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Tiziano Distefano, Simone D'Alessandro

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An Evolutionary Approach to International Environmental Agreements

Tiziano Distefano[*] Simone D'Alessandro[†]

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Abstract

Our work contributes to explain the origin of the failure or success of international environmental agreements (IEA) and their relation with the actual aggregate global level of greenhouse gas emissions, by including climate risks, cross-country inequalities, and consumer's environmental awareness. We introduce a novel multi-scale framework, composed by two tied games, to show under which conditions a country is able to fulfil the IEA: (i) a one-shot 2x2 Game, with asymmetric countries that negotiate on the maximum share of emissions, and (ii) an Evolutionary Game which describes the economic structure through the interaction of households and firms' strategies.

The distance between international environmental targets and country's emissions performances is explained in terms of heterogeneous economic structure, without the need to impose any free-riding behaviour. Consumer's environmental consciousness (micro level) together with global income (and technological) inequality (macro level), are found to be the key variables towards the green transition path. AGGIUNGERE QUALCHE ALTRO RISULTATO We provide analytical results paired with numerical simulations.

Keywords: International environmental agreements, asymmetry, evolutionary process, Multi-level perspective, climate change

JEL: C71, C72, C73, H41, F53, Q20

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[*]Department of Environmental, Land and Infrastructure Engineering, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, (IT). Corresponding author's e-mail: tiziano.distefano@polito.it.

[†]University of Pisa, Department of Economics and Management, via C. Ridolfi, 10, 56124 Pisa (Italy). E-mail: simone.dalessandro@unipi.it

1 Introduction

Anthropogenic climate change and trans-boundary pollution of greenhouse gas emissions justified the emergence of International Environmental Agreements (henceforth IEA), which developed from COP1 in Berlin 1995 to COP23 in Bonn 2017. Classical economic literature focused on modelling the optimal IEA coalition size, through a Game Theory analysis (see de Zeeuw (2015) and Marrouch et al. (2016) for a review). There are several important design issues that self-enforcing IEA have to address: (i) despite the global benefits of reducing green-house gas discharges, no agent has any incentive to reduce her own burden, (ii) there is not any supranational force able to enforce any agreement, (iii) there is a temptation to free ride, and (iv) remarkable historical responsibilities asymmetries in the benefits-costs distribution. This is the classical framework in which completely informed rational agents should operate.

From static non-cooperative games – which go back to Hoel (1992), Carraro and Siniscalco (1993) and Barrett (1994) – a vast game theory literature grew over time in order to explain the formation and the stability of IEA. They included asymmetries (McGinty, 2007; Pavlova and de Zeeuw, 2013; Vogt, 2016), economic transfers (Carraro et al., 2006; Alvarado-Quesada and Weikard, 2017), R& D investments (Endres and Rundshagen, 2013; Battaglini and Harstad, 2016), moral concerns (Jeppesen and Andersen, 1998; Wallbott and Schapper, 2017), uncertainty (Kolstad, 2007; Meya et al., 2017), time dynamic (Rubio and Ulph, 2007; De Zeeuw, 2008; Calvo et al., 2012; Mason et al., 2017), and an evolutionary framework (McGinty, 2010; Vasconcelos et al., 2014; Breton and Garrab, 2014; Ochea and de Zeeuw, 2015). The general consensus is that a global agreement on emission reduction is not feasible (Carraro and Siniscalco, 1993; Yang, 2017), and that only small coalitions are stable (Barrett, 1994; Gelves and McGinty, 2016; Vogt, 2016). Other implicit assumptions, behind these models, are that: (i) the agreement will automatically generate in the real economy the planned effect (e.g., CO_2 emission reduction), (ii) the failure of the compliance of the IEA is due to free-riders (Battaglini and Harstad, 2016), and (iii) "local" level initiatives are ineffective, which entails that people simply passively receive the effects of the environmental policy without making any voluntary efforts to reduce emissions and/or putting any pressure on businesses and governments.

On the contrary, the actual number of signatories of IEA is increasing over time (195 signatories during the conference of Paris 2015) and, notwithstanding the ratification of many policy intervention, we observe a progressive increase in the yearly air pollution, at global level, measured by the greenhouse gas concentration. This observation disconfirms point (ii), indeed the empirical debate on the effectiveness of IEA is yet open (Testa et al., 2016). Moreover, there is a remarkable environmental performances heterogeneity among countries, in terms of the difference between international agreements and actual level of emissions. For instance, some Kyoto participants were well above their target while others were well below.[1] Additionally, even those countries which did not sign past agreements or which were exonerate from emitting controls (i.e., developing countries), implemented different kind of local policies to regulate and limit pollution. This represent a behaviour opposed than free-riding that no previous models included nor explained.

[1] In particular there are some successful examples of emission reductions: France, Italy, Germany and UK among others (see Olivier et al., 2012).

Moreover, many ONGs (e.g., GreenPeace and WWF) and local communities have put pressure to governments in order to actively protect and preserve the ecological systems (Nasiritousi et al., 2016; Carattini et al., 2017), and they also help public opinion to become more sensitive to the care about environment. The importance of local initiatives and communities in the management of natural resources has been recently recognized by several institutions, such as the World Bank.[2] This fact suggest that global solutions, if not backed up by a variety of efforts at national, regional, and local levels, are not guaranteed to work well (Meserve, 2008; Ostrom, 2014) if domestic climate policies are not consistent with domestic initiatives (Bodansky et al., 2004) and people's environmental consciousness. The people most hurt by the detrimental effects of climate change may not have adequate representation at institutional levels and may be unable to claim about the threats they face due to climate change (Agrawal et al., 2010).

Based on these considerations and observations, the current study aims at modelling: (i) how the *economic structure* allows to explain different environmental performances, at country-level scale, with respect to what ratified in the IEA, (ii) the role played by consumers' *environmental awareness*, and (iii) how global income and technological *inequality* might hamper the road toward a green transition. We assume uniform emission reduction quotas, but we depart from the previous literature in three respects: firstly, the actual outcome of the IEA (viz. the level of CO_2 emissions) is not assumed to be coincident with what ratified but can be different (worse or better) depending on country's economic structure. This extension, to classical economic models, allows to explain the failure of IEA without the assumption of free-riding and to show under which conditions a country can over-perform (higher CO_2 reductions than ratified) the IEA standards. Secondly, we define the economic system as an Evolutionary Game where consumers and firms interact, determining the amount of CO_2 emissions for any given level of environmental standards fixed by the IEA. Thirdly, we introduce, as the main novelty, the interaction between the micro (firms and consumers' choices) and the macro (international agreements) scale to establish the actual effectiveness of the IEA and the countries' environmental performances. Note that, given the complexity of the model at hand, we only focus on the impact of international policies on local environmental performance, while the inclusion of the impact of local initiatives on international agreements is out of the scope of the current study and it is postponed for future researches. Finally, we complement the analytical analysis with numerical simulations, using a handy Maple algorithm, to define the alternative scenarios under different IEA settings.

