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Abstract

The present paper compares the Kyoto Protocol and the Paris Agreement in a dynamic game in which countries choose emissions reductions, investments in green energy and the contract duration. Green investment costs are stock-dependent. Applying Harstad's (2020a, 2020b) bargaining model for the Paris Agreement we show that there is a large set of economies at which the Kyoto Protocol performs better in terms of total emissions and welfare than the Paris Agreement, which is in stark contrast to the results of Harstad (2020a, 2020b). Although the stable climate coalition is large at the Paris Agreement and small at the Kyoto Protocol, the emissions reductions of a single coalition country is much deeper at the Kyoto Protocol such that this per-country-emissions reduction effect outweighs the disadvantage of having a smaller stable climate coalition.

JEL classification: C71, F55, Q54

Key words: pledge and review, emissions, investments, stable coalition

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1 Introduction

Climate change is one of the greatest challenges of humanity in the next decades. Both the Kyoto Protocol and the Paris Agreement have been negotiated to stabilize the world climate at safe levels. At the Kyoto Protocol notably the (Annex I) countries committed to reduce their emissions till 2020 by 18% below the 1990 level. After problems of further developing the Kyoto Protocol at the 2009 Copenhagen conference, countries switched 2015 from the Kyoto Protocol to the Paris Agreement. Although the Paris Agreement articulates a long-term goal of keeping the increase in global average temperature to 1.5° Celsius, the current commitments to emission reductions made by the signatories are not even sufficient to limit global warming to 2° Celsius (Hulme, 2016, Rogelj 2016). That raises the question of which type of agreement is more appropriate to bring down world emissions to safe levels.

The Kyoto Protocol and the Paris Agreement exhibit a number of differences. The most fundamental difference is that the Kyoto Protocol is a 'top-down'-approach which is managed by a multilateral institution and which legally binds countries to meet their emissions reductions commitments. In contrast, the Paris Agreement is a 'bottom-up'-approach at which countries submit their Intended Nationally Determined Contributions (pledges) to reduce carbon emissions. Pledges are voluntary commitments. While only 37 countries ratified the Kyoto Protocol, the Paris Agreement has been signed or acceded by 195 nations since the 21st Conference of Parties in Paris.[1] Although there is near-universal state participation at the Paris Agreement, it is not clear whether the Paris Agreement leads to stronger reductions of world emissions since pessimists believe that the Paris Agreement does not represent a breakthrough but instead incrementally extends the business as usual (Bang et al. 2016).

There is a large literature that analyzes the performance of the Kyoto Protocol. The prevailing approach is to apply the Nash bargaining solution in games in which the climate

[1] The Holy Sea cannot accede because it is no member of the UNFCCC, and the United States will withdraw this year.

coalition is both internally and externally stable. In a basic static game in which countries choose their efforts to reduce emissions at the second stage and decide to join the climate coalition at the first stage the size of stable coalitions is not larger than four (Hoel 1992, Carraro and Siniscalco 1993, Barrett 1994, Rubio and Ulph 2006).[2] Rubio and Casino (2005) and Rubio and Ulph (2007) extend the basic static game to a dynamic stetting with a pollution stock. Rubio and Casino (2005) show that the stable coalition remains small if countries once-only decide to participate in a climate coalition. Rubio and Ulph (2007) consider the membership decision being variable and find that the stable coalition may be larger if the potential gains of cooperation are small.[3] Battaglini and Harstad (2016) investigate coalition formation when countries choose emissions, investments in clean technologies and the contract length of the agreement. If contracts are complete, the stable coalition size is three. In case of incomplete contracts, the stable coalition may be larger up to the grand coalition. The driving force for larger stable coalitions is a hold-up problem in the last period of any contract. If a single country deviates by not participating, signing a one-period contract can be optimal to allow for a greater coalition in the next period, which reduces the free-riding incentives. All these contributions have in common that the coalition acts as single player, maximizes the sum of coalition countries' welfares, and that the symmetric Nash bargaining solution (NBS) is applied.

Only two recent contributions model-theoretically study the Paris Agreement. Caparrós (2020) applies a partial commitment bargaining model to implement countries' choice of pledges. With appropriate transfers the mechanism implements first-best emissions reductions in the short-term. Introducing investments in abatement and assuming that invest-

[2]The basic static model is refined in various directions. E.g. Barrett (2006) and Hoel and de Zeeuw (2010) analyzed R&D in breakthrough technologies, Bayramoglu et al. (2018) mitigation and adaptation, McEvoy and McGinty (2018) emissions taxes and Kornek and Edenhofer (2020) compensation funds.

[3]Kovác and Schmidt (2019) analyze a dynamic abatement game in which a long-term contract is suspended for one period if some country participates in climate negotiations but does not sign the climate contract. This delay of the long-term contract reduces the free-riding incentives and enlarges the stable coalition. Karp and Sakamoto (2019) introduce uncertainty about the outcome if climate negotiations fail in a dynamic abatement game and show the existence of multiple equilibria. The uncertainty about the outcome reduces [enhances] the stability of small [large] coalitions and enlarges the stable coalition in the long-run.

ments are not part of the contract, a hold-up problem emerges and countries underinvest. However, Caparrós (2020) does not investigate whether the climate contract is self-enforcing. Harstad (2020a, 2020b) develops a novel bargaining game at which countries simultaneously propose pledges. A contract is concluded if no country finds the vector of pledges unacceptable. Harstad (2020a, 2020b) shows that the solution of the bargaining game is the asymmetric Nash product. Embedded in a game in which countries choose emissions reductions, investments, contract length and in which climate agreements are self-enforcing, the Paris Agreement (asymmetric Nash solution, P&R) is compared with the Kyoto Protocol (symmetric Nash solution, NBS). At P&R stable climate coalitions are large but the emissions reduction of a single coalition country is small. In contrast, at NBS stable climate coalitions are small (three) but a single coalition country undertakes large emissions reductions. In view of total emission there is a coalition-size effect and a per-country-emissions-reduction effect which are countervailing. In Harstad (2020b, Corollary 1 and Proposition 3), the coalition-size effect overcompensates the per-country-emissions-reduction effect such that total emissions are smaller at P&R and countries prefer P&R except there are some unreasonable exogenously given minimum participation levels.

The present paper points to the role that the investment cost function plays for the comparison between P&R and NBS. For that purpose we consider stock-dependent investment costs à la Dutta and Radner (2004) and Battaglini and Harstad (2016) in Harstad's (2020a, 2020b) P&R bargaining game. More precisely, the difference to Harstad (2020a, 2020b) is the investment cost function in green technology which in Harstad (2020a, 2020b) depends on investments, whereas in the present paper it depends both on investments and the technology stock. In line with Harstad (2020a, 2020b), there is a coalition-size-effect and a per-country-emissions-reduction effect. Restricting our attention to economies in which the stable coalition comprises 195 countries at P&R and 37 countries at NBS, for a large set of economies the per-country-emissions-reduction effect dominates the coalition-size-effect such that world emissions are lower and welfare is higher at NBS than at P&R.

The remainder of the paper is organized as follows: In Section 2 the building blocks of the model are presented. In Section 3 the dynamic game is analyzed for both the pledge-and-reviewing bargaining model and for the Nash bargaining solution. In Section 4 we characterize the economies in which the Kyoto Protocol performs better than the Paris Agreement and vice versa presupposed stable coalitions comprise 37 countries at the Kyoto Protocol and 195 countries at the Paris Agreement, respectively. Section 5 concludes.

2 The model

The world economy consists of n countries.[4] In each period $t \geq 1$ country $i \in N = \{1, ..., n\}$ consumes energy that composes of fossil fuel energy $g_{i,t}$ and green energy $R_{i,t}$. The benefit of energy consumption is

$$B_i(y_{i,t}) = -\frac{b}{2}(\bar{y}_i - g_{i,t} - R_{i,t})^2, \tag{1}$$

where $\bar{y}_i$ is an exogenously given satiation point. Emission units are chosen such that $g_{i,t}$ denotes both fossil fuel consumption and carbon emissions from burning fuel by country i.

The stock of pollution evolves according to

$$G_t = q_G G_{t-1} + \sum_{j \in N} g_{j,t}, \tag{2}$$

where $1 - q_G \in [0, 1]$ is the natural depreciation rate. The climate damage from the emissions stock G_t is given by cG_t, where c is a positive parameter.

Green energy is produced by means of a green technology $R_{i,t}$. For sake of simplicity, the generation of green energy is proportional to the green technology. The green technology stock increases with investments $r_{i,t}$, and evolves in time according to

$$R_{i,t+1} = q_R R_{i,t} + r_{i,t}, \tag{3}$$

[4]The model is taken from Battaglini and Harstad (2016). Therefore the model description is as concise as possible.

where $1-q_R \in [0,1]$ is the technological depreciation rate. Following Battaglini and Harstad (2016, p. 167) the investment cost function κ depends on investments $r_{i,t}$ and on the technology stock $R_{i,t}$ according to

$$\kappa\left(r_{i,t}, R_{i,t}\right) = \frac{k}{2}\left(r_{it}^2 + 2q_R r_{i,t} R_{i,t}\right), \tag{4}$$

where k is a positive parameter. Making use of (3) in (4), the investment cost function can be written as $\kappa(\cdot) = \frac{k}{2}(R_{i,t+1}^2 - q_R^2 R_{i,t}^2)$.

