i^2 + \pi_i}{(\pi_T + \pi_R + 1)^2} \\
\Leftrightarrow & \frac{(\pi_T + \pi_R + 1)^2}{\pi_i^2 + \pi_i} > \frac{(t\pi_T + \pi_R + 1)^2}{\pi_T^2 + \pi_i} \\
\Leftrightarrow & \frac{\pi_T^2 + \pi_R^2 + 1 + 2\pi_T\pi_R + 2\pi_T + 2\pi_R}{\pi_i^2 + \pi_i} > \frac{t^2\pi_T^2 + \pi_R^2 + 1 + 2t\pi_T\pi_R + 2t\pi_T + 2\pi_R}{\pi_T^2 + \pi_i}
\end{aligned}$$

$$
\begin{aligned}
\Leftrightarrow & \left[\frac{1}{\pi_i^2+\pi_i}-\frac{1}{\pi_T^2+\pi_i}\right]\pi_R^2 \\
& +\left[\frac{\pi_T+1}{\pi_i^2+\pi_i}-\frac{t\pi_T+1}{\pi_T^2+\pi_i}\right]2\pi_R \\
& +\frac{\pi_T^2+1+2\pi_T}{\pi_i^2+\pi_i}-\frac{t^2\pi_T^2+1+2t\pi_T}{\pi_T^2+\pi_i} \\
& >0 \\
\Leftrightarrow & \left[\frac{1}{\pi_i^2+\pi_i}-\frac{1}{\pi_T^2+\pi_i}\right]\pi_R^2 \\
& +\left[\frac{\pi_T+1}{\pi_i^2+\pi_i}-\frac{t\pi_T+1}{\pi_T^2+\pi_i}\right]2\pi_R \\
& +\frac{(\pi_T+1)^2}{\pi_i^2+\pi_i}-\frac{(t\pi_T+1)^2}{\pi_T^2+\pi_i} \\
& >0
\end{aligned}
$$

Defining the left-hand-side of the equation as $a_i(\pi_i, \pi_T, \pi_R)$ leads to the desired result. □

A.7 Proof of Proposition 4

Proof. Define

$$F(x) = \frac{A}{x^2+x} - \frac{B}{C+x},$$

where A, B and C only depend on π_T, but not on π_i. Let

$$F^{total}(\pi) = \sum_{i \in T} F(\pi_i).$$

I show that $F^{total}(\tilde{\pi}) > F^{total}(\pi)$ for all three terms of $a(\pi)$, as derived in Lemma 3:

$$
\begin{aligned}
& A=1,\ B=1,\ C=\pi_T^2; \\
& A=\pi_T+1,\ B=t\pi_T+1,\ C=\pi_T^2; \\
& A=(\pi_T+1)^2,\ B=(t\pi_T+1)^2,\ C=\pi_T^2.
\end{aligned}
$$

One has

$$\frac{\partial F}{\partial x} = -\frac{A(2x+1)}{x^2(x+1)^2} + \frac{B}{(C+x)^2}.$$

I now show that

$$\frac{\partial F}{\partial x}(\pi_l) < \frac{\partial F}{\partial x}(\pi_h) \ \ \forall \pi_l < \frac{\pi_T}{t}, \pi_h > \frac{\pi_T}{t}.$$

Then, with $d > 0$ approaching zero, one has

$$F(\tilde{\pi}_l) - F(\pi_k) = -d\left(\frac{\partial F}{\partial x}(\pi_l)\right)$$
$$F(\tilde{\pi}_h) - F(\pi_h) = d\left(\frac{\partial F}{\partial x}(\pi_h)\right)$$
$$\Rightarrow F^{total}(\tilde{\pi}) - F^{total}(\pi) = d\left(-\frac{\partial F}{\partial x}(\pi_l) + \frac{\partial F}{\partial x}(\pi_h)\right) \geq 0.$$

Let $\pi_m = \frac{\pi_T}{t}$. I first show that

$$\frac{\partial F}{\partial x}(\pi_l) < \frac{\partial F}{\partial \pi}(\pi_m).$$

$$\frac{\partial^2 F}{\partial^2 x}(\pi_l) = \frac{2A(C+\pi_l)^3((2\pi_l+1)(2\pi_l^2+3\pi_l+1) - \pi_l(\pi_l+1)^2) - 2B\pi_l^3(\pi_l+1)^4}{\pi_l^3(\pi_l+1)^4(C+\pi_l)^3}.$$