The paper is structured as follow: Section 2 briefly describes the methodology and the logic of the two games. Section 3 describes the one-shot 2x2 IEA game and the conditions under which countries have convenience in coordinating their actions. Section 4 shows the results from the evolutionary interaction between household and firms. Section 5 presents and discusses the results from numerical simulations. Finally, Section 6 draws the main conclusions.

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[2]For more details see http://www.worldbank.org/en/topic/environment.

2 Methodology

Before moving to the mathematical details, it is worthy to clarify the logic and the interpretation of our model, given the complexity of the issue at hand. We are interested in an *endogenous* determination of abatement under different economic conditions, showing the impact of global inequality and of environmental awareness. We study the evolutionary dynamics of production convection in a two-step procedure which integrates the results from two games: the former at the global level (IEA) and the latter at national-scale level (evolutionary game).

Game 1 analyses the results of a one-shot 2x2 Game, where two countries bargain over the share of greenhouse gas reductions (θ). The asymmetric nature of IEA lead us to distinguish between two different groups of richer (N) and poorer (S) countries. For simplicity, we model only the case with two countries, each one the leader or the representative of its own group, in order to define a bilateral treaty.[3] Indeed, what matters in the IEA is 'who' signs the treaty (in terms of pollution burden) rather than 'how many', and what is the relation between environmental standards and actual performances. Note that our model can be extended by including more countries at cost of higher mathematical complexity but without altering the key messages.

Game 2 deals with the evolutionary dynamic of the country's economic structure represented by the interaction of the economic decisions of consumers and firms whom can decide of being environmental friendly or polluters. Evolutionary game theory is a growing branch of research proved to be a worth methodology (Weibull, 1996; Young, 1998; Bowles, 2009) whenever players change behaviour over time and interact strategically, in the sense that the outcome for each agent depends on others' behaviour as well as her own. It is especially valuable when the relevance of static equilibria are unclear, for instance when there are several Nash Equilibria. In our context, applying an evolutionary analysis is particularly suitable because we assume that market interactions occur frequently and because we expect that people will devote effort to solve the environmental problems. Interestingly, the mixed strategy equilibrium of a 2x2 game translates, in an evolutionary game framework, in different shares of agents playing either one or the other strategy, when the whole population is considered (Santos et al., 2006; Accinelli and Carrera, 2011).

The *timing* of the whole model is as follow: countries recognize the relevance of transboundary effect of pollution, then they bargain (i.e., game 1 on bilateral IEA) to set-up an international environmental standard (θ). This target is thought as the minimum share of clean production – with respect to industrial profits (or GDP) – and then it reflects a decision on the energy-mix of production processes. Indeed, the higher is θ the higher is the amount of renewable resources that firms must install and then the higher is the reduction in the level of CO_2 emissions. After the ratification of θ, each country enforces the IEA by law. Hence, the international environmental treaty is embodied in game 2 where each country reaches an evolutionary stable state (i.e., total actual polluting emissions) dependent on the initial conditions, that are assumed unknown to the governments, and evolutionary strategic interaction between consumers and firms.

[3] A real case example is the two biggest polluting countries, the USA and China, held in November 2014.

At this point it is straightforward to list the many connections between the two games: (i) the level of industrial efficiency (and profits) determine the gross benefit of a country (viz. the welfare function), (ii) the share of green firms might reduce the negative, local and global, environmental damages, (iii) the citizens' environmental consciousness affects the effectiveness of IEA, and (iv) the nature of interactions at micro level, between firms and consumers, determine the gap between the expected result of the international policy (θ) and the actual one. Point (iii) entails that the free-riding assumption is not necessary to have different performances than what ratified during the IEA. Rather, our model can explain cases of over-performances with respect to IEA (viz. θ).

3 Game 1 - Bilateral IEA

Let us assume: (i) two countries which decide *simultaneously*, (ii) *single* agreement on the oprimal global share of emissions (θ^*) based on the smallest common denominator (SCD)-rule, (iii) *"good-faith"* commitment among countries, and (iv) a direct relation between polluting production and CO_2 emissions (e.g., Pavlova and de Zeeuw, 2013) in order to have a clear comparison of environmental performances and economic structure.

Assumptions (i) and (ii) entail that each party agrees and decides simultaneously over a uniform and unique international environmental standard (θ^*), assuming that governments already recognize the externality before negotiations start. Assumption (ii) ensures the *external stability*,[4] and it is justified by the fact that IEA are voluntary and that there is no any supranational force. Hence, a compromise is sought which only reflects the SCD-decision rule [5] which implies that if $\theta_i < \theta_j$, then $\theta^* = \theta_i$. In an international bargaining context, one would expect that proposals are strategically motivated; however, it is possible to demonstrate that the SCD-decision rule is immune to strategic offers, it is a best-reply and a Nash Equilibrium (Endres and Finus, 1999, p. 539-540). Assumption (iii) ensures *internal stability* and it is motivated by the fact that when states do not comply with an agreement, the reason is often that states do not have the means (viz. the economic conditions) to comply, rather than the desire to free-ride (Chayes and Chayes, 1991, p. 311). Methodologically, this assumption allows us to get rid of free-riding behaviour and then to have a measure of environmental performances directly derived from the economic structure, without the influence of any strategic behaviour.

Let us assume two countries $i = \{N, S\}$ with a welfare[6] objective function $W_i(\theta_i)$, dependent on national environmental regulation (θ_i which define the share of green production or of renewable energies), defined as:

$$W_i(\theta_i) = \Pi_i(\theta_i, \pi_i) - a_i \cdot D_i(\theta, \pi) \tag{1}$$

[4]See Endres and Finus (1999) for the mathematical proof.

[5]See Hoel (1992), Endres (1995), Endres and Finus (1999) and Finus (2002) for a theoretical explanation and empirical assessments.

[6]Note that, in line with the current literature, W does not include consumers' utility for two reasons: i) we want to compare our results within a classical framework to understand the contribution of Γ_1 and ii) consumers' utility does not affect the welfare in equilibrium (i.e when $\beta^* = \theta$). From a mathematical point of view its exclusion simplifies the calculations without any significant loss in the meaning of the results. Indeed, their contribution does not depend on θ but it simply represents a scale factor that cancels out when it is computed the first derivative and, therefore, it does not affect the structure of the game.

where $0 \leq a_i \leq 1$ is the probability to incur in negative climate events with the consequent economic losses Pavlova and de Zeeuw (2013). In our model it is exogenous and it is interpreted as the government's estimation that comes from a social debate in which are taken into account the opinion of the scientific community (Barrett and Dannenberg, 2012), the environmental awareness of citizens, and the pressure of public opinion.[7] $\Pi_i(\theta_i, \pi_i)$ is the overall economic benefit which is a function of industrial production ($\pi_i = \pi_{E,i} + \pi_{P,i}$) that is composed by the profits of clear and green firms ($\pi_{E,i}$, which, for example, utilise only renewable energies), and those of polluting firms ($\pi_{P,i}$, which, for example, utilise fossil fuels). This distinction is crucial to assess how the energy-mix of production, at country scale, determine the country's environmental performance. Section 4 will describe in details how this components influence the evolutionary equilibria at micro scale. The damage $D_i(\theta, \pi)$ is a (quadratic) function of the global emissions – given by the sum of domestic ($\pi_{P,i}$) and foreign pollution ($\pi_{P,-i}$) – representing a proxy of the potential damages caused by extreme climate events. Namely,

$$\Pi_i = b_i[d_i(\theta_i \cdot \pi_{E,i} + (1-\theta_i) \cdot \pi_{P,i}) - 2^{-1}((1-\theta_i) \cdot \pi_{P,i})^2] \tag{2}$$

$$D = (\sum_{k=\{i,j\}} (1-\theta_k) \cdot \pi_{P,k})^2 \tag{3}$$

where $0 \leq b_i, d_i \leq 1$, b_i is the opportunity cost that takes into account the *local* environmental deterioration and health problems due to industrial discharges of polluting firms ($\pi_{P,i}$), while d_i is the marginal industrial benefit.