The time from one consumption decision to the next is $\Delta > 0$, and the time from the investment decision to the technology improvement is $\Lambda \in (0, \Delta]$. Then, the utility of country i in period t is given by

$$u_{i,t} = -\frac{b}{2}\left(\bar{y}_i - g_{i,t} - R_{i,t}\right)^2 - cG_t - \frac{k}{2}\left(R_{i,t+1}^2 - q_R^2 R_{i,t}^2\right) e^{-\rho(\Delta-\Lambda)}, \tag{5}$$

where $\rho > 0$ is the discount rate. The present value of current and future utility is given by $v_{i,t} = \sum_{\tau=t} \delta^{\tau-t} u_{i,\tau}$, where $\delta \equiv e^{-\rho\Delta} \in (0,1)$ is the discount factor.

Battaglini and Harstad (2016) show that the present value $v_{i,t}$ can be represented by a discounted utility stream that depends on the two choice variables ($d_{i,t}$ and $R_{i,t+1}$) and is independent of past stock variables ($G_{t-\tau}$ and $R_{i,t-\tau}$ with $\tau \geq 1$):

Lemma 1 (Battaglini and Harstad 2016) *At any time t, the utility of country $i \in N$ is independent of all past stocks and can be represented by the continuation value function $v_{i,t} = \sum_{\tau=t} \delta^{\tau-t} \hat{u}_{i,\tau}$, where*

$$\hat{u}_{i,t} \equiv -\frac{b}{2} d_{i,t}^2 - \delta \frac{K}{2} R_{i,t+1}^2 - C \sum_{j \in N} \left(\bar{y}_i - d_{j,t} - \delta R_{j,t+1}\right), \tag{6}$$

with

$$d_{i,t} \equiv \bar{y}_i - g_{i,t} - R_{i,t}, \qquad K \equiv k\left(1 - \delta q_R^2\right) e^{\rho\Lambda}, \qquad C \equiv \frac{c}{1-\delta q_G}.$$

The variable $d_{i,t}$ reflects energy consumption - strictly speaking, energy reduction relative to the satiation point $\bar{y}_i$.

Throughout the paper we restrict our attention to Markov-perfect equilibria (MPE) in pure strategies. For later use as benchmarks we briefly characterize the first-best allocation and the non-cooperative MPE. The latter we refer to as business as usual (BAU). The first-best allocation follows from maximizing $\sum_{j \in N} v_{j,t}$ from (6) with respect to $d_{i,t}$ and $R_{i,t+1}$ which yields

$$-bd_{i,t} + nC = 0 \quad \Leftrightarrow \quad d_{i,t} = n\frac{C}{b} \qquad \forall t \geq 1, \tag{7}$$

$$\delta \left(-KR_{i,t+1} + nC \right) = 0 \quad \Leftrightarrow \quad R_{i,t+1} = n\frac{C}{K} \qquad \forall t \geq 1. \tag{8}$$

At BAU, each country i maximizes $v_{i,t}$ from (6) with respect to $d_{i,t}$ and $R_{i,t+1}$. The associated first-order conditions can be rearranged to

$$-bd_{i,t} + C = 0 \quad \Leftrightarrow \quad d_{i,t} = \frac{C}{b} \qquad \forall t \geq 1, \tag{9}$$

$$\delta \left(-KR_{i,t+1} + C \right) = 0 \quad \Leftrightarrow \quad R_{i,t+1} = \frac{C}{K} \qquad \forall t \geq 1. \tag{10}$$

Comparing (7)-(8) and (9)-(10) shows that BAU emissions are inefficiently high and BAU investments are inefficiently low. All countries suffer a welfare loss in BAU because non-cooperative governments ignore the negative impact of their emissions and the positive impact of their green energy investments on all other countries. The ratio between energy reduction and green investment in each case is

$$\frac{d_{i,t}}{R_{i,t}} = x \equiv \frac{K}{b} \qquad \forall t \geq 1. \tag{11}$$

The parameter x reflects the marginal cost of increasing investments relative to the marginal cost of reducing energy consumption and is referred to as *energy-investment* ratio.

3 The dynamic game

In the sequel we analyze a game between coalition countries and non-signatories when contracts are *incomplete*, i.e. coalition countries commit on emissions but not on investments. Non-signatories choose their emissions and green investments non-cooperatively. Since the stocks do not affect the countries' reaction functions, BAU emissions and BAU investments are dominant strategies when countries stay outside the coalition. In line with Harstad (2020b), coalition countries set their emissions via a pledge-and-review bargaining (P&R) and they choose non-cooperatively investments due to the incomplete contract. If m countries have agreed to join a climate coalition, each coalition country $i \in M \subseteq N$ makes pledges $z_{i,t}$ to curb emissions below BAU emissions $g_{i,t}^{BAU}$. Its emissions are given by

$$g_{i,t} = g_{i,t}^{BAU} - z_{i,t}. \tag{12}$$

It is straightforward to show that from a coalition country's perspective, it is equivalent to choose $z_{i,t}$ or $d_{i,t}$. Harstad (2020b) has pointed out that pledges can be implemented by maximizing the asymmetric Nash product[5]

$$d_{i,t}^* = \underset{d_{i,t}}{\operatorname{argmax}} \prod_{j \in M} v_{j,t}(d_{i,t}, \mathbf{d}_{-i,t}^*)^{\omega_i^j}, \tag{13}$$

where $\mathbf{d}_{-i,t}^*$ is the vector of other coalition countries' ($j \in M \backslash i$) equilibrium energy reduction. In (13), $\omega_i^j / \omega_i^i = \omega \in [0, 1)$ is country j's bargaining power vis-a-vis country i. Presupposed countries are symmetric, (13) is equivalent to

$$d_{i,t}^* = \underset{d_{i,t}}{\operatorname{argmax}} \left[v_{i,t}(d_{i,t}, \mathbf{d}_{-i,t}^*) + \omega \sum_{j \in M \backslash i} v_{j,t}(d_{i,t}, \mathbf{d}_{-i,t}^*) \right]. \tag{14}$$

(14) can be interpreted as welfare function of coalition country i, where ω is the relative welfare weight of the other coalition countries ($j \in M \setminus i$). P&R, approximated by the asymmetric Nash bargaining solution for $\omega < 1$, reflects the Paris Agreement. In contrast, for the polar case $\omega = 1$ (14) coincides with the symmetric Nash bargaining solution (NBS) or is

[5] Very elegantly, Harstad (2020a) offers a microfoundation for P&R.

tantamount with maximizing the sum of welfares, which to date is the standard approach in the literature on self-enforcing environmental agreements[6] and may be a good approximation for the Kyoto-Protocol negotiations. In the sequel we are interested in how emissions, investments, the contract length and the stable coalition of climate agreements change upon variations of ω. In the sequel we denote ω simply as welfare weight.

The timing of the game is illustrated in Figure 1. If there is no coalition, each country $i \in N$ decides whether to join a coalition or to stay outside. Then each coalition country $i \in M$ negotiates on emissions pledges. Next, non-signatories non-cooperatively choose emissions and coalition countries pollute as agreed. Finally, non-signatories and coalition countries non-cooperatively choose investments. If an agreement already exists, the participation decision and the negotiations are omitted.

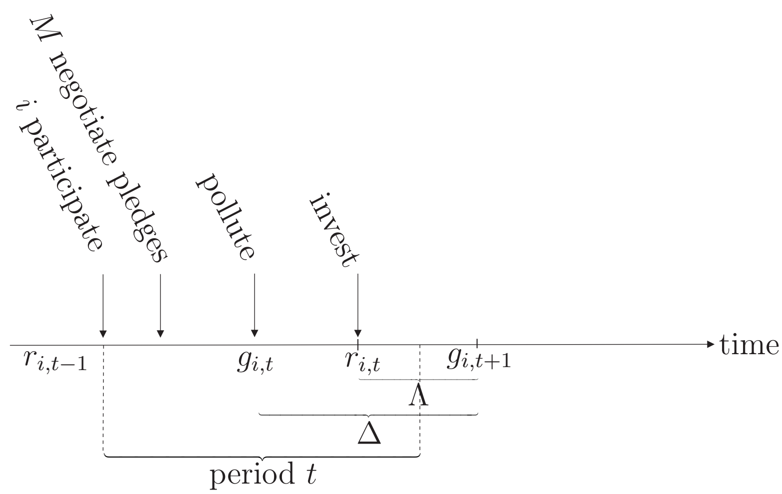

Figure 1: Timing of the game

The MPE of the dynamic game between the coalition and non-signatories is characterized by countries' policies $(d^*_{i,t}(M,T), R^*_{i,t+1}(M,T))_{t=1}^{T}$, the duration $T^*(M)$ of the agreement and the stable coalition M^*.[7] By virtue of backward induction we first derive the equilibrium policies for given M and T, then the equilibrium duration for given M and finally the stable coalition.

[6]See the literature mentioned in the Introduction.

[7]The concept of self-enforcement or stability was originally introduced by D'Aspremont et al. (1983) in the context of cartel formation.

