Environmental Agreements, Research and Technological Spillovers*

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Abstract

This paper considers different contracts of international environmental agreements in a dynamic game in which countries choose emissions, R&D investments and investments in renewable energy generation capacity. R&D investments cause technological spillovers. For the different contracts the size of the stable coalition is analyzed. It turns out that both cooperation over R&D investments and technology transfers within the coalition may enhance the size of stable coalitions. In an empirical calibration, the stable coalition of the complete contract is quite small. An incomplete contract over emission leads to larger stable coalitions which can be further enlarged by a technology transfer within the coalition. An incomplete contract over emissions and R&D investments is the best performer and yields the largest stable coalition up to the grand coalition. The incomplete contract over emissions and R&D investments is pareto-superior to all other contracts and may even be first best.

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Key words: OR in environment and climate change, complete and incomplete contract, R&D, technological spillovers, hold-up problem

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1 Introduction

The substantial reduction of global carbon emissions necessary to stabilize the world climate at safe levels calls for an effective international environmental agreement (IEA). Due to the public good property of climate change, countries cannot achieve substantial emissions reduction by non-cooperative behavior. Therefore countries have negotiated IEAs to cooperatively address the climate change challenge. Since the world emissions are still increasing, it is questionable whether the current climate agreements are appropriate to limit the rate of global warming to a maximum of 1.5° Celsius. In view of the little success of previous and current IEAs and the serious global climate change challenge a continued investigations of the theoretical foundations of successful and effective IEAs is required.

The most prominent IEAs are the *Montreal Protocol*, the *Kyoto Protocol* and the *Paris Agreement*. Better and/or new technologies are an important means to cut greenhouse gas emissions. According to Peters et al. (2017), one of the key indicators to track current progress and future ambition of the Paris Agreement is technological progress. Both the Kyoto Protocol and the Paris Agreement are climate agreements and contain declarations of intent concerning technology. The objective of the so-called Technology Mechanism of the Kyoto-Protocol is to enhance 'action on technology development and transfer to support action on mitigation and adaptation in order to achieve the full implementation of the Convention' (UNFCCC 2010, para. 113). Similarly, Article 10.2 of the Paris Agreement states: 'Parties, noting the importance of technology for the implementation of mitigation and adaptation actions under this Agreement and recognizing existing technology deployment and dissemination efforts, shall strengthen cooperative action on technology development and transfer.' Since the declarations of intent have not led to technology transfer or to R&D cooperations between signatories, both the Kyoto Protocol and the Paris Agreement are contracts on emission reductions that do not include renewable capacity commitments, R&D investment agreements or technology transfer agreements.

The Montreal Protocol is an IEA that is designed to protect the ozone layer. It contains a technology transfer agreement. Industrialized countries have paid into the Montreal Protocol fund that finances the diffusion of new technologies in the developing countries. The fund has been viewed as one of the factor of success of the Montreal Protocol. Finally, without being embedded into a climate agreement there are two R&D agreements that foster the joint development of technologies. The *Asia Pacific-Partnership on Clean Development and Climate* aims to accelerate the development and introduction of low-carbon technologies while the *Carbon Sequestration Leadership Forum* aims to jointly research and assay carbon reservoirs.

In the present paper, we consider a dynamic game in which countries decide on emissions, investments in renewable energy capacity and R&D investments. Capacity investments build up new energy generation facilities such as hydropower stations, wind farms or solar farms. They directly increase the production of renewable energy. R&D investments are necessary to develop new technologies or to improve existing technologies. They have no direct impact on renewable energy production. Rather, new technologies or technology improvements may lower the costs of capacity investments[1] or mitigate climate damages, and they offer a high potential of spillovers. Depending on the contractual design of IEAs countries can (easily) adopt foreign technologies by acquiring licenses or copying it. In that dynamic game countries decide whether to join a climate coalition.

The aim of the present paper is to analyze different forms of climate contracts. In international climate negotiations countries' governments are decision makers that are faced with the task to work out and sign a climate contract. Here, we offer a game theory analysis that helps governments to select the best contract from various climate contracts. We distinguish between complete contracts, incomplete E-contracts, incomplete ER-contracts, incomplete EC-contracts and incomplete Et-contracts. In case of *complete contracts*, coalition countries jointly decide on emissions, capacity investments and R&D investments. In case of *incomplete E-contracts*, the coalition only coordinates emissions, while R&D and capacity investments remain in the authority of the member countries. In case of incomplete EC-contracts, coalition countries negotiate emissions and capacity investments. When coalition countries decide on emissions and additionally agree to transfer technology they sign an *incomplete Et-contract*. Finally, in case of *incomplete ER-contracts*, coalition countries negotiate on emissions and R&D. For each of these contracts, we determine emissions, investments, the contract length and the size of the stable coalition.

Since the early 1990s an economic literature has developed on self-enforcing IEAs. The major share of the literature on IEAs with R&D has focused on breakthrough technologies, i.e. on technological progress that eliminates emissions. In static games Barrett (2006), Hoel and de Zeeuw (2010) and Rubio (2017) analyze R&D of a breakthrough technology as a public good within the coalition that causes positive technological spillovers. Barrett (2006) and Hoel and de Zeeuw (2010) abstain from explicitly modelling emissions and study R&D-contracts. Rubio (2017) considers a three-stage game in which countries decide on joining the coalition (stage 1), on R&D investments (stage 2) and on emissions (stage 3). R&D investments are chosen cooperatively, whereas emissions are chosen non-cooperatively within the coalition. Rubio (2017) points out that an R&D agreement may enhance the size of the stable technology coalition up to the grand coalition if marginal climate damages are large enough to develop the breakthrough technology and technology spillovers are not very important.

El-Sayed and Rubio (2014) analyze coalition formation in the context of R&D investments in cleaner technologies. The static three-stage game is similar to that of Rubio (2017). Coalition

[1]IRENA (2020, chapter 1) reports on strong decreases in total installed costs in recent years of e.g. solar photovoltaic and onshore wind power.

countries decide cooperatively on R&D investments but non-cooperatively on emissions. Harstad et al. (2019) consider a dynamic model where countries decide on emissions and investments in green, brown and adaption technologies. Focusing on complete contracts, they analyze the pareto-efficient self-enforcing IEA. In particular, they show that cooperation is facilitated [hampered] by technology spillovers if the countries are heterogenous [homogenous].

The literature so far discussed has focussed on either complete contracts (Barrett 2006, Hoel and de Zeeuw 2010, Harstad 2019) or incomplete R&D-contracts (El-Sayed and Rubio 2014 and Rubio 2017). In contrast, in view of the Kyoto-Protocol and Paris Agreement our focus lies on incomplete E-contracts that may be supplemented by R&D investment agreements (ER-contract) or technology transfer agreements (Et-contract). These contracts have not been analyzed so far. Our paper aims to fill that gap in the literature and to answer the question which of these incomplete contracts is the best choice for decision makers (governments).[2]

Closest to our approach is Battaglini and Harstad (2016). They study coalition formation in a dynamic game where countries choose emissions and investments in renewables without technological spillovers and without R&D investments. If contracts are complete, i.e. coalition countries cooperate over emissions and investments in renewables, only three countries are in the stable coalition. If contracts are incomplete, i.e. coalition countries negotiate only over emissions but not over investments, a hold-up problem arises, which leads to a reduction of investments in the last period of a contract. If one coalition country defects, the remaining countries sign only a short-term agreement so that the hold-up problem is antedated. Thus, a credible threat is created to end the coalition which counters free-riding incentives. The stable coalition of the incomplete contract may be larger and in some economies the grand coalition is attainable.[3]

Our approach relies on building blocks of the dynamic model of Battaglini and Harstad (2016) but takes account of the difference between capacity and R&D investments. Capacity investments only increase the installed renewable energy generation capacity (e.g. the number of solar or wind farms) and, therefore, the production of green energy. R&D investments change and improve technology, which reduces a country's capacity investment costs or mitigates its climate damage. Introducing R&D investments and technological spillovers in the model of Battaglini and Harstad (2016) allows us to investigate different forms of incomplete contracts. Especially, the new contracts we study are incomplete ER-contracts, incomplete EC-contracts and incomplete Et-contracts. However, the introduction of R&D investments and technological spillovers may also change the

[2]The literature analyzing the formation and stability of IEAs is more diverse than discussed here. A review of early contributions can be found in Finus (2003). Newer operational research contributions to IEAs and transboundary pollution games are Benchekroun and Martín-Herrán (2016), and Sacco and Zaccour (2018).

[3]The hold-up problem also emerges in Hong and Karp (2012) and Helm and Schmidt (2015) who investigate abatement, R&D and coalition formation in the context of mixed strategies and border carbon adjustment, respectively.

performance of the complete contract and the incomplete contract of Battaglini and Harstad (2016).

For each contract we characterize the emissions, investments, contract length and stable coalitions. The general results concerning the stable coalitions are summarized in Propositions 1-4. In addition, we calibrated the dynamic game to the world to obtain more specific results. The stable coalition and welfares of the contracts in the calibrated economy are highlighted in Results 1-5. R&D investments and technological spillovers have the potential to increase the size of the stable coalition of complete contracts, in general. However, this hope is blurred in the calibrated economy because the stable coalition consists at most of 5 countries. R&D investments and technological spillovers within the coalition do not change the stable coalition of incomplete E-contracts such that large coalitions up to the grand coalition are feasible. However, the new insight is that the grand coalition that may form in case of the incomplete E-contract does not implement the first-best outcome, since coalition countries choose inefficient R&D investments due to non-internalized technology spillover externalities.

Technology spillover externalities are also non-internalized in incomplete EC-contracts and in incomplete Et-contracts. When countries negotiate on emissions and renewable energy capacity (incomplete EC-contract), the hold-up problem emerging in incomplete E-contracts disappears with the consequence that the stable coalition has at most three countries. In contrast, a technology transfer agreement further improves the incomplete E-contract. Coalition countries benefit from technology spillovers in the coalition that can enlarge the stable coalition. The best contract is the incomplete ER-contract. When jointly deciding on R&D investments, coalition countries internalize the technology spillover externalities and makes the accession to the coalition attractive. In addition, in case of the incomplete ER-contract, there is also a hold-up problem that restrains countries from leaving the coalition. If all countries sign the incomplete ER-contract, it is first best.