In case a_i is null, each country i chooses the business-as-usual (BAU) solution (θ_i^{BAU}) that maximizes Π_i only. The optimum share of emissions under the business-as-usual hypothesis is:

$$\theta_i^{BAU} = 1 - d_i \frac{(\pi_{P,i} - \pi_{E,i})}{\pi_{P,i}^2} \tag{4}$$

Note that $0 \leq \theta_i^{BAU} \leq 1$ always[8] and that, given d_i and $\pi_{E,i}$, it increases with respect to $\pi_{P,i}$ because the government must fix more stringent environmental standards in order to compensate the local ecological damages. On the other hand, a rich country – with $\pi_{P,i}$ high – might prefer to fix stringent environmental standards if it has an advanced green technology, and then when $\pi_{E,i}$ is high as well. Indeed, in this case, it would be an advantage to speed up the green transition because it can yield high profits without hurting the environment, avoiding public expenditure to recover possible environmental damages.

In contrast, if global externalities are recognized by each state ($a_i > 0$), then an IEA emerges, with possibly coordinated or non-coordinated strategies. The *non-cooperative* (NC) Nash equilibrium is given by the maximisation of Eq. (3). Namely,

$$\begin{aligned} \theta_i^{NC} = K_i^{NC}\{&\pi_{P,j}(b_j b_i + a_j b_i)[\pi_{P,i}^2 - d_i(\pi_{P,i} - \pi_{E,i})] + \\ &+ \pi_{P,i} a_i b_j [\pi_{P,i}\pi_{P,j} + d_j(\pi_{P,j} - \pi_{E,j})]\} \end{aligned} \tag{5}$$

[7] This interpretation recalls the concept of extended-peer-community introduced by Futowicz and Ravetz in their core paper on Post-Normal Science. The interested reader is referred to Funtowicz and Ravetz (1994).

[8] Obviously in case of negative values, the country opts for no environmental laws.

where

$$K_i^{NC} = [\pi_{P,i}^2 \pi_{P,j} \cdot (b_j b_i + a_j b_i + a_i b_j)]^{-1} \tag{6}$$

with $(j, i) = \{\text{N,S}\}$ and $j \neq i$.

On the other side, the *coordinated* (CO) equilibrium is based on the extended welfare function that is obtained by the maximisation of the sum of the welfare functions of the two countries:

$$\begin{aligned}\theta_i^{CO} = K_i^{CO} \cdot [\pi_{P,j}[(b_j b_i + a_j b_i + a_i b_i) \cdot (\pi_{P,i}^2 - d_i(\pi_{P,i} - \pi_{E,i})] + \\ + \pi_{P,i}[(a_i b_j + a_j b_j)(\pi_{P,i}\pi_{P,j} + d_j(\pi_{P,j} - \pi_{E,j})]]\end{aligned} \tag{7}$$

where

$$K_i^{CO} = [\pi_{P,i} \cdot \pi_{P,j}(b_j b_i + a_j b_i + a_i b_j + a_i b_i + a_j b_j)]^{-1} \tag{8}$$

which follows the same structure of the NC equilibrium, but it adds up the interaction effects of opportunity cost (b) and climate risks (a) within each country. Given the high non linearity of the functions involved, it is not possible to establish a simple relationship between the optimal level of environmental standards and the parameters and variables involved. For this reason, Section 5 shows how the different frameworks (BAU, NC, and CO) affect the environmental performance from different numerical simulations, while in Appendix A.2.1 and A.2.2 there are the *ceteris paribus* analytical discussions on θ^{CO} and θ^{NC}.

4 Game 2 - Evolutionary (Micro-)Economic Structure

We construct a dynamic model of the process by which the proportions of various strategies in a population change. This will typically be a stochastic process, but if the random events affecting individual pay-off are independent, and the population is sufficiently large, a good approximation is obtained by examining the expected value of this process (Weibull, 1996). To analyse the evolutionary dynamics governing transitions between the two conventions (Green-Green, Carbon Economy), let us assume a two-person two-strategy game in a large population of individuals subdivided into two groups (consumers and firms), the members of which are randomly matched to interact in a non-cooperative game with members of the other group. Individuals' best-response play is based on a single-period memory: they maximize their expected pay-off based on the distribution of the population in the previous period (Bowles, 2009; Belloc and Bowles, 2013). Both populations are normalized to unit size, so we refer equivalently to the numbers of players and the fraction of the population. Note that this framework does not deal with interactions that take place between more than two individuals at a time.

Table 1 shows the normal-form (strategic) game with a player set composed by individuals that comprise $\Omega = \{\mathcal{H}, \mathcal{F}\}$ finite populations, namely households ($\mathcal{H}$) and firms ($\mathcal{F}$). Each population splits in clubs depending on the strategy $s = \{E, P\}$ – *ecologic* (E) and *polluting* (P), respectively – agents play. Note that the pay-offs out of the diagonal are always zeros because we assume that when people with different strategies are matched they do not sign any contract. In other words, the green consumers do not want to buy polluting goods and vice versa.[9] The

[9]Following Weibull (1996, p. 34) we might consider that the zeros out of diagonal are the results of pay-off's

Table 1: **Normal form of the Evolutionary Game.** $\mathcal{H}$ and $\mathcal{F}$ stand for households' and firms' pay-off, respectively; while E and P are the ecologically friendly and polluting strategies, respectively.

Players	$\mathcal{F}_E$	$\mathcal{F}_p)$
$\mathcal{H}_E$	(h_E, f_E)	(0, 0)
$\mathcal{H}_P$	(0, 0)	(h_P, f_P)

dynamic evolution of the fraction of each club, given the complementarity of the two strategies {E, P}, is simply derivable from the evolution of the proportion of ecological households and firms, namely of α and β, according to the following replicator dynamics (Sigmund, 2010; Santos and Pacheco, 2011; Santos et al., 2012) :

$$\dot{\alpha} = \alpha \cdot (1 - \alpha) \cdot [H_E - H_P] \tag{9}$$

$$\dot{\beta} = \beta \cdot (1 - \beta) \cdot [F_E - F_P] \tag{10}$$

where H_s and F_s are the expected fitness of households and firms' strategies respectively. According to Eq. (9) and (10) the percentage of green players increases if the pay-off given by the green strategy (E) is higher than what expected when the polluting strategy (P) is played. The pay-off depends on the actions of the co-players and hence on the frequencies of the strategies within the population (Sigmund, 2010). The more successful individuals will be "mimicked" by others, so that the number of individuals adopting a given strategy will evolve over time. The significance of the evolutionarily stable strategy (or fixed point) concept is that the process of learning has a tendency to produce monomorphic population states, which can persist in the face of "mutations" or shocks. In what follows, we describe in details the pay-off structure for both players and strategies, the expected values, and the evolutionary dynamic.