The numerator can be rearranged. Using $\pi_T \geq t\pi_l$.

$$\begin{aligned}
&2A(C+\pi_l)^3((2\pi_l+1)(2\pi_l^2+3\pi_l+1) - \pi_l(\pi_l+1)^2) - 2B\pi_l^3(\pi_l+1)^4\\
=&2A(\pi_T^6 + 3\pi_l\pi_T^4 + 3\pi_l^2\pi_T^2 + \pi_l^3)(3\pi_l^3 + 6\pi_l^2 + 4\pi_l + 1) - 2B(\pi_l^7 + 4\pi_l^6 + 6\pi_l^5 + 4\pi_l^4 + \pi_l^3)\\
\geq&2A(t^6\pi_l^6 + 3t^4\pi_l^5 + 3t^2\pi_l^4 + \pi_l^3)(3\pi_l^3 + 6\pi_l^2 + 4\pi_l + 1) - 2B(\pi_l^7 + 4\pi_l^6 + 6\pi_l^5 + 4\pi_l^4 + \pi_l^3)\\
=&\ 2[\pi_l^9(t^2A(3t^4)) + \pi_l^8(t^2A(pt^2+6t^4)) + \pi_l^7(t^2A(4t^4+18t^2+12) - B)\\
&\pi_l^6(t^2A(t^4+12t^2+18+\frac{3}{t^2}) - 4B) + \pi_l^5(t^2A(3t^2+12+\frac{6}{t^2}) - 6B)\\
&\pi_l^4(A(3t^2+4) - 4B) + \pi_l^3(A-B)]
\end{aligned}$$

In the case $A = (\pi_T+1)^2, B = (t\pi_T+1)^2$, this equals

$$\begin{aligned}
&2[\pi_l^9(t^2A(3t^4)) + \pi_l^8(t^2A(pt^2+6t^4)) + \pi_l^7(t^2A(4t^4+18t^2+12) - B)\\
&\quad + \pi_l^6(t^2A(t^4+12t^2+18+\frac{3}{t^2}) - 4B) + \pi_l^5(t^2A(3t^2+12+\frac{6}{t^2}) - 6B)\\
&\quad + \pi_l^4((\pi_T^2+2\pi_T+1)(3t^2+4) - 4(t^2\pi_T^2+2t\pi_T+1)) + \pi_l^3(\pi_T^2+2\pi_T+1-(t^2\pi_T^2+2t\pi_T+1))]\\
=&\ 2[\pi_l^9(t^2A(3t^4)) + \pi_l^8(t^2A(pt^2+6t^4)) + \pi_l^7(t^2A(4t^4+18t^2+12) - B)\\
&\quad + \pi_l^6(t^2A(t^4+12t^2+18+\frac{3}{t^2}) - 4B + (3t^2+4) - 4t^2)\\
&\quad + \pi_l^5(t^2A(3t^2+12+\frac{6}{t^2}) - 6B + 2(3t^2+4) - 8t + 1 - t^2)\\
&\quad + \pi_l^4(3t^2+4-4+2-2t) + \pi_l^3(1-1)]\\
&\geq 0
\end{aligned}$$

as $t^2A \geq B, A \geq 1, B \geq 1, t \geq 2$. The calculations for the other two cases are analogue. This shows that

$$\frac{\partial F}{\partial x}(\pi_l) < \frac{\partial F}{\partial x}(\pi_m).$$

In the second step, I show that

$$\frac{\partial F}{\partial x}(\pi_m + \epsilon) > \frac{\partial F}{\partial x}(\pi_m) \quad \forall 0 < \epsilon < \pi_T - \pi_m.$$