The remainder of the paper is organized as follows: In Section 2 we present the model, derive the countries' value function, and characterize the non-cooperative Markovian equilibrium and the first-best equilibrium as benchmarks. Section 3 determines emissions, investments in capacity and technology, the contract length and the stable coalition of complete contracts. In Section 4 we analyze incomplete E-contracts, EC-contracts, ER-contracts and Et-contracts. Section 5 provides a welfare comparison of these contracts in the calibrated economy and Section 6 concludes.

2 The model

2.1 Utility, pollution, capacity, and technology

Following Battaglini and Harstad (2016), we envisage an economy with two groups of countries, M and L. The members of group $M = \{1, \ldots, m\}$ participate in an international environmental agreement. We refer to group M as coalition. The remaining countries $i \in L = \{m+1, \ldots, n\}$ are non-signatories and act non-cooperatively. In every period $t \geq 1$, each country $i \in M \cup L \equiv N$ derives the benefit

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

from consuming $g_{i,t} + R_{i,t}$ units of energy. Country i's energy consumption consists of fossil fuel energy $g_{i,t}$ and renewable energy $R_{i,t}$ such as wind, solar or hydropower energy. Both types of energy are considered as perfect substitutes, for simplicity. The benefit function is increasing and concave in $g_{i,t} + R_{i,t}$, and the parameter $b > 0$ measures the disutility of energy consumption relative to the exogenously given satiation point $\bar{y}_i$. In the following, b is denoted as energy preference parameter.

CO_2 emissions are proportional to the consumption of fossil fuel energy, and therefore we simply use $g_{i,t}$ to denote both fossil fuel energy consumption and released carbon emissions of country $i \in N$ in period t. The stock G_t of carbon emissions evolves in time according to

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

In (2), $(1 - q_G) \in [0,1]$ is the natural regeneration rate of carbon emissions. Climate damage in country $i \in N$ is proportional to the CO_2 stock and given by

$$D(G_t) = cG_t, \tag{3}$$

where c is the constant marginal climate damage. Golosov et al. (2014, p. 78) defend the linearity assumption. They consider a concave stock of carbon-to-temperature and a convex temperature-to-damage function and write: "Linearity is arguably not too extreme a simplification, since the composition of a concave stock of carbon-to-temperature mapping with a convex temperature-to-damage function may be close to linear."

To produce energy from renewables it is necessary to invest into specialized capital goods such as solar panels, wind turbines or hydropower systems. In other words, it is necessary to build up a renewable energy generation *capacity*. By normalization, each unit of capacity produces one unit of renewable energy, so that $R_{i,t}$ denotes both the installed capacity and the renewable energy production of country i in period t. Country i builds up its capacity by investments $r_{i,t}$. Investments do not immediately increase the capacity but there is an investment time lag. The investments of period t determine the capacity of period $t+1$ according to

$$R_{i,t+1} = q_R R_{i,t} + r_{i,t}, \tag{4}$$

where $(1 - q_R) \in [0,1]$ is the depreciation rate of capacity.

The capacity costs $\kappa(\cdot)$ depend on both the capacity level and investments. The cost function $\kappa(\cdot)$ is quadratic in the targeted capacity level $R_{i,t+1}$ such that $\frac{\partial \kappa}{\partial R_{i,t+1}} = kR_{i,t+1}$, where $k > 0$ is a cost parameter. In addition, the costs are nil if no investments are made, formally $\kappa(\cdot) = 0$ for $r_{i,t} = 0$. These assumptions imply the cost function[4,5]

$$\kappa(R_{i,t+1}, R_{i,t}) = \frac{k}{2}\left(R_{i,t+1}^2 - q_R^2 R_{i,t}^2\right). \tag{5}$$

Battaglini and Harstad (2016) interpret $R_{i,t}$ as a composite variable that covers both capacity and the available technology level. They assume that investments into renewable technologies directly increase green energy production. However, in the real world the characteristics of capacity investments and R&D investments are quite different. To make this distinction formally precise, we differentiate between the renewable energy generation capacity $R_{i,t}$ and technology $\tilde{A}_{i,t}$. On the one hand, an increase of the installed renewable energy generation capacity $R_{i,t}$, e.g. the construction of new wind farms, solar farms or hydropower stations, increases green energy production but makes use of existing technology. Furthermore, transfer and conversion losses of long-range energy transport as well as the costs of the associated infrastructure suggest that the spillovers of capacity investments to other countries are rather small. On the other hand, R&D investments hardly affect the instantaneous green energy production. Rather, new technologies or improvements of technology $\tilde{A}_{i,t}$ may take effect in the following ways:

(i) The technology lowers capacity costs. In this case, the net capacity costs of country i are given by (see Kamien et al. 1992)[6]

$$\kappa(R_{i,t+1}, R_{i,t}) - \gamma\tilde{A}_{i,t}.$$

A technological innovation leads to cheaper wind turbines or solar panels. Consequently, the capacity costs for a given capacity level $R_{i,t+1}$ are lower or more capacity can be installed for a given investment volume.

(ii) The technology mitigates climate damage, so that net damage of country i turns into (see Poyago-Theotoky 2007, Menezes and Pereira 2017)

$$D(G_t) - \gamma\tilde{A}_{i,t}.$$

In this case, a technological innovation represents improvements in CCS-technology, flood control methods, agricultural reforms or geoengineering, such as carbon dioxide removal and solar radiation management.[7]

[4]Solving $\frac{\partial\kappa}{\partial R_{i,t+1}} = kR_{i,t+1}$ gives $\kappa(\cdot) = \frac{k}{2}R_{i,t+1}^2 + Q$, with Q as a variable independent of $R_{i,t+1}$. Using $\kappa(\cdot) = 0$ for $r_{i,t} = 0$ and (4) gives $Q = -\frac{k}{2}q_R^2 R_{i,t}^2$.

[5]By following Battaglini and Harstad (2016), we disregard fossil fuel extraction costs, so that fossil fuel use is not associated with any costs apart of the climate damage. For linear extraction costs, the results do not change qualitatively. Only one additional parameter, which covers the marginal extraction costs, is added. Analyzing convex extraction costs, e.g. quadratic costs, is beyond the scope of the present paper.

[6]In contrast to Kamien et al. (1992), the technology reduces capacity costs and not marginal capacity costs, which is required to apply Markov perfect equilibria.

[7]To ensure the tractability of the model, we need to maintain a linear-quadratic form. In both option (i) and

The parameter $\gamma > 0$ measures the strength of cost reduction or climate damage mitigation and is denoted as mitigation parameter.

New technologies or technology improvements can be easily transferred to other countries implying positive technology spillovers. The degree of spillovers depends, among others, on the strength of international patent law and on the intensity of international cooperation. In the following, we assume that technology spillovers to members of a climate coalition can be larger than spillovers to fringe countries. The technology level $\tilde{A}_{i,t}$ available to a coalition member $i \in M$ is given by

$$\tilde{A}_{i,t} = A_{i,t} + \mu \sum_{j \in M \setminus i} A_{j,t} + \beta \sum_{j \in L} A_{j,t}, \tag{6}$$

if there are additional spillovers between coalition countries, and by

$$\tilde{A}_{i,t} = A_{i,t} + \beta \sum_{j \in M \cup L \setminus i} A_{j,t}. \tag{7}$$

in the absence of additional spillovers within the coalition. In (6) and (7), $A_{i,t}$ is the technology level developed by country i. The technology level available to a fringe country $i \in L$ in any case is given by (7). The exogenously given parameters $\beta, \mu \in [0, 1]$ measure the degree of technological spillovers. Countries within the coalition benefit from larger technological spillovers, $\mu > \beta$, in case of technology transfer agreements or R&D agreements. When these agreements are made, the restrictions of international patent laws are partly relaxed within the coalition (e.g. through lower license fees inside the coalition than outside the coalition) and (6) is the coalition country's technology stock.[8] If coalition countries do not negotiate on R&D investments or technology transfers, larger technology spillovers within the coalition cannot be realized and (7) is the coalition country's technology stock.

Our modeling of technological progress follows Tsur and Zemel (2005) which harks back to the lab equipment approach of Ravira-Batiz and Romer (1991). The technology $A_{i,t}$ of country i increases with R&D investments $a_{i,t}$ and part of the technology stock depreciates according to the rate $(1 - q_A) \in [0, 1]$. Analogously to the green energy capacity, we consider an investment time lag. The R&D investments of period t increase the technology of period $t + 1$ such that the evolution of

option (ii), the stated linear relation can be interpreted as an approximation to a more straightforward multiplicative relation. Consider a cost reducing technology $\breve{A}$, with $\frac{\partial \kappa}{\partial \breve{A}_{i,t}} < 0$. For every $\breve{A}_{i,t}$, we can find an $\tilde{A}_{i,t}$ such that $\kappa(R_{i,t+1}, R_{i,t}, \breve{A}_{i,t}) = \kappa(R_{i,t+1}, R_{i,t}) - \gamma \tilde{A}_{i,t}$ holds. In this sense, $\tilde{A}_{i,t}$ approximates $\breve{A}_{i,t}$. Note that the assumption $\kappa(R_{i,t+1}, R_{i,t}, \breve{A}_{i,t}) > 0$ allows us to focus on interior solutions with respect to $\tilde{A}_{i,t}$, i.e. $\kappa(R_{i,t+1}, R_{i,t}) - \gamma \tilde{A}_{i,t} > 0$. Similar remarks hold for the mitigation technology of option (ii), with technology $\breve{A}$ reducing the marginal climate damage in country i, i.e. with $c(\breve{A}_{i,t})$ and $\frac{\partial c}{\partial \breve{A}_{i,t}} < 0$.