4.1 Households

The utility of a household h depends on his material pay-off and strategy(h_s). For the sake of simplicity, we assume that the consumption of each kind of commodity yields the same level of utility (u);[10] nevertheless, the relation between the environmental standards (θ) and the share of firms operating under green production (β) shape the total pay-off. In particular, the pay-off of the household is a piece-wise continuous function defined as:

$$h_s = \begin{cases} h_E = u - c(\theta - \beta), & \text{iff } \beta < \theta \text{ and s = E} \\ h_P = u - \delta(\theta - \beta), & \text{iff } \beta < \theta \text{ and s = P} \\ u, & \text{otherwise, with s = \{E, P\}.} \end{cases} \tag{11}$$

normalization. In other words, even if we assume that agents get some constant positive pay-off when they play different strategy, it would not be affect the structure of Γ_1. For simplicity we get rid of this possibility and we study only the model with zeros out of diagonal.

[10] In other words, green and polluted goods are perfect substitutes because both goods are able, through their material characteristics, to satisfy in the same manner the needs of consumers.

where $0 < \delta, c \leq 1$, while $u > 0$ is the constant level of utility from consumption, independent from market conditions – not modelled here – because it comes from the material characteristic of the good.[11] Note that, the utility does not depend on quantity because we assume that in each pair-wise matching the amount of exchange is constant. Since that the utility from consumption is the same in both cases, households simply compare the monetary cost of being environmental friendly (c) with the moral cost and social pressure (δ) of buying carbon intensive commodities. Note that if $c = \delta$ than the consumer is indifferent between the two strategies.

Green households carry a monetary cost proportional to the difference between the environmental standard ($0 \leq \theta \leq 1$) and the share of green firms ($0 \leq \beta \leq 1$). This additional cost represents the willingness to finance the (start-up) of ecological friendly production.[12] We assume that in case of no environmental concerns – i.e., $\beta > \theta$ – the green household simply receives utility from consumption. The share of green households, in equilibrium, depends on the gap between the environmental law θ^* and the actual proportion of green firms (β^*).

On the other hand, the *polluting* households face, as a moral cost, how much the public opinion perceives the possible damages from a polluting consumption (δ). Then, δ is a measure of the level of *environmental awareness* spread in the society, that is a proxy of the level of local participation in environmental discussions and practices and it capture how the citizens are willing to "receive" the imposition of green policies. Given δ, the share of h_P decreases inasmuch the environmental standards are not respected, to say when $\theta - \beta$ is high.

At this point, we derive analytically the stationary stable equilibrium in the share of green and polluting households. The expected pay-off of choosing the green and the polluting strategy are $H_E = E(\mathcal{H}_E) = \beta h_E$ and $H_P = E(\mathcal{H}_P) = (1-\beta)h_P$, respectively. Households choose the green (polluting) strategy if and only if $H_E > H_P$ ($H_E < H_P$). At the extremes we have that:

- if $\beta = 0$, then $H_E > H_P$ if and only if $\theta > \theta_0 \equiv \frac{u}{\delta}$. Note that when $\beta = 0$ so does H_E, therefore, the only way to discourage polluting consumption is to fix θ high enough to make H_P (temporarily) negative;[13]
- if $\beta = 1$, then $H_E > H_P$ always.

The interested reader can find the analytical discussion of all the other cases in Appendix A.1.1, while Section 5 will show the resulting equilibria (β^*) coming from the numerical simulations.

[11]For instance, a consumer should be indifferent from an ecological home cleaning product and a chemical one, if they are both equally suitable for housecleaning.

[12]The modelisation of the process of formation of prices and the mechanism of redistribution of this extra payment is out of the scope of the current study. As a matter of example, we report, among the several real-case initiatives, that many green start-ups got off the ground using crowd-funding sites, such as 'FoodCycle', which recycles food waste into nutritious meals for those in need.

[13]We might avoid negative utilities simply by assuming any scale factor – out of the diagonal – big enough to compensate the gap. However, this issue does not alter the nature of the game.

4.2 Firms

Let us assume that the firm's pay-off is a piece-wise continuous function defined as:

$$f_s = \begin{cases} f_E = \pi_E + \frac{c(\theta-\beta)\alpha}{\beta}, & \text{iff } \beta < \theta \text{ and s = E,} \\ f_P = \pi_P - \frac{\gamma(\theta-\beta)}{1-\beta}, & \text{iff } \beta < \theta \text{ and s = P,} \\ \pi_s, & \text{otherwise, with s =\{E, P\}.} \end{cases} \tag{12}$$

where $0 < \pi_E < \pi_P$, and $\gamma > 0$ is a multiplicative factor that measures the monetary cost of the difference $\theta - \beta$. The level of profits coming from production depends on the strategy (π_s); they can be interpreted as an average profit proportional to the market share of the belonging sector. We assume that the green technology is not already developed to be as efficient as the polluting one and its profits are then smaller.[14] In both cases, the level of profits are constant because we focus on their relative values, that is on the gap between polluting and clean production. What matters in our framework is the evolutionary dynamic that the economy attains when the green firms are relatively less efficient (and productive, then profitable) compared to fossil fuel ones.

Green firm[15] – other than their profits – receives a subsidy which is equal to the total amount of extra-cost (c), paid by each green household, multiplied by the share of green consumers (α). This amount decreases as the share of green firms β approaches the environmental standards (θ). We assume that, in every period, the total amount paid by green consumers is equally shared among green firms. The public subsidy sustains and boosts the investments in new green start-ups to stimulate investments in green sectors.

On the other side, the *polluting* firms face a cost ($\frac{\gamma(\theta-\beta)}{1-\beta}$) for local damages that depends on: the relation between the actual level of green production (β), the ecological standards fixed by the government (θ), and the number of polluting firms ($1-\beta$). Since the polluting firms must jointly cover the cost of local environmental damages, the total amount is determined by the percentage of polluting firms. We assume that the amount paid by polluting firms is used by government either to restore their environmental damages or to face future adverse catastrophes due to climate change.