$$
\begin{aligned}
&\frac{\partial F}{\partial x}(\pi_m+\epsilon)-\frac{\partial F}{\partial x}(\pi_m)\\
&=-\frac{A(2(\pi_m+\epsilon)+1)}{(\pi_m+\epsilon)^2(\pi_m+\epsilon+1)^2}+\frac{B}{(C+\pi_m+\epsilon)^2}+\frac{A(2\pi_m+1)}{\pi_m^2(\pi_m+1)^2}-\frac{B}{(C+\pi_m)^2}\\
&=\big\{A(C+\pi_m)^2(C+\pi_m+\epsilon)^2[(2\pi_m+1)(\pi_m+\epsilon)^2(\pi_m+\epsilon+1)^2-(2(\pi_m+\epsilon)+1)\pi_m^2(\pi_m+1)^2]\\
&\quad+B\pi_m^2(\pi_m+1)^2(\pi_m+\epsilon)^2(\pi_m+\epsilon+1)^2[(C+\pi_m)^2-(C+\pi_m+\epsilon)^2]\big\}\\
&\quad/\big\{(\pi_m+\epsilon)^2(\pi_m+\epsilon+1)^2(C+\pi_m+\epsilon)^2\pi_m^2(\pi_m+1)^2(C+\pi_m)^2\big\}
\end{aligned}
$$

The numerator simplifies to

$$
\begin{aligned}
&A(C+\pi_m)^2(C+\pi_m+\epsilon)^2\\
&[6\epsilon\pi_m^4+(12\epsilon^2+12\epsilon)\pi_m^3+(8\epsilon^3+18\epsilon^2+8\epsilon)\pi_m^2+(2\epsilon^4+8\epsilon^3+8\epsilon^2+2\epsilon)\pi_m+\epsilon^2(\epsilon+1)^2]\\
&-B\pi_m^2(\pi_m+1)^2(\pi_m+\epsilon)^2(\pi_m+\epsilon+1)^2(2\epsilon(C+\pi_m)+\epsilon^2)
\end{aligned}
$$

Using $C=\pi_T^2, \pi_m=\frac{\pi_T}{t}$, this equals

$$
\begin{aligned}
&A\left[\pi_T^8+\frac{4}{t}\pi_T^7+\frac{2\epsilon t^2+5}{t^2}\pi_T^6+\frac{6\epsilon t^2+4}{t^3}\pi_T^5+\frac{\epsilon^2t^4+6\epsilon t^2+1}{t^4}\pi_T^4+\frac{2\epsilon^2t^2+2\epsilon}{t^3}\pi_T^3+\frac{\epsilon^2}{t^2}\pi_T^2\right]\\
&\left(\frac{6\epsilon}{t^4}\pi_T^4+\frac{12\epsilon^2+12\epsilon}{t^3}\pi_T^3+\frac{8\epsilon^3+18\epsilon^2+8\epsilon}{t^2}\pi_T^2+\frac{2\epsilon^4+8\epsilon^3+8\epsilon^2+2\epsilon}{t}\pi_T+\epsilon^2(\epsilon+1)^2\right)\\
&-B\left[\frac{1}{t^8}\pi_T^8+\frac{4\epsilon+4}{t^7}\pi_T^7+\frac{6\epsilon^2+14\epsilon+6}{t^6}\pi_T^6+\frac{4\epsilon^3+18\epsilon^2+18\epsilon+4}{t^5}\pi_T^5\right.\\
&\quad\left.\frac{\epsilon^4+10\epsilon^3+19\epsilon^2+10\epsilon+1}{t^4}\pi_T^4+\frac{2\epsilon^4+8\epsilon^3+8\epsilon^2+2\epsilon}{t^3}\pi_T^3+\frac{\epsilon^2(\epsilon+1)^2}{t^2}\pi_T^2\right]\\
&\left(2\epsilon\pi_T^2+\frac{2\epsilon}{t}\pi_T+\epsilon^2\right)
\end{aligned}
$$