[8] Higher technology spillovers inside the coalition are also assumed by Lessmann and Edenhofer (2011) and Rubio (2017). The former refer to transfers of technology, increasing efficiency, and synergies as reasons for higher technology spillovers.

technology is given by

$$A_{i,t+1} = q_A A_{i,t} + a_{i,t}. \tag{8}$$

The R&D costs

$$\alpha(A_{i,t+1}, A_{i,t}) = \frac{s}{2}\left[A_{i,t+1}^2 - q_A^2 A_{i,t}^2\right]. \tag{9}$$

are quadratic in the targeted technology level $A_{i,t+1}$ and nil if no R&D investments are made. In (9) s is a positive parameter. Countries are identical with the exception of the satiation point $\bar{y}_i$ and the endowments $A_{i,1}$ and $R_{i,1}$.

2.2 Value function

In the present paper we use discrete time. Each period t lasts for Ξ moments. At the beginning of each period, the countries simultaneously decide about their fossil fuel consumption $g_{i,t}$ and their investments into capacity $r_{i,t}$ and R&D $a_{i,t}$.[9] The utility of country i in period t reads

$$\begin{aligned}\hat{u}_{i,t} &= B_i(y_{i,t}) - \kappa(R_{i,t+1}, R_{i,t}) - \alpha(A_{i,t+1}, A_{i,t}) + \gamma \tilde{A}_{i,t} - cG_t \\ &= -\frac{b}{2}\left[\bar{y}_i - g_{i,t} - R_{i,t}\right]^2 - \frac{k}{2}\left[R_{i,t+1}^2 - q_R^2 R_{i,t}^2\right] - \frac{s}{2}\left[A_{i,t+1}^2 - q_A^2 A_{i,t}^2\right] + \gamma \tilde{A}_{i,t} - cG_t,\end{aligned} \tag{10}$$

where $\tilde{A}_{i,t}$ is given by (6) or (7) if $i \in M$, and by (7) if $i \in L$. Throughout the paper we solve for Markov-perfect-equilibria (MPE) in pure strategies, so that the decisions of all countries depend only on the current state of the economy but not its history.[10] Let $\rho > 0$ denote the time preference rate and $\delta = e^{-\rho\Xi} < 1$ the discount factor. As shown in Online-Appendix A.2,[11] we can rewrite the value function $\hat{v}_{i,t} = \sum_{\tau=t}^{\infty} \delta^{\tau-t} \hat{u}_{i,t}$ as

$$v_{i,t} = \sum_{\tau=t}^{\infty} \delta^{\tau-t} u_{i,t} \tag{11}$$

with

$$\begin{aligned}u_{i,t} = & -\frac{b}{2}\left[\bar{y}_i - g_{i,t} - R_{i,t}\right]^2 - \frac{K}{2} R_{i,t+1}^2 - \frac{S}{2} A_{i,t+1}^2 + \gamma\delta \tilde{A}_{i,t+1} \\ & + \delta C \sum_{j \in L \cup M} R_{j,t+1} - C \sum_{j \in L \cup M} \left(g_{j,t} + R_{j,t}\right),\end{aligned} \tag{12}$$

where $K := k(1 - \delta q_R^2)$ and $S := s(1 - \delta q_A^2)$ measure the effective costs of capacity investments and R&D investments, respectively, and $C := \frac{c}{1-\delta q_G} = c \sum_{\tau=t}^{\infty} (\delta q_G)^{\tau-t}$ denotes the social costs of carbon of one CO_2 unit emitted in period t.

[9] In contrast to Battaglini and Harstad (2016), we assume that the emission and investment decision are made at the same point in time. Introducing a time lag between the decisions, such that the emission decision precedes the investment decision, complicates the notation without altering the result. The reason is that the investments of period t determine the corresponding stocks of the following period $t+1$, while the emissions in t determine the emission stock of period t.

[10] See Maskin and Tirole (2001), Harstad (2012), and Harstad (2016) for a more detailed discussion of Markov-perfect-equilibria.

[11] The Online-Appendix can be found as supplementary material at the EJOR website.

2.3 Business as usual and first-best

For later use as a benchmark, we briefly characterize the non-cooperative MPE also denoted as business as usual (BAU). The government of country $i \in N$ maximizes its value function $v_{i,t}$ with respect to $g_{i,t}$, $R_{i,t+1}$, and $A_{i,t+1}$, which yields

$$\bar{y}_i - g_{i,t} - R_{i,t} = \frac{C}{b} \qquad \Longleftrightarrow \qquad g_{i,t} = \bar{y}_i - R_{i,t} - \frac{C}{b}, \tag{13}$$

$$R_{i,t+1} = \frac{\delta C}{K} \qquad \Longleftrightarrow \qquad r_{i,t} = \frac{\delta C}{K} - q_R R_{i,t}, \tag{14}$$

$$A_{i,t+1} = \frac{\gamma \delta}{S} \qquad \Longleftrightarrow \qquad a_{i,t} = \frac{\delta \gamma}{S} - q_A A_{i,t}. \tag{15}$$

The terms $\bar{y}_i - g_{i,t} - R_{i,t}$ in (13) capture the energy gap between the satiation point and the energy consumption in BAU. The larger the social costs of carbon C and the smaller the energy preference parameter b the larger is the energy gap. According to (14), countries invest more in capacity, $r_{i,t}$, the higher the social costs of carbon C and the cheaper the accumulation of capacity reflected by the effective capacity cost parameter K. Similarly, the countries' technology investments, $a_{i,t}$, are positively correlated to the mitigation parameter, γ, and negatively to the effective R&D cost parameter S. In BAU the countries' technology stock is (7) and they behave non-cooperatively ignoring the positive spillover effects of their technology on other countries. Due to the value function's linearity in available technology $\tilde{A}_{i,t}$, both investments $a_{i,t}$ and the technology $A_{i,t+1}$ (see (15)) of non-cooperative acting countries do not depend on the spillover parameter β.[12,13]

To evaluate the non-cooperative emissions and investments, we determine the first-best allocation, which coincides with the fully cooperative solution. By maximizing $\sum_{i \in N} v_{i,t}$ with respect to $g_{i,t}$, $R_{i,t+1}$, and $A_{i,t+1}$ we get

$$\bar{y}_i - g_{i,t} - R_{i,t} = \frac{nC}{b} \qquad \Longleftrightarrow \qquad g_{i,t} = \bar{y}_i - R_{i,t} - \frac{nC}{b}, \tag{16}$$

$$R_{i,t+1} = \frac{n\delta C}{K} \qquad \Longleftrightarrow \qquad r_{i,t} = \frac{n\delta C}{K} - q_R R_{i,t}, \tag{17}$$

$$A_{i,t+1} = [1 + (n-1)\mu] \frac{\gamma \delta}{S} \qquad \Longleftrightarrow \qquad a_{i,t} = [1 + (n-1)\mu] \frac{\delta \gamma}{S} - q_A A_{i,t}. \tag{18}$$

Comparing the BAU allocation (13)-(15) with the first-best allocation (16)-(18) reveals that BAU emissions $g_{i,t}$ are inefficiently large, and both capacity investments $r_{i,t}$ and R&D investments $a_{i,t}$ are inefficiently low. The inefficiencies in BAU are caused by negative climate damage externalities and positive technology spillover externalities. In first best, all technology spillover externalities are internalized, because countries cooperatively choose $A_{i,t+1}$ and thus take into account the positive

[12] The same holds for investments and technologies of fringe countries in the complete and incomplete contracts of the following sections. Recall from footnote 7 that we confine ourselves to a linear-quadratic model for the sake of tractability.

[13] The spillover parameter μ also does not emerge in (7), because there is neither a coalition nor an agreement.

spillover effects of their technology, formally reflected by $(n-1)\mu\frac{\gamma\delta}{S}$ in (18), on other countries.[14] In BAU the non-internalized climate damage externalities result in inefficiently high emissions and inefficiently low capacity investments, whereas the inefficiently low R&D investments are driven by the non-internalized technology spillover externalities.

3 Complete contracts

3.1 Timing

In this section we turn to the formation of a coalition when contracts are complete. Coalition countries agree over emissions, investments in capacity and R&D. If there is no coalition at the beginning of a period, countries independently and simultaneously decide whether to join the coalition or not (*coalition formation stage*). Subsequently, the coalition decides on the duration of the agreement T and then coalition members cooperatively set their emissions levels and investments $(g_{i,t}, r_{i,t}, a_{i,t})$ for $i \in M$ and $t \in \{1, ..., T\}$ (*negotiation stage*). During the agreement, fringe country $i \in L = N \backslash M$ independently and simultaneously sets $(g_{i,t}, r_{i,t}, a_{i,t})$ at the beginning of each period, whereas the coalition follows its strategy determined by $(g_{i,t}, r_{i,t}, a_{i,t})$ for all $i \in M$ (*emission and investment stage*). Following a large literature on IEAs, we assume that coalition countries comply with the contract, i.e. that they pollute and invest as agreed in the contract. In case of the Kyoto Protocol, the Conference of Parties to the Convention adopted a decision on the compliance regime (UNFCCC 2001). It comprises procedures and mechanisms relating to compliance.[15] The coalition formation stage and the negotiation stage are omitted if a coalition already exists at the beginning of a period. The timing is illustrated in Figure 1.[16]

The game is solved by backward induction. We first analyze the emission and investment stage, then we study the negotiation stage before we turn to the coalition formation stage.

3.2 Emissions, investments and optimal contract length

In this subsection, we suppose that a coalition with size m exists. At the emission and investment stage, non-signatories still act as non-cooperative players, and they emit and invest according to (13) - (15). At the negotiation stage, the coalition commits to cooperative emissions and investments such that the coalition now behaves as a single player whose payoff is the coalition countries

[14] The spillover parameter β is absent in (18), because full cooperation encompasses all countries, and there are no remaining fringe countries. The countries technology stock is given by (6) with $M = N$ and $L = \emptyset$.