Given the share of households which choose the green or the polluting strategy, firms prefer the green (polluting) production if and only if the expected pay-off of $\mathcal{F}_E$ is greater (lower) than the expected pay-off of $\mathcal{F}_P$. Let us define $F_E = E(\mathcal{F}_E) = \alpha f_E$ and $F_P = E(\mathcal{F}_P) = (1-\alpha) f_P$ the expected pay-off of the green and the polluting production, respectively, then the expected firms' pay-off depend on both α and β. Note that F_E is an increasing function of α, such that: $F_E = 0$ when $\alpha = 0$ and $F_E > 0$ when $\alpha = 1$.[16] On the other hand, the expected pay-off of the polluting strategy is decreasing in α if $\beta > \theta$. Instead, when $\beta < \theta$ the slope of the function F_P depends on the sign of $\pi_P - \frac{\gamma(\theta-\beta)}{1-\beta}$ which expresses the difference between the whole profits of

[14] An instructive example is provided by OECD (2014) that confirms the tiny share (1%), by 2011, of renewable resources in the production of primary energy, while oil, gas and coal together cover more than four-fifths of the total amount (30.7%, 29.2% and 21.5%, respectively).

[15] See Battaglia et al. (2018) for a discussion of green jobs.

[16] The value of F_E at $\alpha = 1$ depends on the relation between θ and β. If $\beta < \theta$ then $F_E = \pi_E + \frac{c(\theta-\beta)}{\beta}$, otherwise $F_E = \pi_E$.

polluting industries and the (monetary evaluation) of the environmental damages. Obviously, when this last expression is negative, that is when $\beta < \bar{\beta} \equiv \frac{\gamma\theta - \pi_P}{\gamma - \pi_P}$, then F_E is greater than F_P for any value of α. The final outcome is then not linear and depends on households strategy. For this reason, and for the sake of clarity, we show the analytical discussion in Appendix A.1.2, while Section 5 will show the results coming from the numerical simulations.

5 Numerical Simulations with 2 Asymmetric Countries

For the sake of simplicity, we identify two key dimensions on which building the numerical simulations: environmental consciousness (δ) and economic and technological inequality (π). Their combination reflects the North-South dichotomy between rich and poor countries but it adds the possibility to be green also in low-income regions, and *vice versa*. In particular, in each scenario, we compare three different regimes of environmental awareness depending on the level of δ (high, medium or low). Appendix A.1 gives insights under a *ceteris paribus* framework where only one parameter is allowed to change.

Numerical simulations allow to examine several alternative scenarios, with many parameters that vary at the same time, giving a range of possibilities which clarifies the relation between the target ratified in the IEA (θ^*) and the actual share of polluting production ($1 - \beta^*$) that depends on country's economic structure.[17] In what follows, we set the parameters as follow: $\gamma = 1$, $\pi_{P,N} = 0.60$ and $\pi_{E,N} = 0.20$ are the green and polluting profits, respectively, in the richer country (N), while the industries of the poor country (S) generate the half of those profits, namely: $\pi_{P,S} = 0.30$ and $\pi_{E,S} = 0.10$. Moreover, we keep constant the cost that each green household faces, that is $c = 0.50$ (medium level) and the utility from consumption at $u = 0.10$.[18] In this way we set the level of δ to: high (0.90), medium (0.50), or low (0.30) to assess the relative impact of the environmental awareness. Parameters about climate risks and opportunity costs, that are $\{a, b, d\}_i$ for each country i, are set so that four alternative scenarios (or cases) can be compared:

1. *High Benefit-Risk in country S*: $a_S > a_N$, $b_S > b_N$, and $d_S = d_N$; in numbers: $\{0.40, 0.80, 0.45\}_S$ and $\{0.20, 0.40, 0.45\}_N$;

2. *High Benefit-Risk in country N*: $a_S < a_N$, $b_S < b_N$, and $d_S = d_N$; in numbers: $\{0.20, 0.60, 0.45\}_S$ and $\{0.45, 0.90, 0.45\}_N$;

3. *Asymmetric Benefit-Risk distribution*: $a_S > a_N$, $b_S < b_N$, and $d_S < d_N$; in numbers: $\{0.60, 0.20, 0.45\}_S$ and $\{0.20, 0.60, 0.75\}_N$;

4. *Extreme Asymmetry*: $a_S \gg a_N$, $b_S \ll b_N$, and $d_S < d_N$; in numbers: $\{0.90, 0.10, 0.45\}_S$ and $\{0.10, 0.90, 0.75\}_N$.

Each scenario yields the level of expected welfare $W_i^*(\theta^*)$, under the 'good-faith' commitment (assumption (iii)) and following the SCD-rule (assumption (ii)) for which countries agree to ratify the weaker environmental standard. We call the country that set the lowest θ as the

[17]Numerical simulations were performed using a Maple algorithm that is available upon request.
[18]Note that our results are robust in case of different parameters settings.

"bottleneck" of the IEA (Endres and Finus, 1999), to say the one that establish how much strong/weak is the policy intervention for reducing CO_2 emissions worldwide. This decision is based on the economic structure and does not reflect any strategic behaviour. Whereupon, we compute the actual welfare $\hat{W}_i(\beta_i^*)$[19] which depends on the actual quota of green firms (β_i^*), the expected ($G_i^* = (1 - \theta^*_{global})\cdot\pi_P$) and actual level (determined by the fraction of polluting firms, to say $\hat{G}_i = (1 - \beta^*)\cdot\pi_P$) of greenhouse gas emissions and the interior equilibrium in each country (α_i^*, β_i^*).

As a simplified example, we show the result from a hypothetical 2x2 static game (Tables 2-5) in which both countries have dichotomic strategies: polluting ($\theta = 0$) or being environmental friendly ($\theta = 1$). There are four different outcomes: $W_i^{00} = b_i(d_i\pi_{P,i} - \frac{\pi_{P,i}^2}{2}) - \frac{a_i(\pi_{P,i}+\pi_{P,j})^2}{2}$ in case both countries neglect environmental issues, $W_i^{11} = b_i d_i \pi_{E,i}$ when they decide to get rid of any polluting production process, $W_i^{10} = b_i d_i \pi_{E,i} - \frac{a_i\pi_{P,j}^2}{2}$ when country j pollutes and i acts unilaterally to green up the production while the reverse holds for $W_i^{01} = b_i(d_i\pi_{P,i} - \frac{\pi_{P,i}^2}{2}) - \frac{a_i(\pi_{P,i})^2}{2}$. The results from the following normal form game give further insights on which country has more convenience in being the bottleneck of the IEA.

Table 2:
High Benefit-Risk in Southern country.

Case 1	S_E	S_P
N_E	(0.036, 0.036)	**(0.027, 0.054)**
N_P	(0.00, -0.036)	(-0.045, -0.09)

Table 3:
High Benefit-Risk in Northern country.

Case 2	S_E	S_P
N_E	(0.081, 0.027)	**(0.06, 0.045)**
N_P	(0.00, -0.009)	(-0.101, -0.27)

Table 4:
Asymmetric Benefit-Risk distribution.

Case 3	S_E	S_P
N_E	(0.09, 0.009)	(0.081, -0.009)
N_P	**(0.126, -0.099)**	(0.081, -0.225)

Table 5:
Extreme Asymmetry.