$$
\begin{aligned}
=A \Bigg[& \frac{6\epsilon}{t^4}\pi_T^{12} + \left(\frac{24\epsilon}{t^5} + \frac{12\epsilon^2+12\epsilon}{t^3}\right)\pi_T^{11} + \left(\frac{30\epsilon}{t^6} + \frac{60\epsilon^2+48\epsilon}{t^4} + \frac{8\epsilon^3+18\epsilon^2+8\epsilon}{t^2}\right)\pi_T^{10} \\
& + \left(\frac{24\epsilon}{t^7} + \frac{96\epsilon^2+60\epsilon}{t^5} + \frac{56\epsilon^3+96\epsilon^2+32\epsilon}{t^3} + \frac{2\epsilon^4+8\epsilon^3+8\epsilon^2+2\epsilon}{t}\right)\pi_T^9 \\
& + \left(\frac{6\epsilon}{t^8} + \frac{84\epsilon^2+48\epsilon}{t^6} + \frac{118\epsilon^3+162\epsilon^2+40\epsilon}{t^4} + \frac{24\epsilon^4+68\epsilon^3+48\epsilon^2+8\epsilon}{t^2} + (\epsilon^4+2\epsilon^3+\epsilon^2)\right)\pi_T^8 \\
& + \left(\frac{24\epsilon^2+12\epsilon}{t^7} + \frac{116\epsilon^3+144\epsilon^2+32\epsilon}{t^5} + \frac{70\epsilon^4+160\epsilon^3+88\epsilon^2+10\epsilon}{t^3} + \frac{4\epsilon^5+20\epsilon^4+24\epsilon^3+8\epsilon^2}{t}\right)\pi_T^7 \\
& + \left(\frac{38\epsilon^3+42\epsilon^2+8\epsilon}{t^6} + \frac{80\epsilon^4+164\epsilon^3+80\epsilon^2+8\epsilon}{t^4} + \frac{20\epsilon^5+71\epsilon^4+66\epsilon^3+17\epsilon^2}{t^2} + (2\epsilon^5+4\epsilon^4+2\epsilon^3)\right)\pi_T^6 \\
& + \left(\frac{30\epsilon^4+56\epsilon^3+24\epsilon^2+2\epsilon}{t^5} + \frac{28\epsilon^5+78\epsilon^4+72\epsilon^3+16\epsilon^2}{t^3} + \frac{2\epsilon^6+14\epsilon^5+20\epsilon^4+8\epsilon^3)}{t}\right)\pi_T^5 \\
& + \left(\frac{12\epsilon^5+35\epsilon^4+26\epsilon^3+5\epsilon^2}{t^4} + \frac{4\epsilon^6+22\epsilon^5+28\epsilon^4+10\epsilon^3}{t^2} + (\epsilon^6+2\epsilon^5+\epsilon^4)\right)\pi_T^4 \\
& + \left(\frac{2\epsilon^6+10\epsilon^5+12\epsilon^4+4\epsilon^3}{t^3} + \frac{2\epsilon^6+4\epsilon^5+2\epsilon^4}{t}\right)\pi_T^3 \\
& + \frac{\epsilon^6+2\epsilon^5+\epsilon^4}{t^2}\pi_T^2 \Bigg] \\
-B \Bigg[& \frac{2\epsilon}{t^8}\pi_T^{10} + \left(\frac{2\epsilon}{t^9} + \frac{8\epsilon^2+8\epsilon}{t^7}\right)\pi_T^9 + \left(\frac{9\epsilon^2+8\epsilon}{t^8} + \frac{12\epsilon^3+28\epsilon^2+12\epsilon}{t^6}\right)\pi_T^8 \\
& + \left(\frac{16\epsilon^3+32\epsilon^2+12\epsilon}{t^7} + \frac{8\epsilon^4+36\epsilon^3+36\epsilon^2+8\epsilon}{t^5}\right)\pi_T^7 \\
& + \left(\frac{14\epsilon^4+50\epsilon^3+42\epsilon^2+8\epsilon}{t^6} + \frac{2\epsilon^5+20\epsilon^4+38\epsilon^3+20\epsilon^2+2\epsilon}{t^4}\right)\pi_T^6 \\
& + \left(\frac{6\epsilon^5+38\epsilon^4+56\epsilon^3+24\epsilon^2+2\epsilon}{t^5} + \frac{4\epsilon^5+16\epsilon^4+16\epsilon^3+4\epsilon^2}{t^3}\right)\pi_T^5 \\
& + \left(\frac{\epsilon^6+14\epsilon^5+35\epsilon^4+26\epsilon^3+5\epsilon^2}{t^4} + \frac{2\epsilon^5+4\epsilon^4+2\epsilon^3}{t^2}\right)\pi_T^4 \\
& + \frac{2\epsilon^6+10\epsilon^5+12\epsilon^4+4\epsilon^3}{t^3}\pi_T^3 + \frac{\epsilon^6+2\epsilon^5+\epsilon^4}{t^2}\pi_T^2 \Bigg]
\end{aligned}
$$