[15] In McEvoy et al. (2011) and Cherry and McEvoy (2013) coalition members may violate their commitments. It is shown that a member-financed third-party enforcer and a deposit-refund system, respectively, which foster compliance may lead to larger stable and more effective coalitions.

[16] Figure 1 illustrates the timing within one period but not for the complete contract duration T. However, the timing is the same for all periods. For the deviation with respect to the timing of Battaglini and Harstad (2016) see footnote 9.

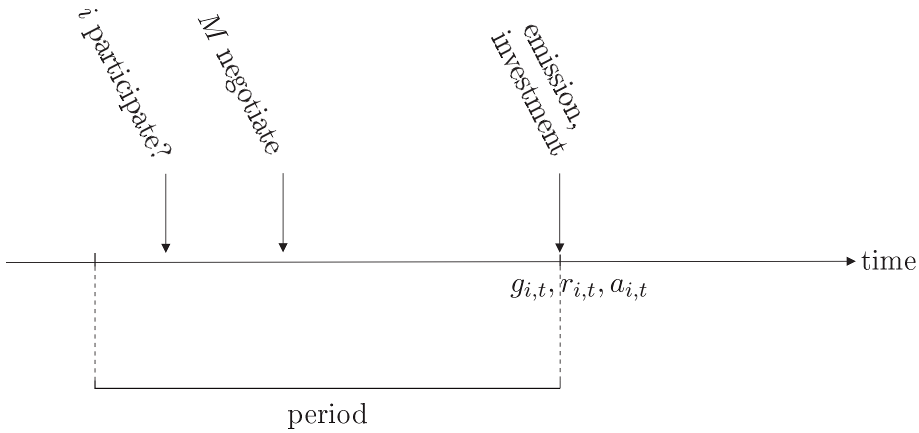

Figure 1: Timing of the game

aggregate value function $\sum_{j \in M} v_{j,t}$ and who plays non-cooperatively against all non-signatories $i \in L$. By maximizing $\sum_{j \in M} v_{j,t}$ with respect to $g_{i,t}$, $R_{i,t+1}$, and $A_{i,t+1}$ we obtain

$$\bar{y}_i - g_{i,t} - R_{i,t} = \frac{mC}{b} \qquad \Longleftrightarrow \qquad g_{i,t} = \bar{y}_i - R_{i,t} - \frac{mC}{b}, \tag{19}$$

$$R_{i,t+1} = \frac{m\delta C}{K} \qquad \Longleftrightarrow \qquad r_{i,t} = \frac{m\delta C}{K} - q_R R_{i,t}, \tag{20}$$

$$A_{i,t+1} = [1 + (m-1)\mu] \frac{\gamma\delta}{S} \qquad \Longleftrightarrow \qquad a_{i,t} = [1 + (m-1)\mu] \frac{\delta\gamma}{S} - q_A A_{i,t}. \tag{21}$$

Coalition countries internalize the climate damage externalities and technology spillover externalities within the coalition but leave climate damage externalities and technology spillover externalities outside the coalition non-internalized. More precisely, in a coalition of size m, a coalition country accounts for the positive technology spillover effects, formally captured by $(m-1)\mu\frac{\gamma\delta}{S}$ in (21), on the other $(m-1)$ coalition countries, but ignores the positive technology spillover effects on fringe countries (see (6)).[17] The coalition's emissions are lower than BAU emissions but still inefficiently high. Both the coalition countries' capacity and R&D investments are larger than BAU investments and lower than first-best investments.

Next, we investigate the optimal duration of the agreement. We refer to the size of the stable coalition as m^*. For any given coalition of size m, the optimal contract length is specified in

Lemma 1. *Suppose that the coalition members coordinate their emission policy, their R&D investments and their capacity investments (complete contract).*

(i) If $m < m^*$, the optimal contract length is $T^* = 1$.

(ii) If $m = m^*$, the optimal contract length is $T^* \in \{1, 2, ..., \infty\}$.

(iii) If $m > m^*$, the optimal contract length is $T^* = \infty$.

[17]The coalition's strategies (19)-(21) are a m-country version of the first-best solution (16)-(18) due to the linear-quadratic model.

Proof: Online-Appendix A.3

According to Lemma 1, the coalition countries conclude the contract for one period if the coalition is smaller than the stable coalition, and for all eternity if the coalition is larger than the stable one. In the more interesting case of the stable coalition, the optimal contract length does not play any role, since contracts are identical. When one contract expires it is replaced by another contract with exactly the same commitments.

3.3 Stable coalitions

In the preceding Subsection 3.2 we have presupposed that a coalition of given size m exists, and our focus has been on characterizing the coalition's emissions, investments and the optimal contract length. Since supranational authorities for the effective enforcement of agreements are not available, international environmental agreement (IEAs) will not prevail unless they are self-enforcing.[18] An IEA is self-enforcing and a climate coalition is stable, respectively, if no fringe country has an incentive to sign the agreement (external stability) and no coalition country has an incentive to defect (internal stability). If an IEA with m^* signatories is stable, the accession of one fringe country implies $T^* = \infty$, while the defection of one coalition country implies $T^* = 1$ and the establishment of the stable coalition in the following period. In Online-Appendix A.4 we analyze the external and internal stability conditions of D'Aspremont et al. (1983) and prove

Proposition 1. *Suppose contracts are complete.*

(i) If $\Gamma - \left(\frac{1}{2}\mu - \beta\right)\mu < 0$, *the grand coalition* $m^* = n$ *is stable.*

(ii) If $\Gamma - \left(\frac{1}{2}\mu - \beta\right)\mu > 0$, *then* $m^* \in \left[\mathcal{MI}^C(b,z) - 1, \min\left\{\mathcal{MI}^C(b,z), n\right\}\right]$ *with*

$$\mathcal{MI}^C(b,z) = 1 + \frac{2\Gamma + (\mu - \beta(1-\mu))}{\Gamma - \left(\frac{1}{2}\mu - \beta\right)\mu}, \tag{22}$$

and $\Gamma := \left(\frac{b\delta^2 + K}{b\delta^2}\right)\frac{SC^2}{2\gamma^2 K} > 0$ *and* $z := (\mu, \beta, \delta, \gamma, C, K, S)$.

In (22), the function $\mathcal{MI}^C(b,z)$ represents the *internal stability function.* Proposition 1 provides the information that the stable coalition is either the grand coalition n or $\mathcal{MI}^C$.[19] When joining the coalition a country faces opposing effects with respect to technology. These are measured by the absolute spillover advantage $\mu - \beta(1-\mu) > 0$ and the relative spillover advantage $\left(\frac{1}{2}\mu - \beta\right)\mu$. The former term indicates that higher technology spillovers for coalition countries ($\mu > \beta$) increase the incentive to join the coalition. The latter term reflects that a coalition country not only receives

[18] The concept of stability or self-enforcement traces back to D'Aspremont et al. (1983). The first applications of this concept to the formation of IEAs can be found in Hoel (1992), Carraro and Siniscalco (1993), and Barrett (1994).

[19] Strictly speaking, the largest integer that is weakly smaller than $\mathcal{MI}^C$.

higher technology spillovers but also bears technology investments above the BAU level. It weights the higher technology spillovers relative to the technology costs.

If the relative spillover advantage is sufficiently high $\left(\Gamma - \left(\frac{1}{2}\mu - \beta\right)\mu < 0\right)$, it outweighs all free-riding incentives and Γ, so that it is beneficial for all countries to join the coalition. Consequently, the grand coalition is the only stable one. If technology spillovers inside the coalition are the same as those for fringe countries ($\mu = \beta$), the spillover terms are of opposite sign but of equal strength, so that they cancel out and it holds $\mathcal{MI}^C(b,z) = 3$. Consequently, the stable coalition has at most $m^* = 3$ signatories, which reproduces Battaglini and Harstad (2016)'s dismal result of complete contracts.

Finally, consider a relative spillover advantage of medium strength $\left(\Gamma - \left(\frac{1}{2}\mu - \beta\right)\ \mu > 0\right)$. In that case, both technology spillover terms positively affect the coalition formation. More specifically, the internal stability function $\mathcal{MI}^C(b,z)$ exceeds 3. Closer inspection of (22) reveals that $\mathcal{MI}^C(b,z)$ increases with the spillovers for coalition countries μ and decreases with the spillovers for fringe countries β such that the stable coalition is the larger the larger μ and the smaller β. The difference between μ and β captures the coalition country's advantage of technology spillovers relative to fringe countries. Increases in μ or decreases in β lead to a gain of both coalition and fringe countries' values, but the value gain of coalition countries is larger than the value gain of fringe countries. To put it differently, increases in μ reduce the free-riding incentives of fringe countries and, thus, promote larger stable coalitions. In particular, the grand coalition may be stable if $\mathcal{MI}^C(b,z) \geq n-1$.

Which of the conditions in Proposition 1 are satisfied is an empirical question. For the sake of more specific results we resort to a numerical example that is based on an empirical calibration of the world in the year 2019. We consider the $n = 30$ largest emitters and producers of renewable energy. Their CO_2 emissions amount to more than 85 % of total CO_2 emissions and their investments in renewable capacity amount to approximately 90% of total capacity investments in renewables in 2019. In the empirical calibration that is outlined in detail in Online-Appendix A.1 the parameters satisfy

$$\begin{aligned} \zeta \quad := \quad & \Bigg(\beta = 0.1, \delta = 0.97, \gamma = 12.41 \cdot 10^9\$, C = 26.211\frac{\$}{(\text{MWh})}, \\ & K = 0.0344\frac{\$}{(\text{GWh})^2}, S = 151.24 \cdot 10^9\$\Bigg). \end{aligned}$$

Since empirical estimates for the spillover parameter μ and the energy intensity parameter b are not available, we consider the values $\mu \in [0.15, 1]$ and leave b unspecified. The associated economies are $z \in [\underline{z}, \overline{z}]$, where $\underline{z} = (\mu = 0.15, \zeta)$ and $\overline{z} = (\mu = 1, \zeta)$. In addition, we define the set of all polar and intermediate economies as $Z = \left\{z \middle| \mu \in (0.15, 1) \text{ and } (\beta, \delta, \gamma, C, K, S)\ = \zeta\right\}$. For all economies $z \in Z$ it holds $\frac{SC^2}{2\gamma^2 K} = 1.17$, $\frac{b\delta^2 + K}{b\delta^2} > 1$, $\Gamma > 1$ and hence $\Gamma - \left(\frac{1}{2}\mu - \beta\right)\mu > 0$. In Proposition 1, item (ii) is relevant. For the economies $\underline{z}$ and $\overline{z}$ the function $\mathcal{MI}^C(b,z)$ is illustrated in Figure 2.