As mentioned before non-signatories set BAU emissions and BAU investments according to (9) and (10). In the Appendix we derive the coalition countries' emissions and investments

$$d_{i,t} = [1 + (m-1)\omega]\frac{C}{b} \qquad \forall i \in M, t \in \{1, ..., T\}, \tag{15}$$

$$R_{i,t+1} = [1 + (m-1)\omega]\frac{C}{K}, \text{ but } R_{i,T+1} = \frac{C}{K} \qquad \forall i \in M, t \in \{1, ..., T\}, \tag{16}$$

which yields the pledges

$$z_{i,t+1} = (m-1)\omega\left(\frac{C}{b} + \frac{C}{K}\right), \text{ but } z_{i,T+1} = (m-1)\omega\frac{C}{b} \quad \forall i \in M, t \in \{1, ..., T\}. \tag{17}$$

In view of (15) and (17) each coalition country reduces its energy consumption relative to its BAU level, and emissions pledges are the higher the larger the welfare weight ω and the larger the coalition m. The larger ω the larger is the internalization of the climate externality within the coalition. A coalition country's technology investment is greater than its BAU level and increasing in ω and m except for the last period of the agreement.[8] In the last period each coalition country realizes that technology investment will be sunk in the next period and chooses BAU investments as non-signatories do. This phenomenon is known as hold-up problem. Recalling that non-signatories choose BAU emissions and BAU investments elucidates the free-riding problem. Coalition countries reduce emissions and step up their green investments to mitigate the climate damage, whereas non-signatories stay at their BAU levels and benefit at zero costs. The larger ω and m the more pronounced are the non-signatories' free-riding incentives.

Next, we determine the optimal duration of the agreement for a given coalition M. The coalition country's investments and emissions pledges $(R^*_{i,t+1}, z^*_{i,t+1})$ from (16) and (17) depend on the contract period at which they are made and offered, respectively. The next lemma specifies the optimal contract length for a given coalition size m.

Lemma 2 *Let M^* denote an equilibrium coalition size $m^* \equiv |M^*|$. Then, a coalition of size*

[8] In the first period of the agreement, $R_{i,1}$ is given, such that $z_{i,1} = d_{i,1} - d_{i,1}^{BAU} = (m-1)\omega\frac{C}{b}$.

$m = |M|$, satisfying $M \subseteq M^*$ or $M^* \subseteq M$, finds it optimal to contract for $T(m)$ periods, where

$$T(m) = \begin{cases} 1 & \textit{if } m < \hat{m}(x, m^*) \\ \{1, ..., \infty\} & \textit{if } m = \hat{m}(x, m^*) \\ \infty & \textit{if } m > \hat{m}(x, m^*), \end{cases} \tag{18}$$

with

$$\hat{m}(x, m^*) \equiv 1 + (m^* - 1)\sqrt{\frac{x + \delta}{x + 1}} < m^*.$$

Each country expects that once the current contract expires, the next contract will be concluded by the equilibrium coalition. For a given contract duration, each coalition country's utility is increasing in the coalition size, and for a given coalition size, each coalition country's utility is increasing in the contract duration due to the hold-up problem. Thus, a coalition greater than or equal to the equilibrium coalition ($m \geq m^*$) finds it optimal to contract forever. However, also a coalition smaller than the equilibrium coalition ($m \in (\hat{m}, m^*)$) can find it optimal to contract forever if it is not too small: It then forgoes a larger (equilibrium) coalition in the future to prevent the hold-up problem. Finally, if the coalition is very small ($m < \hat{m}$), then it contracts for just one period to allow for the equilibrium coalition in the next period. For $m = \hat{m}$, a one-period contract's positive effect, i.e. the larger coalition in the next period, and its negative effect, i.e. the underinvestment in the current period, exactly cancel out such that any contract duration is an equilibrium.

It is worth mentioning that $\hat{m}(x, m^*)$ is independent of the welfare weight. On the one hand, a smaller ω reduces the difference between the investment of each coalition country and that of each non-signatory, which mitigates the hold-up problem. Thus, contracting for just one period and allowing for the equilibrium coalition in the next period becomes more attractive ($\hat{m} \uparrow$). On the other hand, a smaller ω reduces the internalization of the climate externality within any coalition, which reduces the welfare loss of a narrowed coalition.

Thus, contracting forever with a coalition smaller than the equilibrium coalition becomes less costly ($\hat{m} \downarrow$). These two effects exactly cancel out. Note that the duration of the equilibrium coalition's agreement is always infinity ($T(m^*) = \infty$).

Finally, we turn to the stability of the climate coalition. When doing so we have to make a case distinction depending on the contract length in case of deviation. If a single country deviates by not participating, the remaining coalition sets $T = 1$ only if $m^* - 1 \leq \hat{m}(x, m^*) \Leftrightarrow m^* \leq m_M(x)$, where

$$m_M(x) \equiv 1 + \frac{1}{1 - \sqrt{\frac{x+\delta}{x+1}}}. \tag{19}$$

The inequality $m^* \leq m_M(x)$ is referred to as the *discipline constraint* and indicates whether the remaining coalition sets $T = 1$ or $T = \infty$, if a single coalition country leaves the coalition. The discipline constraint depends on the energy-investment ratio x. When $x \equiv \frac{K}{b}$ increases, the technology investment becomes more expensive and countries rely more on consumption reduction than on technology investment, which mitigates the hold-up problem. Thus, signing a one-period contract if a single country deviates by not participating becomes less expensive and relaxes the participation constraint $\left(\frac{\partial m_M(x)}{\partial x} > 0\right)$.

If the discipline constraint is violated ($m^* > m_M(x)$), the coalition sets $T = \infty$ even if a single country deviates by not participating. In that case the internal and external stability condition, respectively, is given by

$$m^* \leq m_{\underline{I}}(\omega) \equiv 1 + 2/w \quad \text{and} \quad m^* > 2/\omega. \tag{20}$$

In view of (20) the stable coalition size is determined by $m^* = \lfloor m_{\underline{I}}(\omega) \rfloor$, where $\lfloor \cdot \rfloor$ is the function that maps its argument to the largest weakly smaller integer.[9] We refer to $m_{\underline{I}}(\omega)$ as *participation constraint* $\underline{I}$. The stable coalition size $\lfloor m_{\underline{I}}(\omega) \rfloor$ decreases in ω. Recall that for exogenously given coalition M, an increase in ω enhances the internalization of climate

[9]If the discipline constraint is violated, the incomplete contract is identical to the complete contract in terms of emissions, investments, contract length and stable coalition size.

externalities within the coalition. As a consequence coalition countries decrease emissions and raise investments. This in turn enhances the free-riding incentives of non-signatories and decreases the size of the stable coalition.

Approximating the coalition size by $m^* = 1 + 2/\omega$, the coalition countries' emissions and investments are given by $d^*_{i,t} = 3\frac{C}{b}$ and $R^*_{i,t+1} = 3\frac{C}{K}$ for $t \in \{1, ..., T\}$. In the MPE of the dynamic game (i.e. for $M = M^*$), each coalition country's energy consumption and technology investment is independent of ω. Since the stable coalition is the smaller the larger ω, in the MPE total energy consumption and the climate damage are increasing and total technology investment is decreasing in ω, such that each coalition country's utility is decreasing in ω. Note, however, that even if ω is so small that $m^* = n$, total consumption [investment] is $n/3$ times too high [low] compared to the first-best allocation.

If the discipline constraint is satisfied ($m^* \leq m_M(x)$), then the coalition sets $T = 1$ if a single country deviates by not participating. In this period, the hold-up problem leads to underinvestment, such that the punishment for free riding is higher than with $T = \infty$. In that case the internal stability condition is given by

$$m^* \leq m_{\bar{I}}(x, \omega) \equiv 1 + \frac{2/\omega}{1 - \frac{2-\omega}{\omega}\frac{\delta}{x}} > m_{\underline{I}}(\omega), \tag{21}$$

whereas the external stability condition remains unchanged $m^* > 2/\omega$. $m_{\bar{I}}(x, \omega)$ is referred to as *participation constraint* $\bar{I}$. Presupposed $m_{\bar{I}}(x, \omega) < \min\{m_M(x), n\}$ the stable coalition is given by $m^* = \lfloor m_{\bar{I}}(x, \omega) \rfloor$. With the same interpretation as before, increases in ω enhance free-riding incentives and reduce the size of the stable coalition $\left(\frac{\partial m_{\bar{I}}(x,\omega)}{\partial \omega} < 0\right)$. When x increases, the technology investment becomes more expensive and, thus, less important relative to the consumption reduction. Thus, deviating by not participating if the remaining coalition signs a one-period contract becomes less expensive, which reduces the size of the stable coalition $\left(\frac{\partial m_{\bar{I}}(x,\omega)}{\partial x} < 0\right)$. A complete characterization of the stable coalition is provided in[10]

[10]Proposition 1 is proved in the Appendix.