Case 4	S_E	S_P
N_E	(0.135, 0.005)	(0.13, -0.03)
N_P	**(0.225, -0.15)**	(0.20, -0.35)

Note: N stands for rich country and S for the poor one. The subscript E stands for ecological strategy ($\theta = 1$), while P stands for polluting actions ($\theta = 0$).

Case 1 and 2 have only one Nash Equilibrium (bold) in pure strategy in which S prefers to pollute while N acts unilaterally to abolish fossil fuels and any other polluting source. Case 3 and 4 present the different equilibria in case N opts for dirty productions while S is environmental friendly. In any case, who finds optimal to choose the strategy $\theta = 1$ receives the greatest pay-off. These simple games are worthy because, depending on the Nash equilibrium, they predict who will be the bottleneck of the IEA game when θ is allowed to get any value in the continuum $\Re$ within the interval [0,1]. Indeed, the polluter will result in who dictates the IEA. However, these example, based on classical economic analyses, although worthy, provide no insights about the actual level of pollution and on what comes out when the decision is not

[19] In order to compute the actual welfare we assume that even when country i does not attain the IEA ($\beta_i^* \neq \theta^*$), the other one does.

discrete. The following numerical simulations provide consistent scenarios able to capture the interaction between top-down policy decision and (micro-level) economic structure.

5.1 Scenario 1

In the first scenario S faces a medium risk, higher than that of N ($a_S > a_N$), to incur in damages due to global pollution and higher opportunity costs ($b_S > b_N$). Under the BAU hypothesis S chooses to not impose any environmental restrictions ($\theta_S = 0$), while N prefers to halved its polluting production ($\theta_N = 0.5$) then acting unilaterally and independently from S. This is an interesting outcome that reverses the logic of free-riding, since that the country is willing to curb emissions voluntary. When environmental externality is recognized ($a > 0$), both countries are involved in an international agreement.

In the *non-cooperative* game, the two countries agree on the stronger environmental policies than under coordination ($\theta^{*NC} = 0.5 > 0.46 = \theta^{*CO}$), which is usually not predicted by the standard economic literature. However, the complexity of the issue at hand might generate couter-intuitive results that our model is able to capture. Given the SCD-rule the bottleneck (bold) is always the poor country that, despite the higher risk of environmental damages ($a_S > a_N$), prefers to boost a polluting economic growth. Indeed, in the poorest region, the absolute difference between polluting and green profit, and the extremely low level of the latter ($\pi_{E,S} = 0.1$), overwhelm the weight put to local damages, making the ecological strategy less convenient.

Table 6: **High Benefit-Risk in Southern country.** θ^* is the target fixed in the IEA, W^* and G^* are the expected level of welfare and CO_2 emissions, respectively. α^* and β^* are the evolutionary stable states after the imposition of the environmental target, $\hat{W}$ and $\hat{G}$ are the actual level of welfare and CO_2 emissions attained, respectively. N and S stands for rich and poor country, respectively.

		BAU ($a = 0$)		NON-COOP. (NC)		COORD. (CO)	
Scenario	*Outcome*	N	S	N	S	N	S
	θ^*	*0.50*	*0.00*	*0.75*	**0.50**	*0.96*	**0.46**
'Good-Faith'	W*	0.054	0.072	0.034	0.023	0.030	0.017
	G*	0.30	0.30	0.30	0.15	0.320	0.161
	α^*	0.75	0.00	0.75	0.75	0.67	0.59
δ HIGH	β^*	**0.50**	*0.00*	**0.50**	**0.50**	*0.404*	*0.404*
	$\hat{W}$	*0.054*	0.072	0.034	0.023	0.026	0.016
	$\hat{G}$	0.30	0.30	0.30	0.15	0.36	0.18
	α^*	0.47	0.00	0.47	0.10	0.47	0.15
δ MEDIUM	β^*	*0.30*	*0.00*	*0.30*	*0.30*	*0.26*	*0.26*
	$\hat{W}$	0.051	0.072	0.019	0.017	0.013	0.015
	$\hat{G}$	0.42	0.30	0.42	0.21	0.44	0.22
	α^*	0.23	0.00	0.23	0.00	0.24	0.00
δ LOW	β^*	*0.125*	*0.00*	*0.125*	*0.125*	*0.098*	*0.098*
	$\hat{W}$	0.044	0.072	0.001	0.008	-0.007	0.001
	$\hat{G}$	0.52	0.30	0.52	0.26	0.54	0.27

Under *coordinated* actions, S is again the bottleneck, thought it fixes a slightly lower percentage of green production ($\theta_S^{*NC} > \theta_S^{*CO}$). Note that here, and in the subsequent examples, the expected pay-off is always greater under the most stringent environmental standard. This is obvious because θ maximizes the welfare function, so that the more β is close to that value the higher is the welfare.

When θ^* is enforced in the economic structure, it becomes evident the crucial role played by the level of environmental awareness (δ): only when it is *high*, keeping constant the other parameters, both countries are able to *precisely* attain the treaty under the non-cooperative framework ($\beta^*_{NC} = \theta^{*NC} = 0.5$) and the emissions are then minimised ($\hat{G}_N + \hat{G}_S = G^* = 0.45$). On the other hand, if they had coordinated their action they would attain a quota of green firms slightly below than what ratified ($\beta^*_C = 0.404$). In the other cases, when δ is lower, the actual environmental outcome is always worse independently from any free-riding behaviour.

Note that here, as in the other three cases, $\beta^*_N = \beta^*_S$ and that $\alpha^*_N \geq \alpha^*_S$ always. The fraction of green firms is the same because in each (sub-)scenario, dependent on δ, the value of the parameters (c, u, δ, θ), which determine β^*, are the same in both country. On the other hand, the fraction of green consumers, that makes the firms indifferent, is bigger in the richer country because, even thought the proportion between polluting and green profits is the same in both countries, the absolute difference $\pi_P - \pi_E$ is greater in the richer region. They are then needed more green consumers to make the polluted firms indifferent.

5.2 Scenario 2

In Scenario 2, the parameters d_i, $\pi_{P,i}$, and $\pi_{E,i}$ are the same as in Scenario 1 then the same considerations holds true under the BAU hypothesis. Country S is again the bottleneck in the NC framework but, in this case, the outcome is in line with the current literature since that the coordinated actions generate more stringent environmental standards ($\theta^{*CO} = 0.75 > 0.36 = \theta^{*NC}$), that yield lower emissions and higher welfare. Parameter δ plays a crucial role only under the NC framework; indeed, when it is *low* both countries reaches an interior equilibrium close to (0,0) where the emissions are maximum.

Under the *coordinated* game the target is high ($\theta^{*CO} = 0.75$) but not ambitious or unrealistic; indeed, IPCC (2014) suggested that, in order to avoid a temperature increasing greater than 2 Celsius degree, it is necessary to curb global greenhouse gas emissions up to 70% (compared with 2010) by mid-century, and to near 100% by the end of this century. Ambitious mitigation might even require removing carbon dioxide from the atmosphere. If both countries have ratified θ^{*CO} – where country N is the bottleneck – they would attain a complete green transition with only green firms and consumers ($\alpha^* = \beta^* = 1$), to say they obtain environmental performances better than what ratified independently from the level of environmental awareness. The latter does not play any role because in this case $\theta^{*CO}_N > \theta_1$ (see Eq. 6 in Appendix A.1) which is the threshold upon which the system converges to the (1,1) equilibrium (see Regime 3(f) in Appendix A.1.3). Inasmuch as inequality increases the level of emissions grows as well showing that a more equal distribution of environmental risks and industrial profits would lead to better environmental status.