The energy preference parameter b is varied.[20]

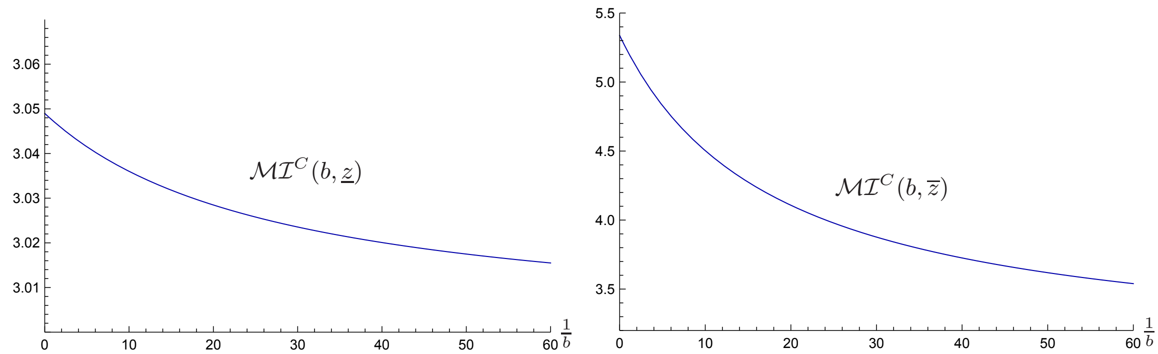

Figure 2: Stable coalitions for complete contracts in the economies $\underline{z}$ and $\overline{z}$

The left panel of Figure 2 shows that $3.05 > \mathcal{MI}^C(b, \underline{z})$ and from the right panel we infer $5.4 > \mathcal{MI}^C(b, \overline{z})$. Since both functions converge to 3 for $b \to 0$, we get in view of Proposition 1(ii)[21]

Result 1. *Suppose that the coalition members coordinate their emission policy, their R&D investments and their capacity investments (complete contract). In the economies $z \in Z$ the stable coalition consists of three, four or five countries.*

Although large stable coalitions are theoretically possible either when the relative spillover advantage is large or it is of medium strength and μ is sufficiently high, the performance of complete contracts in Result 1 is disappointing. In empirically relevant economies, the largest stable coalition of complete contracts comprises at most 5 of 30 countries.

4 Incomplete contracts

So far we have analyzed the complete contract in Section 3. In Section 4 and 5 we investigate different incomplete contracts. In Subsection 4.1 the coalition concludes a contract for emissions only, in Subsection 4.2 for emissions and capacity investments, and in Subsection 4.3 for emissions and R&D investments. Finally, in Subsection 4.4 coalition countries sign an emissions contract and a technology transfer agreement. For sake of convenience, the following Table 1 provides an overview of the contracts. Column 2 lists the variables that are chosen together in the coalition, column 3 shows the coalition country's technology stock $\tilde{A}_{i,t}$, column 4 lists the decision variables that are chosen by the coalition countries independently, and column 5 shows how the contracts are marked.

[20] To make our results comparable with Battaglini and Harstad (2016) $\frac{1}{b}$ is shown along the abscissa.

[21] In the Figures we prove the Results for the economies $\underline{z}$ and $\overline{z}$. The proof that the Results hold for all economies $z \in Z$ can be obtained from the authors upon request.

contract	decided together	coalition country's technology stock	decided independently	marked by
complete contract	g, r, R, a, A, T	(6)	–	C
incom. E-contract	g, T	(7)	r, R, a, A	E
incom. EC-contract	g, r, R, T	(7)	a, A	EC
incom. ER-contract	g, a, A, T	(6)	r, R	ER
incom. E-contract with techn. transfer	g, T	(6)	r, R, a, A	Et

Table 1: Contracts

4.1 Incomplete E-contract

At this type of contract, coalition countries negotiate on emissions $g_{i,t}$, but non-cooperatively choose investments $r_{i,t}$ and $a_{i,t}$. To avoid clumsy wording, we denote these contracts as *incomplete E-contracts.* The equilibrium of the game is determined by a stable coalition size m^*, an optimal contract length T^* and an allocation $(a_{i,t}, g_{i,t}, r_{i,t})_{t=1}^{T^*}$ for all $i \in N$. Recall that the technology spillovers within the coalition are contract-specific. In the incomplete E-contract countries neither negotiate on R&D investments nor on technology transfers and, therefore, a coalition country's technology stock is given by (7).

4.1.1 Emissions, investments and optimal contract length

Fringe countries choose non-cooperatively their emissions levels $g_{i,t}$ and investments $r_{i,t}$ and $a_{i,t}$ in every period according to (13)-(15) implying $g_{i,t} = \bar{y}_i - R_{i,t} - \frac{C}{b}$. In Online-Appendix A.5.1 we show that the coalition countries' emissions, investments in capacity and R&D are characterized by

$$
\begin{aligned}
R_{i,t} &= \frac{b\delta(\bar{y}_i - g_{i,t})}{K + b\delta} \quad \text{for } t \in \{2, ..., T\}, & (23) \\
R_{i,T+1} &= \frac{\delta C}{K}, & (24) \\
A_{i,t} &= \frac{\delta\gamma}{S} \quad \text{for } t \in \{2, ..., T+1\}, & (25) \\
g_{i,1} &= \bar{y}_i - R_{i,1} - m\frac{C}{b}, & (26) \\
g_{i,t} &= \bar{y}_i - m\delta\frac{C}{K} - m\frac{C}{b} \quad \text{for } t \in \{2, ..., T\}. & (27)
\end{aligned}
$$

In view of (23), the coalition countries' investments in capacity depend on the negotiated emissions level of the agreement. The higher the emissions level, the lower the capacity investments. At the last period of the agreement, T, the coalition country underinvests, because it does not know whether a new contract materializes in the period $T + 1$ and the capacity investments will pay off. The fact that at T the coalition country does not receive all the fruits of its capacity investments leads her to underinvest and constitutes a *hold-up problem.* According to (26) and (27), the coalition internalizes the climate damage inside the coalition. It chooses the same emissions and capacity investments as in the complete contract except for the last period of the agreement where coalition countries underinvest due to the hold-up problem. Because coalition countries non-cooperatively decide on R&D investments, they ignore the positive technological spillovers on other countries, and choose BAU R&D investments (see (25)).

For given coalition of size m the optimal duration of an agreement, T^*, is characterized by

Lemma 2. *Suppose that the coalition members only coordinate their emission policy but not their R&D investments and capacity investments (incomplete E-contract).*

(i) If $m < m^E$, the optimal contract length is $T^* = 1$.

(ii) If $m = m^E$, the optimal contract length is $T^* \in \{1, 2, ..., \infty\}$.

(iii) If $m > m^E$, the optimal contract length is $T^* = \infty$,

with

$$m^E = 1 + \sqrt{(m^* - 1)^2 \Delta} < m^* \quad \textit{and} \quad \Delta := \frac{b\delta^2 + K}{b\delta + K}.$$

Proof: Online-Appendix A.5.2

Lemma 2 is similar albeit not identical to Lemma 1. There exists a threshold m^E at which the coalition M is indifferent between all contract lengths. In case of Lemma 2(i), the duration of the agreement is exactly one period, whereas in Lemma 2(iii) it lasts forever. Since $m^* > m^E$, the optimal contract length for the stable coalition is infinity. The threshold in Lemma 2 is smaller than in Lemma 1 due to the hold-up problem, which causes an additional costs of signing a short-term agreement.

To prepare the analysis of the stable coalition we introduce the discipline constraint. If a participating country leaves the coalition, the remaining coalition countries sign a short-term agreement ($T = 1$) only if $m^* - 1 < m^E$ which is equivalent to

$$m^* < \mathcal{MD}^E(b, z) = 1 + \frac{1}{1 - \sqrt{\Delta}}. \tag{28}$$

(28) is referred to as *discipline constraint.* If it is satisfied, the hold-up problem comes fully to bear and is a credible threat to sign a short-term contract if one coalition country defects. If it is violated, the remaining coalition countries sign a long-term agreement ($T = \infty$) and the hold-up problem disappears.

4.1.2 Stable coalition

The size of the stable coalition depends on whether the discipline constraint is violated or not. The following proposition provides more specific information about the stable coalition

Proposition 2. *Suppose that the coalition members only coordinate their emissions policy, but not their R&D investments and capacity investments (incomplete E-contract).*

(i) If $m^* \geq \mathcal{MD}^E(b,z)$*, then* $m^* \in [2,3]$.

(ii) If $m^* < \mathcal{MD}^E(b,z)$ *and*

(a) $\frac{1}{b} < \frac{\delta^2}{K}$*, then* $m^* \in \left[2, \min\left\{\mathcal{MD}^E(b,z), n\right\}\right]$*;*

(b) $\frac{1}{b} > \frac{\delta^2}{K}$*, then* $m^* \in \left[2, \min\left\{\mathcal{MI}^E(b,z), \mathcal{MD}^E(b,z), n\right\}\right]$

with

$$\mathcal{MI}^E(b,z) = 3 + \frac{2b\delta^2}{K - b\delta^2}.$$

Proof: Online-Appendix A.5.3

Proposition 2 is identical to Battaglini and Harstad (2016)'s Proposition 8, i.e. the incomplete E-contract does not change when introducing R&D investments and technology spillovers. If the discipline constraint is violated, according to Proposition 2, the largest stable coalition is $m^* = 3$. If the discipline constraint is satisfied, larger stable coalitions are possible. In that case, the remaining countries of a climate coalition will sign a short-term contract of only one period if one coalition member defects. The hold-up problem, i.e. the low capacity investments, immediately emerges. The remaining coalition countries credibly threat every defecting country to substantially reduce their capacity investments, which in turn would increase emissions and, therefore, mitigates free-riding incentives.