Proposition 1 *M^* is an equilibrium coalition if and only if either $m^* = \lfloor m_{\underline{I}}(\omega) \rfloor$ or $\lfloor m_{\underline{I}}(\omega) \rfloor < m^* \leq \min\{n, m(x,\omega)\}$, where*

$$m(x,\omega) = \min\{m_M(x), m_{\bar{I}}(x,\omega)\} = \begin{cases} m_M(x) & \text{if } x < \hat{x}(\omega) \\ m_{\bar{I}}(x,\omega) & \text{if } x \geq \hat{x}(\omega), \end{cases} \tag{22}$$

with

$$\hat{x}(\omega) \equiv \frac{1+\delta+\sqrt{(1+\delta)^2+12\delta\Theta(\omega)}}{6\Theta(\omega)} > \max\left\{\frac{1}{3}, \frac{2-\omega}{\omega}\delta\right\}, \quad \tfrac{\partial \hat{x}(\omega)}{\partial \omega} < 0,$$

where

$$\Theta(\omega) \equiv \frac{\omega(4-\omega)}{3(2-\omega)^2} \in (0,1], \quad \tfrac{\partial \Theta(\omega)}{\partial \omega} > 0.$$

Proposition 1 points out that either the participation constraint $\underline{I}$, the participation constraint $\bar{I}$ or the discipline constraint $m_M(x)$ is relevant for the stable coalition. One constraint of the set $\{m_M(x), m_{\underline{I}}(x,\omega), m_{\bar{I}}(x,\omega)\}$ 'binds' and determines the size of the stable coalition.

4 Kyoto Protocol versus Paris Agreement

In this section we compare the Kyoto Protocol with the Paris Agreement. We assume that the total number of countries is $n = 197$. The Kyoto Protocol is represented by $\omega = 1$ and the Paris Agreement by $\omega < 0.5$. Since the Kyoto Protocol has been signed by 37 countries (Canada withdrew in 2012) and the Paris Agreement has been signed by 195 countries (the United Stated will withdraw this year), we have $m^* = 37$ if $\omega = 1$ and $m^* = 195$ if $\omega < 0.5$. There are three types of feasible economies, denoted as economies $\mathcal{E}_1$-$\mathcal{E}_3$, that are different with respect to the binding constraint. Table 1 provides an overview of the relevant constraint in economies $\mathcal{E}_1$-$\mathcal{E}_3$. For each economy we present an example.[11,12]

[11] Following Harstad (2020b) we assume $\omega < 0.5$ for the Paris Agreement. Therefore, the case that with the Paris Agreement the participation constraint $\bar{I}$ binds, which emerges if and only if $\omega = 0.977$, is excluded.

[12] A complete characterization of the economies $\mathcal{E}_1$-$\mathcal{E}_3$ is given in Lemma A1 of the Appendix.

Economy	Paris Agreement ($\omega < 0.5$)	Kyoto Protocol ($\omega = 1$)
$\mathcal{E}_1$	discipline constraint	participation constraint $\bar{I}$
$\mathcal{E}_2$	participation constraint $\underline{I}$	participation constraint $\bar{I}$
$\mathcal{E}_3$	participation constraint $\underline{I}$	discipline constraint

Table 1: Binding constraints in the feasible economies $\mathcal{E}_1$-$\mathcal{E}_3$

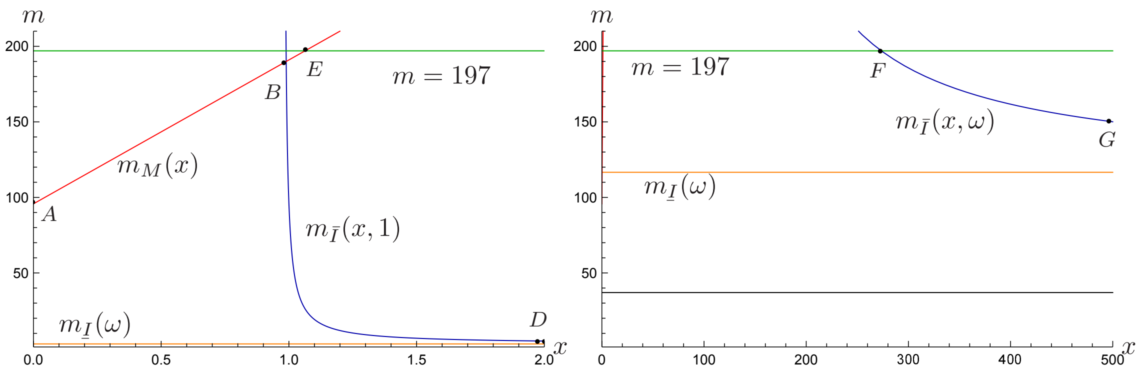

Figure 2: Stable coalitions in Example 1 ($\delta = 0.979$, $\omega = 0.0174$)

We begin with the numerical Example 1 which represents the economy $\mathcal{E}_1$. The parameter values are $\delta = 0.979$, $\omega = 0.0174$ and $\omega = 1$. Figure 2 illustrates the associated size of the stable coalition m^* in dependence of the energy-investment ratio x. The discipline curve m_M is increasing in x and independent of ω, while the participation curve $m_{\bar{I}}$ is decreasing in x and it shifts downwards if ω increases. The left panel shows that the stable coalition for $\omega = 1$ is characterized by the polyline ABD. At AB the discipline constraint is binding, whereas at BD the participation constraint $\bar{I}$ is binding. Reducing ω from 1 to 0.0174 shifts the participation curve $m_{\bar{I}}$ to the right as shown in the right panel of Figure 2. Now the stable coalition lies on the polyline $AEFG$, where AE is in the left panel and FG is in the right panel of Figure 2. For $\omega = 0.0174$ the grand coalition ($m^* = 197$) is stable if x is on the line EF.

Next, consider Figure 3 which is an enlarged segment of Figure 2. In order to compare the Paris Agreement with the Kyoto Protocol we select $x^* = 1.037$ such that the stable coalition is $m^* = 195$ for $\omega = 0.0174$ (point H) and $m^* = 37$ for $\omega = 1$ (point Q). At point

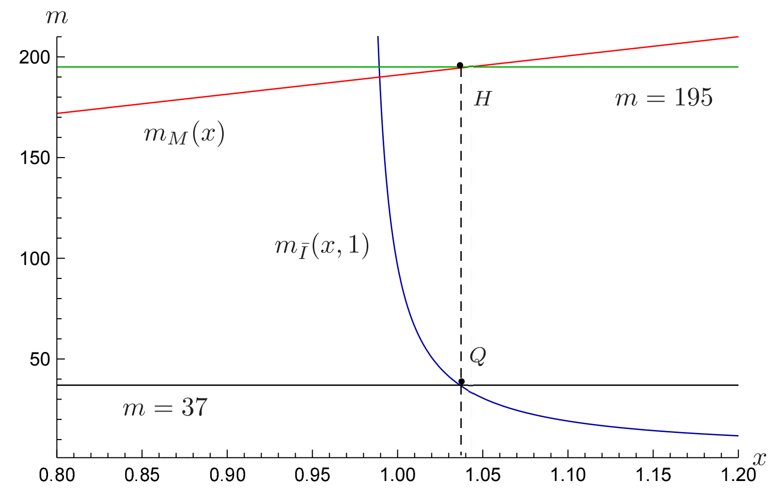

Figure 3: Stable coalitions in Example 1 ($\delta = 0.979$, $\omega = 0.0174$)

Q ($\omega = 1$) the participation constraint $\bar{I}$ is binding, whereas at point H ($\omega = 0.0174$) the discipline constraint is binding (see Table 1). Closer inspection of the two MPE reveals the following: If the discipline constraint is satisfied as in point H, then the coalition countries' policy is given by $bd_{i,t} = KR_{i,t+1} = [1 + (m_M(x) - 1)\omega]C = 4.37C$. In contrast, if the participation constraint is satisfied as in point Q, then the coalition countries' policy is given by $bd_{i,t} = KR_{i,t+1} = [1 + \frac{2x\omega}{\omega(x+\delta)-2\delta}]C = 37C$. In the transition from H ($\omega = 0.0174$) to Q ($\omega = 1$) there are two countervailing effects. On the one side each coalition country emits less and invests more. On the other side the coalition size decreases such that more countries free ride. In the transition from the Kyoto Protocol to the Paris Agreement, the stable coalition becomes broader and shallower. Aggregate emissions increase and aggregate investments decline. In Example 1 a coalition country's welfare with the Kyoto Protocol exactly coincides with a coalition country's welfare with the Paris Agreement. Reducing [enhancing] ω below [above] the threshold $\tilde{w} := 0.0174$ increases [decreases] a coalition country's emissions and reduces [enhances] its investments such that each coalition country's welfare decreases [increases].[13,14] We summarize these results in

[13] Observe that reducing ω below 0.0174 does not change Figure 3. Only curve FG in the right panel of Figure 2 is further shifted to the right.