Table 7: **High Benefit-Risk in Northern country.** θ^* is the target fixed in the IEA, W^* and G^* are the expected level of welfare and CO_2 emissions, respectively. α^* and β^* are the evolutionary stable states after the imposition of the environmental target, $\hat{W}$ and $\hat{G}$ are the actual level of welfare and CO_2 emissions attained, respectively. N and S stands for rich and poor country, respectively.

		BAU ($a = 0$)		NON-COOP. (NC)		COORD. (C)	
Scenario	*Outcome*	N	S	N	S	N	S
	θ^*	*0.50*	*0.00*	*0.77*	**0.36**	**0.75**	*0.77*
'Good-Faith'	W*	0.121	0.072	0.044	0.017	0.10	0.033
	G*	0.30	0.30	0.382	0.19	0.146	0.072
	α^*	0.75	0.00	0.62	0.50	1.00	1.00
δ HIGH	β^*	**0.50**	*0.00*	*0.275*	*0.275*	**1.00**	**1.00**
	$\hat{W}$	0.121	0.054	0.025	0.016	0.079	0.024
	$\hat{G}$	0.30	0.30	0.38	0.19	0.00	0.00
	α^*	0.47	0.00	0.43	0.21	1.00	1.00
δ MEDIUM	β^*	*0.30*	*0.00*	*0.163*	*0.163*	**1.00**	**1.00**
	$\hat{W}$	0.115	0.054	-0.005	0.013	0.079	0.024
	$\hat{G}$	0.42	0.30	0.50	0.25	0.00	0.00
	α^*	0.23	0.00	0.01	0.00	1.00	1.00
δ LOW	β^*	*0.125*	*0.00*	*0.023*	*0.023*	**1.00**	**1.00**
	$\hat{W}$	0.099	0.054	0.05	0.008	0.079	0.024
	$\hat{G}$	0.52	0.30	0.59	0.295	0.00	0.00

5.3 Scenarios 3 and 4

Scenario 3 is more realistic: the richer country is less risky ($a_S > a_N$) but faces higher opportunity cost ($b_S < b_N$) since it has to convert advanced, and profitable, polluting production processes through high technological and infrastructural investments. Scenario 4 proposes an extreme version of inequality to underline the impact of unequal distribution of risks and profits among countries. In both cases, country N dictates the IEA because has less convenience in reducing the emissions since it faces higher cost-risk ratios.

Under the BAU hypothesis both countries have low incentive in promoting environmental laws, therefore the quota of green firm is (almost) null independently from δ which plays a marginal role when it is not supported by governmental policies. Under the *NC* game, the IEA is utterly ineffective ($\beta^* = 0$) when the environmental awareness is low. This is a remarkable result that show the necessity of the participation of people for the success of environmental policies. It also shows another source of failure of IEA different from free-riding that depends on the actual socio-economic structure. Under the *CO* game, the international target is about 45% but the actual outcome strongly depend on δ. Indeed, the actual share of green firms goes from the 38% when δ is high to 8% when δ is low. In case of Scenario 4, the same considerations hold true, although the environmental performances are dramatically worse. In brief, these two scenarios show the importance of local environmental consciousness in attaining higher level of clean production. In Scenario 4 with $\theta^{*CO} = 0.29$ both countries converge to $\beta^* = 0$ when δ is *low*, while in Scenario 3 with $\theta^{*CO} = 0.27$ both countries converge to $\beta^* = 0.17$ if δ is *high.*

This confirms previous findings of the literature that state that more stringent environmental regulation does not necessarily reduce pollution levels (Ye and Zhao, 2016). It clearly shows that local participation can have the positive impact to fasten the process of cleaning production and to save resources for alternative use, because they allow governments to fix less stringent standards and to avoid additional expenditures to recover environmental damages.

Table 8: **Asymmetric Benefit-Risk distribution.** θ^* is the target fixed in the IEA, W^* and G^* are the expected level of welfare and CO_2 emissions, respectively. α^* and β^* are the evolutionary stable states after the imposition of the environmental target, $\hat{W}$ and $\hat{G}$ are the actual level of welfare and CO_2 emissions attained, respectively. N and S stands for rich and poor country, respectively.

		BAU ($a = 0$)		NON-COOP. (NC)		COORD. (CO)	
Scenario	*Outcome*	N	S	N	S	N	S
	θ^*	*0.17*	*0.00*	**0.27**	*1.00*	**0.45**	*1.00*
'Good-Faith'	W*	0.165	0.018	0.120	-0.112	0.132	-0.058
	G*	0.50	0.30	0.438	0.219	0.332	0.166
	α^*	0.47	0.00	0.57	0.44	0.66	0.57
δ HIGH	β^*	*0.07*	*0.00*	*0.17*	*0.17*	*0.38*	*0.38*
	$\hat{W}$	0.163	0.018	0.113	-0.012	0.131	-0.06
	$\hat{G}$	0.558	0.30	0.50	0.25	0.372	0.186
	α^*	0.00	0.00	0.353	0.187	0.463	0.17
δ MEDIUM	β^*	*0.00*	*0.00*	*0.07*	*0.07*	*0.247*	*0.247*
	$\hat{W}$	0.162	0.018	0.107	-0.136	0.126	-0.07
	$\hat{G}$	0.60	0.30	0.558	0.28	0.452	0.226
	α^*	0.00	0.00	0.00	0.00	0.233	0.00
δ LOW	β^*	*0.00*	*0.00*	**0.00**	**0.00**	*0.08*	*0.08*
	W*	0.162	0.018	0.09	-0.145	0.113	-0.11
	G*	0.60	0.30	0.60	0.30	0.552	0.276

Table 9: **Extreme Asymmetry.** θ^* is the target fixed in the IEA, W^* and G^* are the expected level of welfare and CO_2 emissions, respectively. α^* and β^* are the evolutionary stable states after the imposition of the environmental target, $\hat{W}$ and $\hat{G}$ are the actual level of welfare and CO_2 emissions attained, respectively. N and S stands for rich and poor country, respectively.