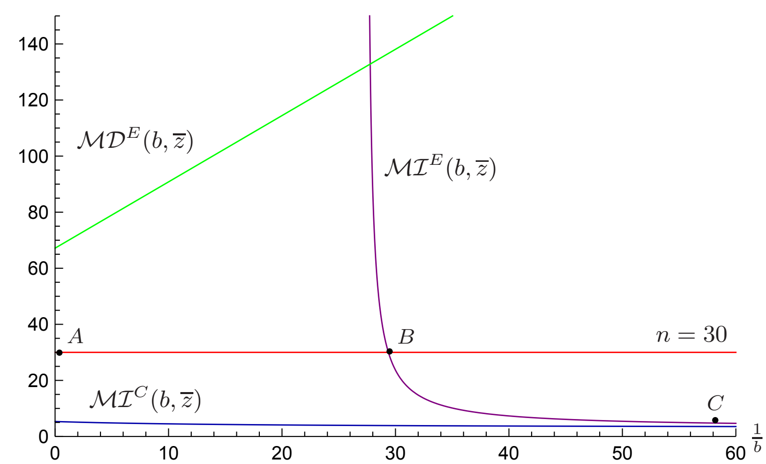

Figure 3: Stable coalitions in the economy $\overline{z}$ for incomplete E-contracts

For the economy $\overline{z}$ the curves $\mathcal{MI}^E$, $\mathcal{MD}^E$ and n are plotted in Figure 3 in dependence of the energy preference parameter $1/b$. Recall that $\mathcal{MI}^E(b,z)$ reflects the internal stability function and $\mathcal{MD}^E(b,z)$ the discipline constraint. Ignore for a moment the $\mathcal{MI}^C$-curve of the complete contract. Since the $\mathcal{MD}^E$-curve lies above the $n = 30$-line, the discipline constraint is satisfied, and item (ii) of Proposition 2 is relevant. For high energy preference parameter b ($1/b < 27.35$), we have $\min\{\mathcal{MI}^E, \mathcal{MD}^E, n\} = n$ and the grand coalition is stable. For low energy preference parameter b ($1/b > 27.36$) it holds $\min\{\mathcal{MI}^E, \mathcal{MD}^E, n\} = \mathcal{MI}^E$ and the stable coalition is characterized by the $\mathcal{MI}^E$-curve. In Figure 3 the stable coalition size moves from A to B on the $n = 30$-line and from B to C on the $\mathcal{MI}^E$-curve.

Finally, we compare the incomplete E-contract with the complete contract. Recall that the stable coalition of the complete contract is characterized by the $\mathcal{MI}^C$-curve in Figure 3. Since $\mathcal{MI}^C < n$ and $\mathcal{MI}^C < \mathcal{MI}^E$, we get

Result 2. *In the economies $z \in Z$ the stable coalition of the incomplete E-contract is (weakly) larger than the stable coalition of the complete contract.*

4.2 Incomplete EC-contract

The next contract we briefly consider is the incomplete *EC-contracts*, in which the coalition countries negotiate on emission levels $g_{i,t}$ and capacity investments $r_{i,t}$. As shown in Online-Appendix A.6.1, the investments and emissions levels of coalition countries are given by

$$R_{i,t} = m\delta\frac{C}{K} \qquad \text{for } t \in \{2, ..., T+1\} \tag{29}$$

$$A_{i,t} = \frac{\delta\gamma}{S} \qquad \text{for } t \in \{2, ..., T+1\}, \tag{30}$$

$$g_{i,1} = \bar{y}_i - R_{i,1} - m\frac{C}{b}, \tag{31}$$

$$g_{i,t} = \bar{y}_i - m\delta\frac{C}{K} - m\frac{C}{b} \quad \text{for } t \in \{2, ..., T\}. \tag{32}$$

In case of incomplete EC-contracts, coalition countries cooperatively choose capacity investments with the consequence that the hold-up problem disappears. Moreover, coalition countries non-cooperatively choose R&D investments.[22] When doing so they ignore the positive technology spillover effects of their R&D investments on other countries and underinvest in R&D. According to Online-Appendix A.6.2, the optimal contract length is as in Lemma 1. For the stable coalition we find

Proposition 3. *Suppose that the coalition members only coordinate their emissions policy and their capacity investments, but not their R&D investments. Then the stable coalition consists of maximal three countries.*

Proof: Online-Appendix A.6.3

[22]In the incomplete EC-contract, the coalition countries' technology stock is (7) and there are no additional technology spillovers within the coalition.

The EC-contract is the worst contract. The missing hold-up problem and missing technology spillovers within the coalition make the EC-contract unattractive such that the stable coalition is very small. Due to the poor performance of the incomplete EC-contract, it is ignored in future comparisons.

4.3 Incomplete ER-contract

Next, we assume that coalition members jointly choose their emission levels $g_{i,t}$ and their R&D investments $a_{i,t}$ but set their capacity investments $r_{i,t}$ non-cooperatively. These contracts are denoted as *incomplete ER-contracts.*

4.3.1 Emissions, investments and optimal contract length

As shown in Online-Appendix A.7.1, the coalition countries' investments in capacity and R&D in incomplete ER-contracts are given by

$$R_{i,t} = \frac{(\bar{y}_i - g_{i,t})b\delta}{b\delta + K} \qquad \text{for } t \in \{2, ..., T\}, \tag{33}$$

$$R_{i,T+1} = \delta \frac{C}{K}, \tag{34}$$

$$A_{i,t} = \frac{\delta\gamma}{S}\left[1 + \mu(m-1)\right] \quad \text{for } t \in \{2, ..., T+1\} \tag{35}$$

and the associated emissions levels are

$$g_{i,1} = \bar{y}_i - R_{i,1} - m\frac{C}{b}, \tag{36}$$

$$g_{i,t} = \bar{y}_i - m\delta\frac{C}{K} - m\frac{C}{b} \quad \text{for } t \in \{2, ..., T\}. \tag{37}$$

As in case of incomplete E-contracts, coalition countries internalize the climate externality within the coalition when choosing investments in capacity and emissions except for the last period of the agreement at which they underinvest in capacity due to the hold-up problem discussed in Subsection 4.1 (see (33) and (34)). Since coalition countries also negotiate over R&D investments, they internalize the technological spillovers within the coalition. Consequently, they step-up their R&D investments relative to BAU R&D investments (compare (15) and (35)). When signing an incomplete ER-contract coalition countries do not only internalize the climate externalities but also technological spillover externalities within the coalition.

The optimal duration of the incomplete ER-contract is specified in

Lemma 3. *Suppose that the coalition members coordinate their emission policy and their R&D investments but not their capacity investments (incomplete ER-contract).*

(i) If $m < m^{ER}$, the optimal contract length is $T^* = 1$.

(ii) If $m = m^{ER}$, the optimal contract length is $T^* \in \{1, 2, ..., \infty\}$.

(iii) If $m > m^{ER}$, the optimal contract length is $T^* = \infty$

with

$$m^{ER} = 1 - \frac{\Pi}{2} + \left[\frac{\Pi^2}{4} + \Theta(m^* - 1)^2 + \Pi(m^* - 1)\right]^{0.5} < m^*, \tag{38}$$

$$\Theta = \frac{\left(\frac{K+b\delta^2}{b\delta}\right)\frac{SC^2}{\gamma^2 K} + \delta\mu^2}{\left(\frac{K+b\delta}{b\delta}\right)\frac{SC^2}{\gamma^2 K} + \delta\mu^2} \in (0,1) \text{ and } \Pi = \frac{2\delta(\mu - \beta)}{\left(\frac{K+b\delta}{b\delta}\right)\frac{SC^2}{\gamma^2 K} + \delta\mu^2} \geq 0.$$

Proof: Online-Appendix A.7.2

As in E-contracts, in incomplete ER-contracts there is an additional cost of signing a short-term agreement which now depends also on the technology spillovers μ and β. The discipline constraint turns into

$$m^* < \mathcal{MD}^{ER}(b,z) = 1 + \frac{1 - \Pi}{1 - \sqrt{\Theta + \Pi(1 - \Theta)}} \tag{39}$$

and the stable coalition is characterized by

Proposition 4. *Suppose that the coalition members coordinate their emissions policy and their R&D investments but not their capacity investments (incomplete ER-contract).*

(i) If $\Gamma - \mu\left(\frac{\mu}{2} - \beta\right) < 0$, the grand coalition $m^* = n$ is stable.

(ii) If $\Gamma - \mu\left(\frac{\mu}{2} - \beta\right) > 0$ and

(a) $m^* \geq \mathcal{MD}^{ER}(b,z)$, then $m^* \in \left[\mathcal{MI}^C(b,z) - 1, \mathcal{MI}^C(b,z)\right]$.

(b) $m^* < \mathcal{MD}^{ER}(b,z)$ and $\frac{1}{b} < \frac{\delta^2}{K} + \mu(\mu - 2\beta)\frac{\delta^2\gamma^2}{SC^2}$, then $m^* \in \left[\mathcal{MI}^C(b,z) - 1, \min\left\{\mathcal{MD}^{ER}(b,z), n\right\}\right]$.