[14] If $w = \tilde{w}$ each non-signatory's welfare is higher with the Kyoto Protocol than with the Paris Agreement. Recall that non-signatories always set BAU emissions and BAU investments. Each non-signatory's welfare depends over aggregate emissions indirectly on the welfare weight ω. Aggregate emissions are decreasing in ω. Thus, there exists a second threshold $\tilde{\omega} := 0.0352$ such that a non-signatory's welfare is higher with the

Proposition 2 *In economy $\mathcal{E}_1$ the welfare of a coalition country is higher with the Kyoto Protocol ($m^* = 37, \omega = 1$) than with the Paris Agreement ($m^* = 195, \omega < 0.5$) if and only if $\omega < 0.0174$.*

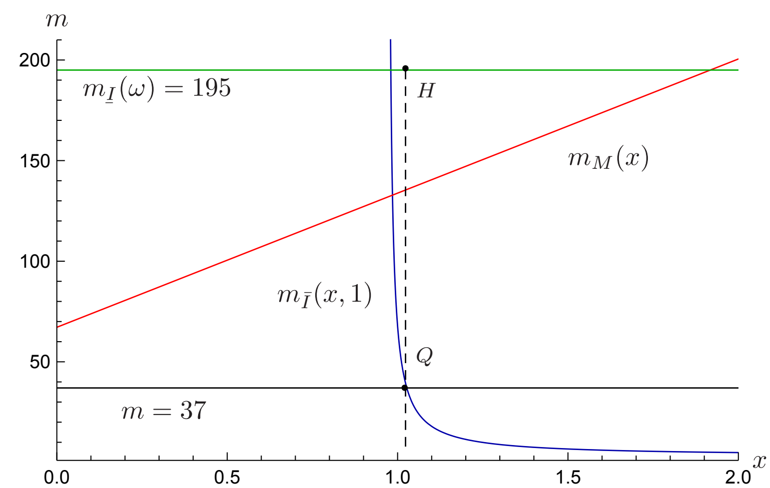

Figure 4: Stable coalitions in Example 2 ($\delta = 0.97$, $\omega = \frac{1}{97}$)

In economy $\mathcal{E}_2$ for the Kyoto Protocol the participation constraint $\bar{I}$ is still binding but for the Paris Agreement the participation constraint $\underline{I}$ is binding. To shift the participation line $m_{\underline{I}}$ to the top such that $m = 195$, the welfare weight ω has to be reduced to $\omega = \frac{1}{97}$. Economies $\mathcal{E}_2$ satisfy $x > \frac{35}{37}$ and $\delta = \frac{17}{18}x$. In Example 2, which is shown in Figure 4, the parameter values are $\delta = 0.97$ and $\omega = \frac{1}{97}$. Again point H reflects the Paris Agreement and point Q captures the Kyoto Protocol. The small welfare weight $\frac{1}{97} < \tilde{w}$ implies that a coalition country's welfare decreases in the transition from the Kyoto Protocol to the Paris Agreement.

Proposition 3 *In economy $\mathcal{E}_2$ the welfare of a coalition country is higher with the Kyoto Protocol ($m^* = 37, \omega = 1$) than with the Paris Agreement ($m^* = 195, \omega = \frac{1}{97}$).*

Finally, we turn to economy $\mathcal{E}_3$. In this economy the participation constraint $\underline{I}$ is binding for the Paris Agreement and the discipline constraint is binding for the Kyoto Protocol. To ensure that the participation constraint $\underline{I}$ provides $m^* = 195$, we have to set

Kyoto Protocol than with the Paris Agreement if and only if $w < \breve{w}$. See Lemma A2 of the Appendix.

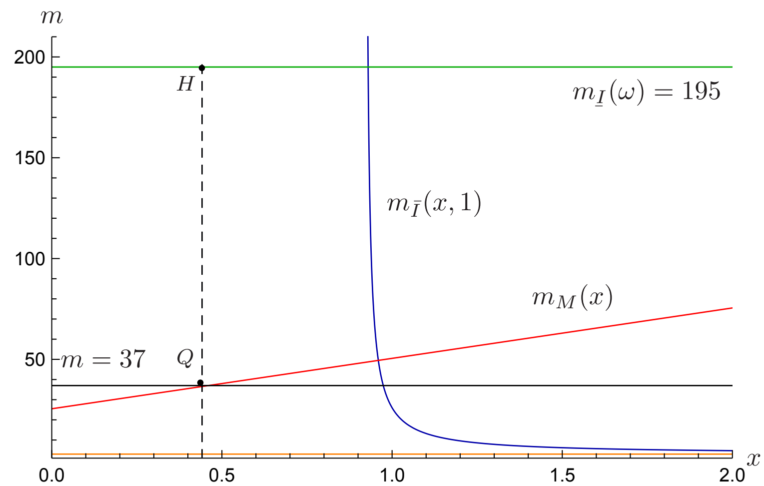

Figure 5: Stable coalitions in Example 3 ($\delta = 0.92$, $\omega = \frac{1}{97}$)

$\omega = \frac{1}{97}$. Furthermore, the stable coalition $m^* = 37$ lies on the discipline constraint $m_M(x)$ if $x < \frac{35}{37}$ and $\delta = \frac{1225}{1296} - \frac{71}{1296}x$. Example 3, whose parameters are $\delta = 0.92$ and $\omega = \frac{1}{97}$, is depicted in Figure 5 with H and Q being the MPE for $\omega = \frac{1}{97}$ and $\omega = 1$, respectively. Due to $\omega < \tilde{\omega}$ we infer

Proposition 4 *In economy $\mathcal{E}_3$ the welfare of a coalition country is higher with the Kyoto Protocol* ($m^* = 37, \omega = 1$) *than with the Paris Agreement* ($m^* = 195, \omega = \frac{1}{97}$).

The set of feasible economies is illustrated in Figure 6. The economy $\mathcal{E}_2$ [$\mathcal{E}_3$] lies on the line AB [BG]. In these economies the Kyoto Protocol performs better for coalition countries (Proposition 3 and 4). The line ED captures the economy $\mathcal{E}_1$ and point F is the threshold $\tilde{w} = 0.0174$. For all economies $\mathcal{E}_1$ on the line FD [EF] a coalition country's welfare is higher [lower] with the Kyoto Protocol than with the Paris Agreement (Proposition 2).

5 Concluding remarks

The present paper has compared the Kyoto Protocol with the Paris Agreement in a dynamic game in which countries choose emissions reductions, investments in green energy, decide to join a climate coalition and negotiate the climate contract. It is shown that the stable coalition is large at the Paris Agreement and small at the Kyoto Protocol but coalition

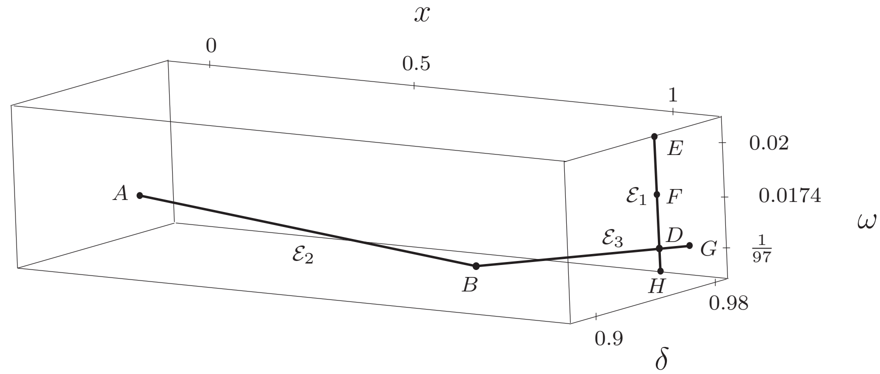

Figure 6: Feasible economies

countries' efforts to reduce emissions are much stronger at the Kyoto Protocol. It turns out that there is a large set of feasible economies in which world emissions are smaller and countries' welfare is larger at the Kyoto Protocol than at the Paris Agreement. Our results are in contrast to Harstad (2020a, 2020b) who finds that countries prefer the Paris Agreement. The difference of results goes back to differences in assumptions with regard to the investment cost function. Whereas in Harstad (2020a, 2020b) costs purely depend on investments, we follow Battaglini and Harstad (2016) and consider costs that are also stock-dependent.

The present analysis can be extended into various directions. Country-specific asymmetries, especially the distinction between industrial and developing countries, have played an important role in the transition from the Kyoto Protocol to the Paris Agreement. In the same vein transfers between countries may impact on the performance of P&R and NBS differently. Finally, trade sanctions and positive spillovers from research and development of breakthrough technologies stand on the agenda for future research in the comparison between P&R and NBS.

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Appendix

Derivation of equations (15)-(17)

Rewriting (6) yields

$$\begin{aligned}
v_i &= \sum_{t=1}^{T} \delta^{t-1} \left[-\frac{b}{2} d_{i,t}^2 - \delta \frac{K}{2} R_{i,t+1}^2 - C \sum_{j \in N} \left(\bar{y}_i - d_{j,t} - \delta R_{j,t+1} \right) \right] + \delta^T v_i \\
&= \sum_{t=1}^{T} \delta^{t-1} \left[-\frac{b}{2} \left(\bar{y}_i - g_{i,t} - R_{i,t} \right)^2 - \delta \frac{K}{2} R_{i,t+1}^2 - C \sum_{j \in N} \left(g_{j,t} + R_{j,t} - \delta R_{j,t+1} \right) \right] + \delta^T v_i \\
&= \sum_{t=1}^{T} \delta^{t-1} \left[-\frac{b}{2} \left(\bar{y}_i - g_{i,t} - R_{i,t} \right)^2 - \delta \frac{K}{2} R_{i,t+1}^2 - C \sum_{j \in N} g_{j,t} \right] + \delta^T v_i \\
&\quad - C \sum_{j \in N} \left(R_{j,1} - \delta^T R_{j,T+1} \right), \qquad \text{(A1)}
\end{aligned}$$