For $A = (\pi_T + 1)^2, B = (t\pi_T + 1)^2$, this equals

$$\Bigg[\frac{6\epsilon}{t^4}\pi_T^{14} + \left(\frac{24\epsilon}{t^5} + \frac{12\epsilon}{t^4} + \frac{12\epsilon^2 + 12\epsilon}{t^3}\right)\pi_T^{13}$$

$$+ \left(\frac{28\epsilon}{t^6} + \frac{48\epsilon}{t^5} + \frac{60\epsilon^2 + 54\epsilon}{t^4} + \frac{24\epsilon^2 + 24\epsilon}{t^3} + \frac{8\epsilon^3 + 18\epsilon^2 + 8\epsilon}{t^2}\right)\pi_T^{12}$$

$$+ \left(\frac{18\epsilon}{t^7} + \frac{60\epsilon}{t^6} + \frac{88\epsilon^2 + 76\epsilon}{t^5} + \frac{120\epsilon^2 + 96\epsilon}{t^4} + \frac{56\epsilon^3 + 108\epsilon^2 + 44\epsilon}{t^3} + \frac{16\epsilon^3 + 36\epsilon^2 + 16\epsilon}{t^2} \right.$$
$$\left. + \frac{2\epsilon^4 + 8\epsilon^3 + 8\epsilon^2 + 2\epsilon}{t}\right)\pi_T^{11}$$

$$+ \left(\frac{48\epsilon}{t^7} + \frac{59\epsilon^2 + 54\epsilon}{t^6} + \frac{192\epsilon^2 + 120\epsilon}{t^5} + \frac{106\epsilon^3 + 194\epsilon^2 + 76\epsilon}{t^4} + \frac{112\epsilon^3 + 192\epsilon^2 + 64\epsilon}{t^3} \right.$$
$$\left. + \frac{24\epsilon^4 + 76\epsilon^3 + 66\epsilon^2 + 16\epsilon}{t^2} + \frac{4\epsilon^4 + 16\epsilon^3 + 16\epsilon^2 + 4\epsilon}{t} + (\epsilon^4 + 2\epsilon^3 + \epsilon^2)\right)\pi_T^{10}$$

$$+ \left(\frac{-2\epsilon}{t^9} + \frac{12\epsilon}{t^8} + \frac{-2\epsilon^2 + 12\epsilon}{t^7} + \frac{168\epsilon^2 + 96\epsilon}{t^6} + \frac{76\epsilon^3 + 152\epsilon^2 + 56\epsilon}{t^5} + \frac{236\epsilon^3 + 324\epsilon^2 + 80\epsilon}{t^4} \right.$$
$$+ \frac{62\epsilon^4 + 180\epsilon^3 + 148\epsilon^2 + 34\epsilon}{t^3} + \frac{48\epsilon^4 + 136\epsilon^3 + 96\epsilon^2 + 16\epsilon}{t^2} + \frac{4\epsilon^5 + 22\epsilon^4 + 32\epsilon^3 + 16\epsilon^2 + 2\epsilon}{t}$$
$$\left. + (2\epsilon^4 + 4\epsilon^3 + 2\epsilon^2)\right)\pi_T^9$$

$$+ \left(\frac{-9\epsilon^2 - 2\epsilon}{t^8} + \frac{48\epsilon^2 + 24\epsilon}{t^7} + \frac{6\epsilon^3 + 34\epsilon^2 + 20\epsilon}{t^6} + \frac{232\epsilon^3 + 288\epsilon^2 + 64\epsilon}{t^5} + \frac{50\epsilon^4 + 106\epsilon^3 + 128\epsilon^2 + 24\epsilon}{t^4} \right.$$
$$+ \frac{140\epsilon^4 + 320\epsilon^3 + 176\epsilon^2 + 20\epsilon}{t^3} + \frac{18\epsilon^5 + 75\epsilon^4 + 96\epsilon^3 + 45\epsilon^2 + 6\epsilon}{t^2} + \frac{8\epsilon^5 + 40\epsilon^4 + 48\epsilon^3 + 16\epsilon^2}{t}$$
$$\left. + (2\epsilon^5 + 5\epsilon^4 + 6\epsilon^3 + \epsilon^2)\right)\pi_T^8$$