(c) $m^* < \mathcal{MD}^{ER}(b,z)$ and $\frac{1}{b} > \frac{\delta^2}{K} + \mu(\mu - 2\beta)\frac{\delta^2\gamma^2}{SC^2}$, then $m^* \in \left[\mathcal{MI}^C(b,z) - 1, \min\left\{\mathcal{MI}^{ER}, \mathcal{MD}^{ER}(b,z), n\right\}\right]$

with

$$\mathcal{MI}^{ER}(b,z) = 3 + 2\frac{\delta + \frac{\delta\gamma^2 K}{SC^2}(1+\mu)(\mu - \beta)}{\frac{K}{b\delta} - \delta - \frac{\delta\gamma^2 K}{SC^2}\mu(\mu - 2\beta)}.$$

Proof: Online-Appendix A.7.3

Consider Proposition 4(i). If the research spillover within the coalition is sufficiently large, the relative spillover advantage $\left(\frac{\mu}{2} - \beta\right)\mu$ outweighs Γ and, therefore, all free-riding incentives. Consequently, the grand coalition is established. Otherwise, the coalition size depends on whether the discipline constraint (39) is violated or not. If it is violated [item (iia)] and one coalition country defects, the remaining coalition countries sign a long-term contract ($T = \infty$), so that the hold-up problem vanishes and there is no capacity underinvestment. In contrast to the incomplete E-contact but in accordance with the complete contract, coalition countries in the ER-contract cooperate over R&D investments. Therefore, the stable coalition of the incomplete ER-contract coincides with the stable coalition of the complete contract.

If the discipline constraint (39) is satisfied, coalition countries credibly threaten to sign a short-term agreement when one country defects, and thus there is a hold-up problem. Proposition 4(iib) and 4(iic) reveal that the lower bound of the stable coalition coincides with the lower bound of the complete contract. Hence, also for $m^* < \mathcal{MD}^{ER}$ the stable coalition of incomplete ER-contracts is at least as large as the stable coalition of complete contracts. The upper bound of the stable coalition in Proposition 4(iib) depends on the interplay of the discipline constraint $\mathcal{MD}^{ER}$, the interior stability function $\mathcal{MI}^{ER}$ and the n-function. Proposition 4(iib) and 4(iic) are similar to Proposition 2(ii) with the qualification that the $\mathcal{MD}^{ER}$- and $\mathcal{MI}^{ER}$-constraints now depend on the technology spillovers μ and β. In the following, we are interested in how the stable coalition is affected by changes in the technology parameter μ if $m^* < \mathcal{MD}^{ER}$. Since the function $\mathcal{MD}^{ER}$ from (39) is too complex to provide analytical results, we resort to the economy $\overline{z}$ of Subsection 4.1 that is illustrated in Figure 4. For the sake of reference, we plot the stable coalition of incomplete E-contracts that lies on the polyline ABC. In case of the incomplete ER-contract, the $\mathcal{MI}^{E}$-curve

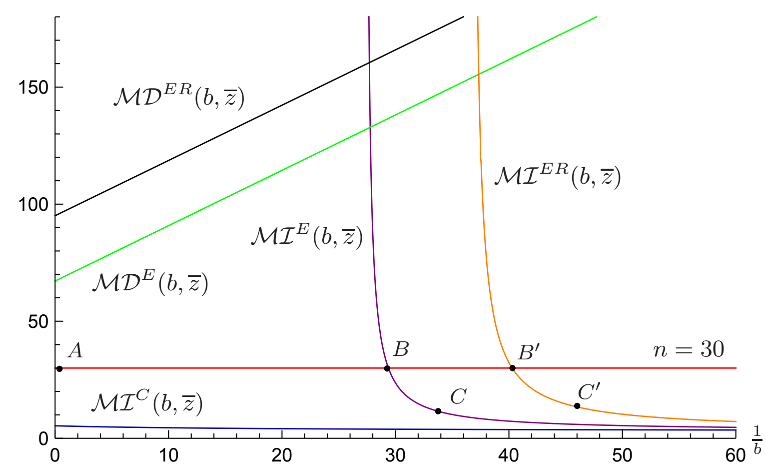

Figure 4: Stable coalitions in the economy $\overline{z}$ for incomplete E-contracts and ER-contracts

moves to the right and turns into the $\mathcal{MI}^{ER}$-curve while the $\mathcal{MD}^{E}$-curve shifts upwards and turns into the $\mathcal{MD}^{ER}$-curve. Because the interior stability constraint is relaxed, the stable coalition lies on the polyline $AB'C'$ and is larger than or equal to the stable coalition of the incomplete E-contract.

The $\mathcal{MI}^{ER}$-function (see Proposition 4 (iib) depends on absolute and relative spillover advantages. While the absolute spillover advantage $(1+\mu)(\mu-\beta) > 0$ increases the coalition size, the effect of the relative spillover advantage $\mu\left(\frac{1}{2}\mu-\beta\right)$ depends on the relation of the spillover parameter μ and β. If μ is sufficiently high, as in case of Figure 4, the higher R&D investments inside a coalition always cause higher benefits for coalition members than for fringe countries.[23] In the economy $\overline{z}$, switching from the E-contract to the ER-contract either increases or leaves unchanged the size of the stable coalition.

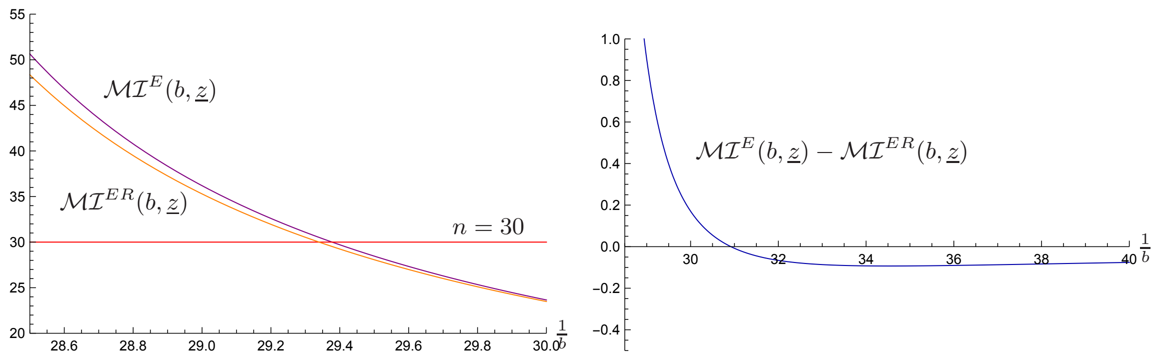

Figure 5: Stable coalitions in the economy $\underline{z}$ for incomplete E-contracts and ER-contracts

Next, we turn to the economy $\underline{z}$ in which the spillover parameter μ is low. The left and right panel of Figure 5 show that $\mathcal{MI}^E(b,\underline{z}) \gtreqless \mathcal{MI}^{ER}(b,\underline{z})$ if and only if $\frac{1}{b} \lesseqgtr 30.92$. I.e. for high energy preference parameter b $\left(\frac{1}{b} < 30.92\right)$ the stable coalition of the incomplete E-contract is weakly larger than the stable coalition of the incomplete ER-contract and for low energy preference parameter b $\left(\frac{1}{b} > 30.92\right)$ the result is reversed. Closer inspection of the economies $z \in Z$ leads to

Result 3. *Compare the incomplete ER-contract with the complete contract and the incomplete E-contract, and consider the economies $z \in Z$.*

(i) The stable coalition of the incomplete ER-contract is (weakly) larger than the stable coalition of the complete contract.

(ii) If $\mu > 0.2$, the stable coalition of the incomplete ER-contract is (weakly) larger than the stable coalition of the incomplete E-contract.

4.4 Incomplete Et-contract

Finally, in this subsection we assume that coalition countries sign an incomplete E-contract that is augmented by a technology transfer agreement. The associated contract is referred to as Et-contract. In the Et-contract, coalition countries cooperate over their emissions policy and commit to transfer technologies to other coalition countries. Thus, the coalition countries' technology stock

[23] However, for low μ the relative spillover advantage is negative implying that the benefits of fringe countries outweigh the benefits of coalition members.

is given by (6) and coalition countries benefit from larger technological spillovers compared to non-signatories.

In case of incomplete Et-contracts, fringe countries' emissions and investments are given by (13)-(15) and the coalition countries' emissions and investments by (23)-(27).[24] The optimal contract length is as in Lemma 2 with qualification that m^E now turns into

$$m^{Et} = 1 - \frac{\Lambda}{2} + \sqrt{\frac{\Lambda^2}{4} + \Delta(m^* - 1)^2 + \Lambda(m^* - 1)} < m^*,$$

with $\Lambda := \frac{(\mu-\beta)b\delta^2}{2(K+b\delta)}\frac{SC^2}{\gamma^2 K}$ and $\Delta := \frac{K+b\delta^2}{K+b\delta}$.[25] The stable coalition is characterized in

Proposition 5. *Suppose that the coalition members only coordinate their emissions policy, but not their R&D and capacity investments, and transfer technology (incomplete Et-contract).*

(i) If $m^* \geq \mathcal{MD}^{Et}(b,z)$*, then* $m^* \in \left[2 + \frac{\mu-\beta}{\Gamma}, 3 + \frac{\mu-\beta}{\Gamma}\right]$.

(ii) If $m^* < \mathcal{MD}^{Et}(b,c)$ *and*

- *(a)* $\frac{1}{b} < \frac{\delta^2}{K}$*, then* $m^* \in \left[2 + \frac{\mu-\beta}{\Gamma}, \min\left\{\mathcal{MD}^{Et}(b,c), n\right\}\right]$;
- *(b)* $\frac{1}{b} > \frac{\delta^2}{K}$*, then* $m^* \in \left[2 + \frac{\mu-\beta}{\Gamma}, \min\left\{\mathcal{MI}^{Et}(b,c), \mathcal{MD}^{Et}(b,c), n\right\}\right]$

with

$$\mathcal{MD}^{Et}(b,c) = 1 + \frac{1-\Lambda}{1-\sqrt{\Delta + \Lambda(1-\Delta)}}, \quad \mathcal{MI}^{Et}(b,c) = 3 + \frac{2b\delta^2}{K - b\delta^2}\left(1 + (\mu-\beta)\frac{\gamma^2 K}{SC^2}\right).$$

Proof: Online-Appendix A.5.3

Proposition 5 contains the incomplete E-contract as special case and coincides with Proposition 2 for $\mu = \beta$. Technological transfers within the coalition $\mu > \beta$ relax the discipline constraint and the interior stability constraint. Both $\mathcal{MD}^{Et}$ and $\mathcal{MI}^{Et}$ are increasing in μ. Proposition 5 makes a case distinction in the the same way as Proposition 2 and 4 between a satisfied and a violated discipline constraint. The interpretation of Proposition 5 is analogous to the interpretation of Proposition 2 with the difference that the constraints are now relaxed through technology spillovers within the coalition such that technology transfers enlarge the stable coalition compared to the incomplete E-contract.