The participants' technology investment is given by maximizing v_i from (A1) for given $g_{i,t}$ over $R_{i,t+1}$:

$$\delta^t b \left(\bar{y}_i - g_{i,t+1} - R_{i,t+1} \right) - \delta^{t-1} \delta K R_{i,t+1} = 0 \quad \Leftrightarrow \quad R_{i,t} = \frac{b}{b+K} \left(\bar{y}_i - g_{i,t} \right) \quad \forall t \in \{2, ..., T\}, \qquad \text{(A2)}$$

$$-\delta^{T-1} \delta K R_{i,T+1} + \delta^T C = 0 \quad \Leftrightarrow \quad R_{i,T+1} = \frac{C}{K}. \qquad \text{(A3)}$$

Substituting (A2) and (A3) into (A1), we get

$$\begin{aligned}
v_i = &\sum_{t=1}^{T} \delta^{t-1} \left[-\frac{b}{2} \left(\frac{K}{b+K} \left(\bar{y}_i - g_{i,t} \right) \right)^2 - \delta \frac{K}{2} \left(\frac{b}{b+K} \left(\bar{y}_i - g_{i,t+1} \right) \right)^2 - C \sum_{j \in N} g_{j,t} \right] + \delta^T v_i \\
&- C \sum_{j \in N} \left(R_{j,1} - \delta^T \frac{C}{K} \right). \qquad \text{(A4)}
\end{aligned}$$

The participants' fossil fuel consumption for $t \in \{2, ..., T\}$ is given by maximizing $v_i + \omega \sum_{j \in M \setminus i} v_j$ from (A4) over $g_{i,t+1}$:

$$\begin{aligned}
&\delta^t b \left(\frac{K}{b+K} \right)^2 \left(\bar{y}_i - g_{i,t+1} \right) + \delta^{t-1} \delta K \left(\frac{b}{b+K} \right)^2 \left(\bar{y}_i - g_{i,t+1} \right) - \delta^t \Omega(m) C = 0 \\
\Leftrightarrow \quad &\bar{y}_i - g_{i,t} = \Omega(m) \frac{C(b+K)}{bK} \quad \forall t \in \{2, ..., T\}, \qquad \text{(A5)}
\end{aligned}$$

where $\Omega(m) \equiv 1 + (m-1)\omega$. Substituting (A5) into (A2) and $d_{i,t} = \bar{y}_i - g_{i,t} - R_{i,t}$, we get

$$R_{i,t} = \frac{b}{b+K}\Omega(m)\frac{C(b+K)}{bK} = \Omega(m)\frac{C}{K} \qquad \forall t \in \{2, ..., T\}, \tag{A6}$$

$$d_{i,t} = \bar{y}_i - g_{i,t} - R_{i,t} = \Omega(m)\frac{C(b+K)}{bK} - \Omega(m)\frac{C}{K} = \Omega(m)\frac{C}{b} \qquad \forall t \in \{2, ..., T\}. \tag{A7}$$

Equation (16) then follows from (A3) and (A6). The participants' fossil fuel consumption for $t = 1$ is given by maximizing $\hat{u}_{i,1} + \omega \sum_{j \in M \setminus i} \hat{u}_{j,1}$ from (6) over $d_{i,1}$:

$$-bd_{i,1} + \Omega(m)C = 0 \quad \Leftrightarrow \quad d_{i,1} = \Omega(m)\frac{C}{b}. \tag{A8}$$

Equation (15) then follows from (A7) and (A8). From (12), $d_{i,t} = \bar{y}_i - g_{i,t} - R_{i,t}$, (9) and (10) for BAU emissions and investments, and (A3), (A6) and (A7) for the coalition countries' emissions and investments, we get

$$\begin{aligned} z_{i,t+1} &= g^{BAU}_{i,t+1} - g_{i,t+1} = [\bar{y}_i - d^{BAU}_{i,t+1} - R^{BAU}_{i,t+1}] - [\bar{y}_i - d_{i,t+1} - R_{i,t+1}] \\ &= \begin{cases} \left[\bar{y}_i - \frac{C}{b} - \frac{C}{K}\right] - \left[\bar{y}_i - \Omega(m)\frac{C}{b} - \Omega(m)\frac{C}{K}\right] & \text{if } t \in \{1, ..., T-1\} \\ \left[\bar{y}_i - \frac{C}{b} - \frac{C}{K}\right] - \left[\bar{y}_i - \Omega(m)\frac{C}{b} - \frac{C}{K}\right] & \text{if } t = T. \end{cases} \end{aligned} \tag{A9}$$

Equation (17) then follows from (A9).

Proof of Lemma 2

We first prove that the optimal contract duration T^* of the equilibrium coalition M^* is infinity. If m^* countries contract for $T^* \leq \infty$ periods, each participant's continuation value from (6), (9) and (10) for $i \notin M$, and (15) and (16) for $i \in M$ is given by

$$\begin{aligned} v(m^*, T^*) = \sum_{i=t}^{T^*-1} \delta^{t-1} \Bigg\{ &-\frac{b}{2}\left(\Omega(m^*)\frac{C}{b}\right)^2 - \delta\frac{K}{2}\left(\Omega(m^*)\frac{C}{K}\right)^2 \\ &- C\left[\bar{y}_i - \left(m^*\Omega(m^*) + n - m^*\right)\left(\frac{C}{b} + \frac{\delta C}{K}\right)\right]\Bigg\} \\ &+ \delta^{T^*-1}\Bigg\{-\frac{b}{2}\left(\Omega(m^*)\frac{C}{b}\right)^2 - \delta\frac{K}{2}\left(\frac{C}{K}\right)^2 \\ &- C\left[\bar{y}_i - \left(m^*\Omega(m^*) + n - m^*\right)\frac{C}{b} - n\frac{\delta C}{K}\right]\Bigg\} + \delta^{T^*} v(m^*, T^*) \end{aligned}$$

$$
\begin{aligned}
&= -\frac{1-\delta^{T^*}}{1-\delta} C \left[\bar{y}_i - C \left(m^* \Omega(m^*) - \frac{\Omega(m^*)^2}{2} + n - m^* \right) \left(\frac{1}{b} + \frac{\delta}{K} \right) \right] \\
&\quad - \delta^{T^*} \frac{C^2}{2K} [\Omega(m^*) - 1][2m^* - 1 - \Omega(m^*)] + \delta^{T^*} v(m^*, T^*) \\
&= -\frac{1}{1-\delta} C \left[\bar{y}_i - C \left(m^* \Omega(m^*) - \frac{\Omega(m^*)^2}{2} + n - m^* \right) \left(\frac{1}{b} + \frac{\delta}{K} \right) \right] \\
&\quad - \frac{\delta^{T^*}}{1-\delta^{T^*}} \frac{C^2}{2K} [\Omega(m^*) - 1][2m^* - \Omega(m^*) - 1]. \qquad \text{(A10)}
\end{aligned}
$$

From (A10), we get the difference in each participant's continuation value between $T^* = \infty$ and $T^* < \infty$

$$
v(m^*, T^* = \infty) - v(m^*, T^* < \infty) = \frac{\delta^{T^*}}{1-\delta^{T^*}} \frac{C^2}{2K} [\Omega(m^*) - 1][2m^* - \Omega(m^*) - 1] > 0, \quad \text{(A11)}
$$

such that $T^* < \infty$ cannot be optimal.

Now we derive the optimal contract duration T of a given coalition M. If m countries contract for T periods and $T^* = \infty$, each participant's continuation value for from (6), (9) and (10) for $i \notin M$, and (15) and (16) for $i \in M$ is given by

$$
\begin{aligned}
v(m, T) = &-\frac{1-\delta^{T}}{1-\delta} C \left[\bar{y}_i - C \left(m \Omega(m) - \frac{\Omega(m)^2}{2} + n - m \right) \left(\frac{1}{b} + \frac{\delta}{K} \right) \right] \\
&- \delta^{T} \frac{C^2}{2K} [\Omega(m) - 1][2m - \Omega(m) - 1] \\
&- \frac{\delta^{T}}{1-\delta} C \left[\bar{y}_i - C \left(m^* \Omega(m^*) - \frac{\Omega(m^*)^2}{2} + n - m^* \right) \left(\frac{1}{b} + \frac{\delta}{K} \right) \right]. \qquad \text{(A12)}
\end{aligned}
$$

Note that the derivative of $v(m, T)$ with respect to T or, equivalently, with respect to $-\delta^T$ is always negative if and only if

$$
\begin{aligned}
&\frac{C^2}{1-\delta} \left(m \Omega(m) - \frac{\Omega(m)^2}{2} + n - m \right) \left(\frac{1}{b} + \frac{\delta}{K} \right) + \frac{C^2}{2K} [\Omega(m) - 1][2m - \Omega(m) - 1] \leq \\
&\frac{C^2}{1-\delta} \left(m^* \Omega(m^*) - \frac{\Omega(m^*)^2}{2} + n - m^* \right) \left(\frac{1}{b} + \frac{\delta}{K} \right) \\
\Leftrightarrow \quad &\frac{x+1}{x+\delta} \frac{(m-1)^2 \omega(2-\omega)}{2} - \frac{1}{2} \leq \frac{(m^*-1)^2 \omega(2-\omega)}{2} - \frac{1}{2}, \qquad \text{(A13)}
\end{aligned}
$$

where $x \equiv K/b$. From (A13), the optimal contract duration is one period if $m < \hat{m}(x, m^*)$, infinity if $m > \hat{m}(x, m^*)$, and arbitrary if $m = \hat{m}(x, m^*)$, where $\hat{m}(x, m^*)$ is defined in Lemma 2. QED