$$+ \left(\frac{-16\epsilon^3 - 8\epsilon^2}{t^7} + \frac{76\epsilon^3 + 84\epsilon^2 + 16\epsilon}{t^6} + \frac{-6\epsilon^4 + 36\epsilon^3 + 48\epsilon^2 + 10\epsilon}{t^5} + \frac{160\epsilon^4 + 328\epsilon^3 + 160\epsilon^2 + 16\epsilon}{t^4} \right.$$
$$+ \frac{24\epsilon^5 + 108\epsilon^4 + 156\epsilon^3 + 66\epsilon^2 + 6\epsilon}{t^3} + \frac{40\epsilon^5 + 142\epsilon^4 + 132\epsilon^3 + 34\epsilon^2}{t^2}$$
$$\left. + \frac{2\epsilon^6 + 14\epsilon^5 + 24\epsilon^4 + 16\epsilon^3 + 4\epsilon^2}{t} + (4\epsilon^5 + 8\epsilon^4 + 4\epsilon^3)\right)\pi_T^7$$

$$+ \left(\frac{-14\epsilon^4 - 12\epsilon^3}{t^6} + \frac{60\epsilon^4 + 112\epsilon^3 + 48\epsilon^2 + 4\epsilon}{t^5} + \frac{-2\epsilon^5 + 19\epsilon^4 + 40\epsilon^3 + 17\epsilon^2 + 2\epsilon}{t^4} \right.$$
$$+ \frac{56\epsilon^5 + 156\epsilon^4 + 144\epsilon^3 + 32\epsilon^2}{t^3} + \frac{3\epsilon^6 + 20\epsilon^5 + 32\epsilon^4 + 18\epsilon^3 + 4\epsilon^2}{t^2} + \frac{4\epsilon^6 + 28\epsilon^5 + 40\epsilon^4 + 16\epsilon^3}{t}$$
$$\left. + (\epsilon^6 + 2\epsilon^5 + 1\epsilon^4)\right)\pi_T^6$$

$$+ \left(\frac{-6\epsilon^5 - 8\epsilon^4}{t^5} + \frac{24\epsilon^5 + 70\epsilon^4 + 52\epsilon^3 + 10\epsilon^2}{t^4} + \frac{6\epsilon^5 + 4\epsilon^4 + 8\epsilon^3 + 2\epsilon^2}{t^3} \right.$$
$$\left. + \frac{8\epsilon^6 + 44\epsilon^5 + 56\epsilon^4 + 20\epsilon^3}{t^2} + \frac{2\epsilon^6 + 4\epsilon^5 + 2\epsilon^4}{t} + (2\epsilon^6 + 4\epsilon^5 + 2\epsilon^4)\right)\pi_T^5$$

$$+ \left(\frac{-\epsilon^6 - 2\epsilon^5}{t^4} + \frac{4\epsilon^6 + 20\epsilon^5 + 24\epsilon^4 + 8\epsilon^3}{t^3} + \frac{\epsilon^6 + 2\epsilon^5 + \epsilon^4}{t^2} + \frac{4\epsilon^6 + 8\epsilon^5 + 4\epsilon^4}{t}\right)\pi_T^4$$

$$+ \frac{2\epsilon^6 + 4\epsilon^5 + 2\epsilon^4}{t^2}\pi_T^3\Bigg]$$

Using $t \geq 2$, this is larger than zero. The other cases of A and B are analogue. Therefore

$$\frac{\partial F}{\partial x}(\pi_m + \epsilon) > \frac{\partial F}{\partial x}(\pi_m) \quad \forall 0 < \epsilon < \pi_T - \pi_m.$$

and

$$\frac{\partial F}{\partial x}(\pi_l) < \frac{\partial F}{\partial x}(\pi_h) \;\; \forall \pi_l < \frac{\pi_T}{t}, \pi_h > \frac{\pi_T}{t}.$$

□

B Parameter estimation

Table 3: Abatement cost parameter μ and damage cost parameter π for non-G20 countries. Values of μ and π in $\frac{EUR}{10^{15}*(tCO_2)^2}$.