The case of a satisfied discipline constraint, tackled in Proposition 5(ii), is illustrated for the economies $\overline{z}$ and $\underline{z}$ in Figure 6. In both economies $\overline{z}$ and $\underline{z}$ the size of the stable coalition of the incomplete Et-contract has increased in comparison to the incomplete E-contract (due to $\mathcal{MI}^{Et} > \mathcal{MI}^{E}$ in Figure 6). Comparing incomplete Et-contracts with incomplete ER-contracts, in the left panel of Figure 6 it holds $\mathcal{MI}^{Et} > \mathcal{MI}^{ER}$, whereas in the right panel of Figure 6 it

[24] See Online-Appendix A.5.1.
[25] See Online-Appendix A.5.2.

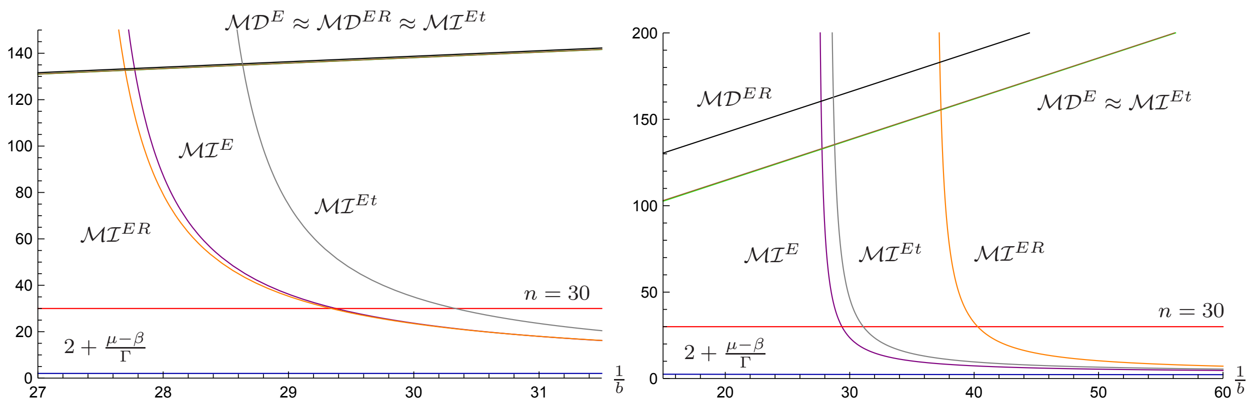

Figure 6: Stable coalitions in the economy $\underline{z}$ (left panel) and $\overline{z}$ (right panel)

holds $\mathcal{MI}^{Et} < \mathcal{MI}^{ER}$. Hence, for low [large] spillovers μ the incomplete Et-contract leads to larger [smaller] stable coalitions than the incomplete ER-contract. We summarize the results provided in Figure 6 in

Result 4. *Compare the incomplete Et-contract, the incomplete E-contract and the incomplete ER-contract, and consider the economies $z \in Z$.*

(i) The stable coalition of the incomplete Et-contract is (weakly) larger than the stable coalition of the incomplete E-contract.

(ii) In the economy $\overline{z}$ [$\underline{z}$] the stable coalition of the incomplete ER-contract is (weakly) larger [smaller] than the stable coalition of the incomplete Et-contract.

A final remark relates to the spillover parameter μ. So far, we have assumed that μ is an exogenous parameter. Endogenizing μ and treating it as the coalition's decision variable in the complete contract, the incomplete ER-contract and the incomplete Et-contract, the coalition would choose $\mu = 1$, because the value function $v_{i,t}$ from (11) is increasing in μ. Recall that $\mu = 1$ holds in the economy $\overline{z}$. In that economy (see Result 1 - 4) the stable coalitions of the contracts are ranked according to

$$m^{*ER} \geq m^{*Et} \geq m^{*E} \geq m^{*C} \geq m^{*EC}.$$

5 Welfare comparison of contracts

In this section we briefly turn to a welfare comparison of contracts in the economy $\overline{z}$. Figure 7 illustrates the aggregate welfare levels V in the different incomplete contracts.[26] For sake of reference we have also plotted the first-best welfare V^{FB}. Figure 7 reveals that the incomplete ER-contracts yields the largest welfare levels, whereas the complete contract performs worst of

[26]For the exact definition of V we refer to Online-Appendix A.8.

all. It is interesting to observe that the incomplete ER-contract is even first best on the line AB. In the midfield are the incomplete E-contract and the incomplete Et-contract. For high energy preference intensities (low $1/b$), both contracts yield approximately the same welfare. For medium energy preference intensities (medium $1/b$) the incomplete Et-contract is pareto-superior to the incomplete E-contract. We summarize these insights in

Result 5. *Comparing complete contract, the incomplete Et-contract, the incomplete E-contract, the incomplete ER-contract and the first best in the economy $\overline{z}$ yields the welfare ranking*

$$V^{FB} \geq V^{ER} \geq V^{Et} \geq V^{E} \geq V^{C}.$$

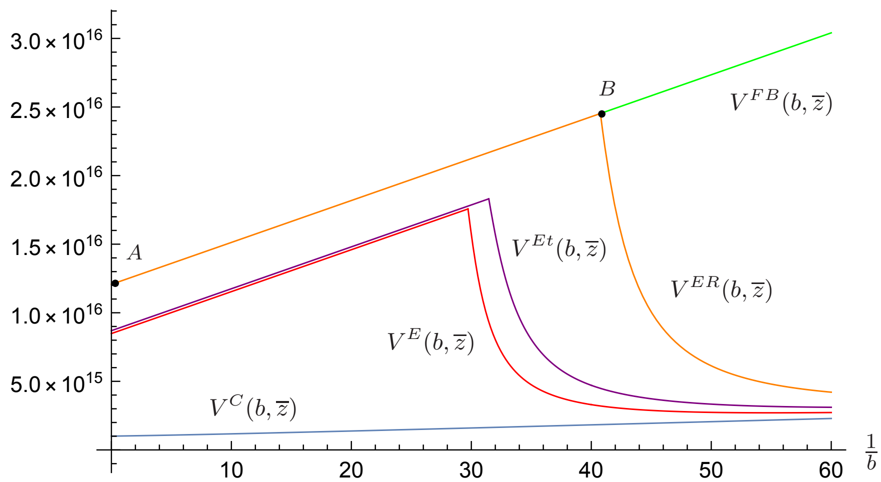

Figure 7: Welfare comparison in the economy $\overline{z}$

It is worth mentioning that the incomplete ER-contract is the only incomplete contract in which the coalition countries internalize technology spillovers within the coalition. In addition, in the incomplete ER-contract the hold-up problem creates a credible threat to restrain countries from leaving the coalition. Both mechanisms mitigate free-riding incentives and stabilize large coalitions. If the grand coalition ist stable, the incomplete ER-contract is first best.

6 Conclusion

We analyzed the formation of self-enforcing climate agreements, or stable climate coalitions, in a dynamic game for different contract types. To identify the components of climate contracts which lead to large stable coalitions, we distinguish between investments into a renewable energy generation capacity and R&D investments. Depending on the specific contract, technology spillovers are larger inside than outside the coalition. These spillovers influence the advantages of coalition membership if pooling of R&D investments is part of the coalition contract. In addition, the hold-up problem discovered by Battaglini and Harstad (2016) may stabilize large coalitions.

In the calibrated economy, the incomplete ER-contract, in which the coalition countries coordinate emissions and R&D investments, outperforms all other contracts with regard to the stable coalition and welfare. The driving forces for the good performance of the incomplete ER-contract are the technological spillover externalities that are internalized in the contract, and the hold-up problem. Our recommendation for governments as decision makers in international climate negotiations is to cooperate over emissions and R&D investments, but not over investments in renewable energy capacity.

The model of the present paper is very stylized. It is needless to say that while the assumption of homogeneous and symmetric countries is crucial for deriving meaningful analytical results,[27] it abstracts from many real-world complexities which are severe barriers to reaching stable climate agreements, and it therefore likely underestimates the difficulties of forming such agreements. Turning to the specific model of the present paper some caveats need to be reemphasized, however. It is not clear how robust our results are because tractability, in especially applying Markovian equilibria, requires imposing restrictive assumption on functional forms. Moreover, the model has abstracted from many real world features such trade policies, political economy aspects, renegotiations, transfer payments, negotiation costs etc.[28] These issues are beyond the scope of the present paper but may be interesting and importing tasks for future research.

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A Appendix

A.1 List of Symbols

a	research investment
A	technology
b	energy preference parameter
B	benefit function
c	marginal climate damage
C	social cost of carbon
g	fossil fuel energy, carbon emissions
D	climate damage
G	stock of carbon
$k(K)$	(effective) capacity cost parameter
L	set of non-signatories
m	coalition size, number of coalition countries
$\mathcal{MD}$	discipline function
$\mathcal{MI}$	internal stability function
M	set of coalition countries
n	number of countries
N	set of countries
$1-q$	depreciation rate
r	renewable investment
R	renewable energy, capacity
$s(S)$	(effective) research cost parameter
t	time period
T	contract length
u	utility
v	present value
$\bar{y}$	satiation point
$\alpha(\kappa)$	research (capacity) cost function
β, μ	spillover parameter
δ	discount factor
γ	mitigation parameter
ρ	time preference rate
Ξ	length of one time period
$\Delta, \Gamma, \Lambda, \Pi, \Theta$	composed parameters

The Online-Appendix to this article can be found, in the online version, at...