Proof of Proposition 1

We first derive the condition for external stability. If a non-participant joins in equilibrium, then $m = m^* + 1$, which is not beneficial to him if his continuation value in case of participation for $m = m^* + 1$ from (A10) for $T^* = \infty$ falls short of his continuation value in case of non-participation for $m = m^*$ from (6) for $d_{i,t}$ and $R_{i,t+1}$ from (9) and (10):

$$
\begin{aligned}
& -\frac{C}{1-\delta}\left[\bar{y}_i - C\left((m^*+1)\Omega(m^*+1) - \frac{\Omega(m^*+1)^2}{2} + n - (m^*+1)\right)\left(\frac{1}{b} + \frac{\delta}{K}\right)\right] < \\
& -\frac{C}{1-\delta}\left[\bar{y}_i - C\left(m^*\Omega(m^*) - \frac{1}{2} + n - m^*\right)\left(\frac{1}{b} + \frac{\delta}{K}\right)\right] \\
\Leftrightarrow \quad & \left[(m^*+1)\Omega(m^*+1) - \frac{\Omega(m^*+1)^2}{2} - m^*\Omega(m^*) + \frac{1}{2}\right]\frac{C^2}{1-\delta}\left(\frac{1}{b} + \frac{\delta}{K}\right) < 0 \\
\Leftrightarrow \quad & -m^*\omega^2\left(m^* - \frac{2}{\omega}\right)\frac{C^2}{2(1-\delta)}\left(\frac{1}{b} + \frac{\delta}{K}\right) < 0, \qquad \text{(A14)}
\end{aligned}
$$

requiring $m^* > 2/\omega$ for external stability.

Now we derive the conditions for internal stability. Suppose $m^* > m_M(x)$. If a participant deviates in equilibrium, then $m = m^* - 1 > \hat{m}(x, m^*)$; so $T = \infty$ by Lemma 2. Such a permanent deviation is not beneficial to him if his continuation value in case of participation for $m = m^*$ from (A10) for $T^* = \infty$ exceeds his continuation value in case of non-participation for $m = m^* - 1$ from (6) for $d_{i,t}$ and $R_{i,t+1}$ from (9) and (10):

$$
\begin{aligned}
& -\frac{C}{1-\delta}\left[\bar{y}_i - C\left(m^*\Omega(m^*) - \frac{\Omega(m^*)^2}{2} + n - m^*\right)\left(\frac{1}{b} + \frac{\delta}{K}\right)\right] \geq \\
& -\frac{C}{1-\delta}\left[\bar{y}_i - C\left((m^*-1)\Omega(m^*-1) - \frac{1}{2} + n - (m^*-1)\right)\left(\frac{1}{b} + \frac{\delta}{K}\right)\right] \\
\Leftrightarrow \quad & \left[m^*\Omega(m^*) - \frac{\Omega(m^*)^2}{2} - (m^*-1)\Omega(m^*-1) - \frac{1}{2}\right]\frac{C^2}{1-\delta}\left(\frac{1}{b} + \frac{\delta}{K}\right) \geq 0
\end{aligned}
$$

$$\Leftrightarrow \quad (m^*-1)\omega^2\left(\frac{2}{\omega}-(m^*-1)\right)\frac{C^2}{2(1-\delta)}\left(\frac{1}{b}+\frac{\delta}{K}\right)\geq 0, \tag{A15}$$

requiring $m^* \leq m_{\underline{I}}(x,\omega) = 1 + 2/\omega$ for internal stability. From (A14), the coalition is externally stable if $m^* > 2/\omega$, which is only fulfilled for the largest internally stable coalition. Thus, $m^* > m_M(x)$ implies $m^* = \lfloor 1 + 2/\omega \rfloor$.

Now suppose $m^* \leq m_M(x)$. If a participant deviates in equilibrium, then $m = m^* - 1 \leq \hat{m}(x, m^*)$; so $T = 1$ by Lemma 2, and the participant is expected to join the coalition next period. Such a one-period deviation is not beneficial to him if his one-period utility in case of participation for $m = m^*$ from (A10) for $T^* = \infty$ exceeds his one-period utility in case of non-participation for $m = m^* - 1$ from (6) for $d_{i,t}$ and $R_{i,t+1}$ from (9) and (10):

$$\begin{aligned}
& -C\left[\bar{y}_i - C\left(m^*\Omega(m^*) - \frac{\Omega(m^*)^2}{2} + n - m^*\right)\left(\frac{1}{b}+\frac{\delta}{K}\right)\right] \geq \\
& -\frac{b}{2}\left(\frac{C}{b}\right)^2 - \delta\frac{K}{2}\left(\frac{C}{K}\right)^2 \\
& -C\left[\bar{y}_i - \left((m^*-1)\Omega(m^*-1) + n - (m^*-1)\right)\frac{C}{b} - n\frac{\delta C}{K}\right] \\
\Leftrightarrow \quad & \left[m^*\Omega(m^*) - \frac{\Omega(m^*)^2}{2} - (m^*-1)\Omega(m^*-1) - \frac{1}{2}\right]\frac{C^2}{b} \\
& + \left[m^*\Omega(m^*) - \frac{\Omega(m^*)^2}{2} - m^* + \frac{1}{2}\right]\frac{\delta}{x}\frac{C^2}{b} \geq 0 \\
\Leftrightarrow \quad & (m^*-1)\,\omega^2\left[\frac{2}{\omega} - (m^*-1) + (m^*-1)\frac{2-\omega}{\omega}\frac{\delta}{x}\right]\frac{C^2}{2b} \geq 0 \\
\Leftrightarrow \quad & (m^*-1)\,\omega^2\left[\frac{2}{\omega} + (m^*-1)\left(\frac{2-\omega}{\omega}\frac{\delta}{x} - 1\right)\right]\frac{C^2}{2b} \geq 0,
\end{aligned} \tag{A16}$$

requiring $m^* \leq m_{\bar{I}}(x,\omega) = 1 + \frac{2/\omega}{1 - \frac{2-\omega}{\omega}\frac{\delta}{x}}$ for internal stability. For $x \leq \frac{2-\omega}{\omega}\delta$, any coalition is internally stable. From (A14), the coalition is externally stable if $m^* > 2/\omega$, which is definitely fulfilled for the largest internally stable coalition. Furthermore, $m^* = m_M(x) < \lfloor 1 + 2/\omega \rfloor$ would imply $m^* = m_M(x) \leq 2/\omega$, such that the coalition would not be externally stable and $m^* > m_M(x)$ would hold. Thus, $m^* \leq m_M(x)$ implies $m^* \in \left[\lfloor 1 + 2/\omega \rfloor, \min\{n, m_{\bar{I}}(x,\omega)\}\right]$.

Comparing $m_M(x)$ from (19) with $m_{\bar{I}}(x,\omega)$ from (21) yields $m_M(x) \gtreqless m_{\bar{I}}(x,\omega) \Leftrightarrow$

$x \gtreqless \hat{x}(\omega)$ as defined in Proposition 1, which proves the cases in (22). Differentiating $\hat{x}(\omega)$ and $\Theta(\omega)$ from Proposition 1 with respect to ω, we get

$$\frac{\partial \hat{x}(\omega)}{\partial \omega} = -\frac{6\delta\Theta(\omega) + (1+\delta)^2 + (1+\delta)\sqrt{(1+\delta)^2 + 12\delta\Theta(\omega)}}{6\Theta(\omega)^2\sqrt{(1+\delta)^2 + 12\delta\Theta(\omega)}} \cdot \frac{8}{3(2-\omega)^3} < 0, \tag{A17}$$

$$\frac{\partial \Theta(\omega)}{\partial \omega} = \frac{8}{3(2-\omega)^3} > 0, \tag{A18}$$

which proves the signs of the derivatives in Proposition 1. Furthermore, $\frac{\partial \hat{x}(\omega)}{\partial \delta} > 0$, $\hat{x}(\omega)|_{\delta=0} - 1/3 = 0$ and

$$\hat{x}(\omega) - \frac{2-\omega}{\omega}\delta = \frac{\frac{4\delta(1-\delta)}{\omega}}{\sqrt{(1+\delta)^2 + 12\delta\Theta(\omega)} + \frac{\omega(1+\delta)-2+6\delta}{2-\omega}} \geq 0, \tag{A19}$$

proves the lower bounds of $\hat{x}(\omega)$ in Proposition 1. Finally, $\frac{\partial \Theta(\omega)}{\partial \omega} > 0$, $\Theta(\omega = 0) = 0$ and $\Theta(\omega = 1) = 1$ proves the bounds of $\Theta(\omega)$ in Proposition 1. QED

To prove Propositions 2-4, we first characterize the feasible economies $\mathcal{E}_1$-$\mathcal{E}_3$ in Lemma A1 and then derive the welfare difference of each participant and that of each non-participant between the Kyoto Protocol and the Paris Agreement in Lemma A2.