Country	μ	π	Ratio $\frac{\pi}{\mu}$
Albania	2,608,628	0.2	9.27E-08
Algeria	103,511	4.2	4.07E-05
Angola	35,907	3.2	8.87E-05
Armenia	1,508,351	0.4	2.76E-07
Azerbaijan	230,907	2.3	1.02E-05
Bahrain	1,158,149	0.5	4.11E-07
Bangladesh	62,093	9.7	1.56E-04
Belarus	86,908	2.8	3.17E-05
Benin	138,527	0.8	5.85E-06
Bolivia	465,053	0.5	1.05E-06
Bosnia and Herzegovina	400,052	0.3	7.98E-07
Botswana	172,703	1.8	1.02E-05
Brunei Darussalam	676,847	0.6	9.60E-07
Cambodia	1,453,484	0.8	5.40E-07
Cameroon	104,469	3.2	3.09E-05
Chile	91,656	4.4	4.80E-05
Colombia	106,432	5.7	5.35E-05
Congo	199,502	1.5	7.34E-06
Costa Rica	1,242,956	0.9	7.29E-07
Côte d'Ivoire	77,117	3.0	3.94E-05
Croatia	1,081,274	0.7	6.28E-07
Cuba	362,417	1.7	4.72E-06
Democratic Republic of Congo	170,578	1.8	1.08E-05
Dominican Republic	383,818	1.5	3.90E-06
Ecuador	232,848	1.0	4.12E-06
Egypt	19,413	34.8	1.79E-03
El Salvador	1,289,130	0.6	4.64E-07
Eritrea	1,264,804	0.2	1.49E-07

Ethiopia	127,307	4.3	3.37E-05
Gabon	282,095	1.5	5.44E-06
Georgia	833,195	0.6	7.40E-07
Ghana	65,173	2.0	3.08E-05
Guatemala	834,609	1.1	1.33E-06
Haiti	3,349,752	0.1	4.22E-08
Honduras	1,028,626	0.4	4.06E-07
Iceland	5,552,626	0.1	2.61E-08
Iran (Islamic Republic of)	37,714	19.3	5.12E-04
Iraq	1,104,628	0.9	7.77E-07
Israel	88,136	9.8	1.11E-04
Jordan	373,428	0.9	2.33E-06
Kazakhstan	20,967	4.7	2.25E-04
Kenya	47,756	4.7	9.89E-05
Kuwait	579,374	2.2	3.87E-06
Kyrgyzstan	810,864	0.3	3.11E-07
Lebanon	472,666	1.5	3.07E-06
Libyan Arab Jamahiriya	334,042	5.6	1.67E-05
Macedonia (the former Yugoslavian Republic of)	1,059,975	0.2	1.70E-07
Malaysia	30,840	13.8	4.48E-04
Moldova (Republic of)	841,704	0.2	2.68E-07
Mongolia	405,080	0.2	4.99E-07
Morocco	93,014	7.0	7.47E-05
Mozambique	174,220	2.4	1.36E-05
Namibia	259,284	1.3	5.17E-06
Nepal	807,129	1.0	1.21E-06
New Zealand	227,561	1.8	8.04E-06
Nicaragua	1,733,032	0.3	1.53E-07
Nigeria	8,237	23.9	2.90E-03
Norway	213,383	2.7	1.26E-05
Oman	501,023	1.1	2.17E-06
Pakistan	24,932	13.9	5.57E-04
Panama	730,838	0.8	1.14E-06
Paraguay	1,448,104	0.4	2.84E-07
Peru	174,473	3.5	2.02E-05
Philippines	72,481	12.7	1.75E-04
Qatar	495,301	1.8	3.55E-06
Senegal	91,816	1.8	1.97E-05
Singapore	101,527	10.8	1.07E-04
Sri Lanka	197,722	3.0	1.53E-05
Sudan	41,546	5.8	1.40E-04
Switzerland	347,140	4.1	1.18E-05
Syrian Arab Republic	156,143	1.7	1.10E-05
Tajikistan	1,839,606	0.3	1.38E-07

Tanzania (United Republic of)	72,448	5.6	7.71E-05
Thailand	31,263	16.0	5.12E-04
Togo	428,717	0.4	9.59E-07
Trinidad and Tobago	203,235	0.5	2.45E-06
Tunisia	242,017	3.6	1.50E-05
Turkmenistan	106,978	0.7	6.57E-06
Ukraine	18,849	3.6	1.89E-04
United Arab Emirates	256,310	5.1	2.00E-05
Uruguay	872,032	1.2	1.34E-06
Uzbekistan	61,045	3.0	4.94E-05
Venezuela (Bolivarian Republic of)	45,989	6.1	1.33E-04
Vietnam	51,433	5.5	1.08E-04
Yemen	2,041,362	0.6	2.78E-07
Zambia	158,429	1.8	1.13E-05
Zimbabwe	80,097	0.9	1.11E-05

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