Lemma A1 *Suppose $m^* = 37$ holds for $\omega = 1$ (Kyoto Protocol) and $m^* = 195$ holds for $\omega \leq 0.5$ (Paris Agreement). Then, Table A1 characterizes the feasible economies.*

Economy	Paris Agreement	Kyoto Protocol	$x \in$	$\delta \in$	$\omega \in$
$\mathcal{E}_1$	$m^* = m_M(x)$	$m^* = m_{\bar{I}}(x, 1)$	1.037	0.979	$[0.01, 0.5)$
$\mathcal{E}_2$	$m^* = m_{\underline{I}}(\omega)$	$m^* = m_{\bar{I}}(x, 1)$	$(0.946, 1.059]$	$(0.893, 1]$	0.01
$\mathcal{E}_3$	$m^* = m_{\underline{I}}(\omega)$	$m^* = m_M(x)$	$(0, 0.946]$	$[0.893, 0.945)$	0.01

Table A1: Feasible economies $\mathcal{E}_1$-$\mathcal{E}_3$

Proof of Lemma A1

For the Kyoto Protocol, $m^* = 37$ and $\omega = 1$ imply that either $m^* \leq m_M(x)$ or $m^* \leq m_{\bar{I}}(x, \omega = 1)$ is binding. Else, $m^* = m_{\underline{I}}(\omega = 1) = 3$ or $m^* = n = 197$ would hold. First suppose $m^* \leq m_M(x)$ and $m^* = m_{\bar{I}}(x, \omega = 1)$ hold for the Kyoto Protocol. From (19) and

(21), we then get

$$m_M(x) = 1 + \frac{1}{1 - \sqrt{\frac{x+\delta}{x+1}}} \geq 37 \qquad \Leftrightarrow \qquad \delta \geq \frac{1225}{1296} - \frac{71}{1296}x, \tag{A20}$$

$$m_{\bar{I}}(x, \omega = 1) = 1 + \frac{2x}{x - \delta} = 37 \qquad \Leftrightarrow \qquad x = \frac{18}{17}\delta. \tag{A21}$$

Substituting (A21) into (A20) and rearranging yields $\delta \geq \frac{595}{666} \approx 0.893$, and substituting this into (A21) yields $x \geq \frac{35}{37} \approx 0.946$. $\delta \leq 1$ then implies $\delta \in \left[\frac{595}{666}, 1\right]$ and $x \in \left[\frac{35}{37}, \frac{18}{17}\right]$.

For the Paris Agreement, $m^* = 195$ and $\omega \leq 0.5$ imply that $m^* \leq m_{\underline{I}}(\omega)$, $m^* \leq m_M(x)$ or $m^* \leq m_{\bar{I}}(x, \omega)$ is binding. Else, $m^* = n = 197$ would hold. Substituting $x = \frac{18}{17}\delta$ from (A21) into (19) and (21), we get

$$m_M\left(x = \frac{18}{17}\delta\right) = 1 + \frac{1}{1 - \sqrt{\frac{35\delta}{18\delta+17}}} = 195 \qquad \Leftrightarrow \qquad \delta = \frac{633233}{646778} \approx 0.979, \tag{A22}$$

$$m_{\bar{I}}\left(x = \frac{18}{17}\delta, \omega\right) = 1 + \frac{36}{35\omega - 34} = 195 \qquad \Leftrightarrow \qquad \omega = \frac{3316}{3395} \approx 0.977. \tag{A23}$$

$m_{\bar{I}}\left(x = \frac{18}{17}\delta, \omega\right) = 195$ cannot hold since $\omega < 0.5$, and $m_M\left(x = \frac{18}{17}\delta\right) = 195$ holds for $\delta \approx 0.979$ and $x = \frac{18}{17}\delta \approx 1.037$. Finally, $m_{\underline{I}}(\omega) = 1 + \frac{2}{\omega} = 195$ holds for $\omega = \frac{1}{97} \approx 0.010$. Thus, economy $\mathcal{E}_1$ is characterized by $m_{\bar{I}}(x, \omega = 1) = 37$, $m_M(x) = 195$ and $m_{\underline{I}}(\omega) \geq 195$, which implies the values in the second line of Table A1, and economy $\mathcal{E}_2$ is characterized by $m_{\bar{I}}(x, \omega = 1) = 37$, $m_M(x) \geq 37$ and $m_{\underline{I}}(\omega) = 195$, which implies the values in the third line of Table A1.

Now suppose $m^* = m_M(x)$ and $m^* \leq m_{\bar{I}}(x, \omega = 1)$ hold for the Kyoto Protocol. From (19) and (21), we then get

$$m_M(x) = 1 + \frac{1}{1 - \sqrt{\frac{x+\delta}{x+1}}} = 37 \qquad \Leftrightarrow \qquad \delta = \frac{1225}{1296} - \frac{71}{1296}x, \tag{A24}$$

$$m_{\bar{I}}(x, \omega = 1) = 1 + \frac{2x}{x - \delta} \geq 37 \qquad \Leftrightarrow \qquad x \leq \frac{18}{17}\delta. \tag{A25}$$

Substituting (A25) into (A24) and rearranging yields $\delta \geq \frac{595}{666} \approx 0.893$, and substituting this into (A25) yields $x \leq \frac{35}{37} \approx 0.946$. $x \geq 0$ then implies $\delta \in \left[\frac{595}{666}, \frac{1225}{1296}\right]$ and $x \in \left[0, \frac{35}{37}\right]$.

For the Paris Agreement, $m^* = 195$ and $\omega \leq 0.5$ imply that $m^* \leq m_{\underline{I}}(\omega)$ or $m^* \leq m_{\bar{I}}(x, \omega)$ is binding. Else, $m_M(x) = 37$ or $m^* = n = 197$ would hold. Substituting $x = \frac{1225}{71} - \frac{1296}{71}\delta$ from (A24) into (21), we get

$$m_{\bar{I}}\left(x = \frac{1225}{71} - \frac{1296}{71}\delta, \omega\right) = 1 + \frac{142\delta - 2450(1-\delta)}{142\delta - 1225\omega(1-\delta)} = 195 \quad \Leftrightarrow \quad \omega = \frac{12478\delta + 1225}{118825(1-\delta)}. \tag{A26}$$

$m_{\bar{I}}\left(x = \frac{1225}{71} - \frac{1296}{71}\delta, \omega\right) = 195$ cannot hold since $\delta \geq \frac{595}{666}$ implies $\omega \geq \frac{3316}{3395} > 0.5$. Finally, $m_{\underline{I}}(\omega) = 1 + \frac{2}{\omega} = 195$ holds for $\omega = \frac{1}{97} \approx 0.010$. Thus, economy $\mathcal{E}_3$ is characterized by $m_M(x) = 37$, $m_{\bar{I}}(x, \omega = 1) \geq 37$ and $m_{\underline{I}}(\omega) = 195$, which implies the values in the last line of Table A1. QED

Lemma A2 *Suppose* $m^* = 37$ *holds for* $\omega = 1$ *(Kyoto Protocol) and* $m^* = 195$ *holds for* $\omega \leq 0.5$ *(Paris Agreement). Then, the welfare of each participant [non-participant] is higher with the Kyoto Protocol than with the Paris Agreement if and only if* $\omega < 0.0174$ *[*$\omega < 0.0352$*]. Furthermore, the intertemporal climate damage is smaller with the Kyoto Protocol than with the Paris Agreement if and only if* $\omega < 0.0352$.

Proof of Lemma A2

For the Kyoto Protocol, we have $m^* = 37$ and $\omega = 1$, and for the Paris Agreement, we have $m^* = 195$ and $\omega \leq 0.5$. From (A10) for $T^* = \infty$, we get the welfare difference of each participant

$$v(m = 37, \omega = 1) - v(m = 195, \omega < 1) = \frac{C^2}{1-\delta}\left[648 - 18818\omega(2-\omega)\right]\left(\frac{1}{b} + \frac{\delta}{K}\right), \tag{A27}$$

which is positive [negative] for $\omega <$ [>]0.0174, and from the first line's right-hand side of (A14), we get the welfare difference of each non-participant

$$v(m = 37, \omega = 1) - v(m = 195, \omega < 1) = \frac{C^2}{1-\delta}\left[1332 - 37830\omega\right]\left(\frac{1}{b} + \frac{\delta}{K}\right), \tag{A28}$$

which is positive [negative] for $\omega <$ [>]0.0352. Since each nonparticipant always chooses the business-as-usual energy consumption and technology investment, its welfare difference stems from the difference in the intertemporal climate damage, such that $\omega < [>]0.0352$ implies a smaller [greater] intertemporal climate damage with the Kyoto Protocol than with the Paris Agreement. QED

Proof of Proposition 2

From Lemma A1, $\omega \in [0.1, 0.5]$ holds in economy $\mathcal{E}_1$, such that the welfare of each participant is higher with the Kyoto Protocol than with the Paris Agreement if and only if $\omega < 0.0174$ in economy $\mathcal{E}_1$ from Lemma A2. QED

Proof of Proposition 3

From Lemma A1, $\omega = 0.1$ holds in economy $\mathcal{E}_2$, such that the welfare of each participant is higher with the Kyoto Protocol than with the Paris Agreement in economy $\mathcal{E}_2$ from Lemma A2. QED

Proof of Proposition 4

From Lemma A1, $\omega = 0.1$ holds in economy $\mathcal{E}_3$, such that the welfare of each participant is higher with the Kyoto Protocol than with the Paris Agreement in economy $\mathcal{E}_3$ from Lemma A2. QED

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