		BAU ($a = 0$)		NON-COOP. (NC)		COORD. (CO)	
Scenario	*Outcome*	N	S	N	S	N	S
	θ^*	*0.17*	*0.00*	**0.17**	*1.00*	**0.29**	*1.00*
'Good-Faith'	W*	0.247	0.009	0.22	-0.23	0.224	-0.17
	G*	0.50	0.30	0.50	0.25	0.427	0.213
	α^*	0.47	0.00	0.47	0.34	0.58	0.45
δ HIGH	β^*	*0.07*	*0.00*	*0.07*	*0.07*	*0.192*	*0.192*
	$\hat{W}$	0.246	0.009	0.21	-0.257	0.223	-0.19
	$\hat{G}$	0.558	0.30	0.558	0.279	0.484	0.242
	α^*	0.00	0.00	0.00	0.00	0.38	0.199
δ MEDIUM	β^*	*0.00*	*0.00*	**0.00**	**0.00**	*0.09*	*0.09*
	$\hat{W}$	0.243	0.009	0.20	-0.273	0.217	-0.214
	$\hat{G}$	0.60	0.30	0.60	0.30	0.546	0.273
	α^*	0.00	0.00	0.00	0.00	0.00	0.00
δ LOW	β^*	*0.00*	*0.00*	**0.00**	**0.00**	**0.00**	**0.00**
	$\hat{W}$	0.243	0.009	0.20	-0.273	0.209	-0.22
	$\hat{G}$	0.60	0.30	0.60	0.30	0.60	0.60

To conclude, a cross-scenario comparison highlights that: (i) global income and technological inequality reduces the level of the IEA targets (θ^*), (ii) the possible ineffective role of citizens when they are hampered by insufficient environmental laws, and (iii) the need to integrate the bottom-up level with the top-down one in order to achieve successful climate targets. This observations entail that governments should not simply impose an environmental law, rather they should stimulate citizens' responsibility because it is a channel to save resource otherwise spent to recover the environmental damages.

6 Conclusion

This study considered two countries, with different economic structures, negotiating emission reductions and it compared – both analytically and with numerical simulations – the environmental performances based on a set of drivers: abatement costs, environmental awareness, climate risks, and consumers' and firms' preferences. In game 1 parties of the IEA were assumed to agree on the smallest common denominator, defining an unique global environmental standard. In game 2 the (evolutionary) interaction of firms' and consumers' strategies – considering the IEA target as a *datum* – determined the actual level of emissions and then the success of the IEA. Our model shows that 'global solutions', negotiated at international level, do not automatically produce the expected effects; rather, it is necessary the integration of efforts at national and local levels to attain the expected impact on CO_2 reduction. Indeed, our numerical simulations suggests that the same international target may lead to diverging results depending on the economic structure and not on free-riding. In this respect, this study highlights the role of environmental awareness as a key feature to force markets to shift towards cleaner production.

To best of our knowledge, this study is the first combining two different games in a consistent framework, which is a methodological novelty. From a theoretical point of view, we offer an innovative perspective where grounding a multi-scale analysis. The main contribution, with respect to the current literature on IEA, stands on the modelisation of the economic structure which gives further insights to explain the gap between the promises of the agreements and the actual results. The notion of free-riding might be misleading when dealing with collective entities, like countries, which do not behave as (rational) individual. Rather, at country-scale the environmental performance is the outcome of a complex system where agents interact to fulfil their needs and desires. Our framework allows to define a more accurate picture of the problem at hands. Indeed, differently from what found in a large part of literature, the model shows that coordinated actions are not necessary more environmental friendly, but their success depends on the level of inequality, in terms of potential economic losses due to climate change.

Numerical simulations identified the impact of inequality, asymmetric risks, and opportunity costs distribution. Firstly, given a certain level of inequality, a country establishes environmental friendly standards inasmuch the benefit–cost ratio is high. Secondly, historical inequality – in terms of different level of profits generated by the industries and different technological development of both green and polluting firms – and climatic risks play a key role. Extreme inequality Kolstad (2011) lead to weak environmental target which determines higher level of emissions and a lower welfare for the poorest country. Thirdly, the coordination of action does not automatically imply more stringent international environmental standards. Rather, when the inequality is large and the expected loss from climate change is not too high (in the bottleneck country), the bargaining process could lead to ratify a smaller θ^*. This is a possible explanation of the fact that, in the case of the Kyoto Protocol, for many developing countries (non-Annex I Parties) the compliance of the treaty was not mandatory.

While simplifications are essential to modelling complex systems, the effects of simplifying assumptions on the theoretical outcomes should not be ignored when interpreting the results (Madani, 2013; Kolstad, 2011). Future research can benefit from the inclusion of other drivers linked with climate change, such as: population and economic growth, technological progress, stock of emitted GHGs remaining in the atmosphere, international trade, and the time and cost of conversion from a fossil-based economy towards a new one fed by renewable energies. Obviously, taking into account all these features in an unique, simple and tractable mathematical model is a challenge.

Acknowledgments

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Appendix

A.1 Analytical discussion of evolutionary equilibrium

In what follows we provide a *ceteris paribus* analysis of the different evolutionary stable states (ESS), of both households and firms' share of green strategies (α, β),[20] depending on the stringency of the international environmental law (θ). The solutions (ESS) come from the replicator dynamics (see Eq. (9) and (10)): in case of the households the share of green consumers stabilises when $H_E = H_P$ that ensures that $\dot{\alpha} = 0$, while in case of firms when $F_E = F_P$ that ensures that $\dot{\beta} = 0$. The discussion of the different fixed points proceeds for households and firms separately because – given θ – it is possible to establish analytically the share of firms only once the proportion of households stabilises, and vice versa. Hence, in the households section we will discuss the different evolutionary stable states of green firms given the proportion of households, and vice versa.

For the sake of clarity, we recall the meaning of the different symbols:

- u: constant level of utility from consumption;
- δ: environmental awareness;
- c: extra-cost to finance green start-ups;
- π_P: profits from polluting production;
- π_E: profits from green production;
- γ: multiplicative factor of environmental damages.

A.1.1 Households

Figure 1 shows the three cases – of optimal proportion of green firms – that the system attains once the share of green households stabilises (i.e., $H_E = H_P$ that makes them indifferent between the two strategies). Figure 1(a) shows the case of a single interior intersection between the curves of the expected pay-off of green households (H_E, green line) and polluting consumers (H_P, red line), which are a function of the share of green firms (β). In case $0 < \theta \leq \theta_0 \equiv \frac{u}{\delta}$ there solutions is given either by:

$$\beta_0^* \equiv \frac{1}{2}, \text{ if } 0 < \theta < \min\{\theta_0, \frac{1}{2}\} \tag{13}$$

or by

$$\beta_1^* \equiv \frac{\theta(c+\delta) + \delta + \sqrt{\Delta_\beta}}{2(c+\delta)} \text{ if } \frac{1}{2} < \theta < \theta_0, \tag{14}$$

where $\Delta_\beta = [\theta(c+\delta)+\delta-2u]^2 - 4(c+\delta)(\delta\theta - u)$. From the last term of Δ_β, it is straightforward that $\theta < \theta_0$ is a sufficient condition for $\Delta_\beta > 0$. It holds that if $\delta \leq \frac{c^2+4u^2}{4u}$ the determinant is

[20] We recall that the proportion of polluting agents is the complement of the green one, since the two shares sum up to 1.

always positive, otherwise

$$\Delta_\beta \geq 0 \Longleftrightarrow \theta \leq \theta_1 \equiv \frac{\delta + 2u - 2\sqrt{(\delta - c)u}}{c + \delta}. \tag{15}$$

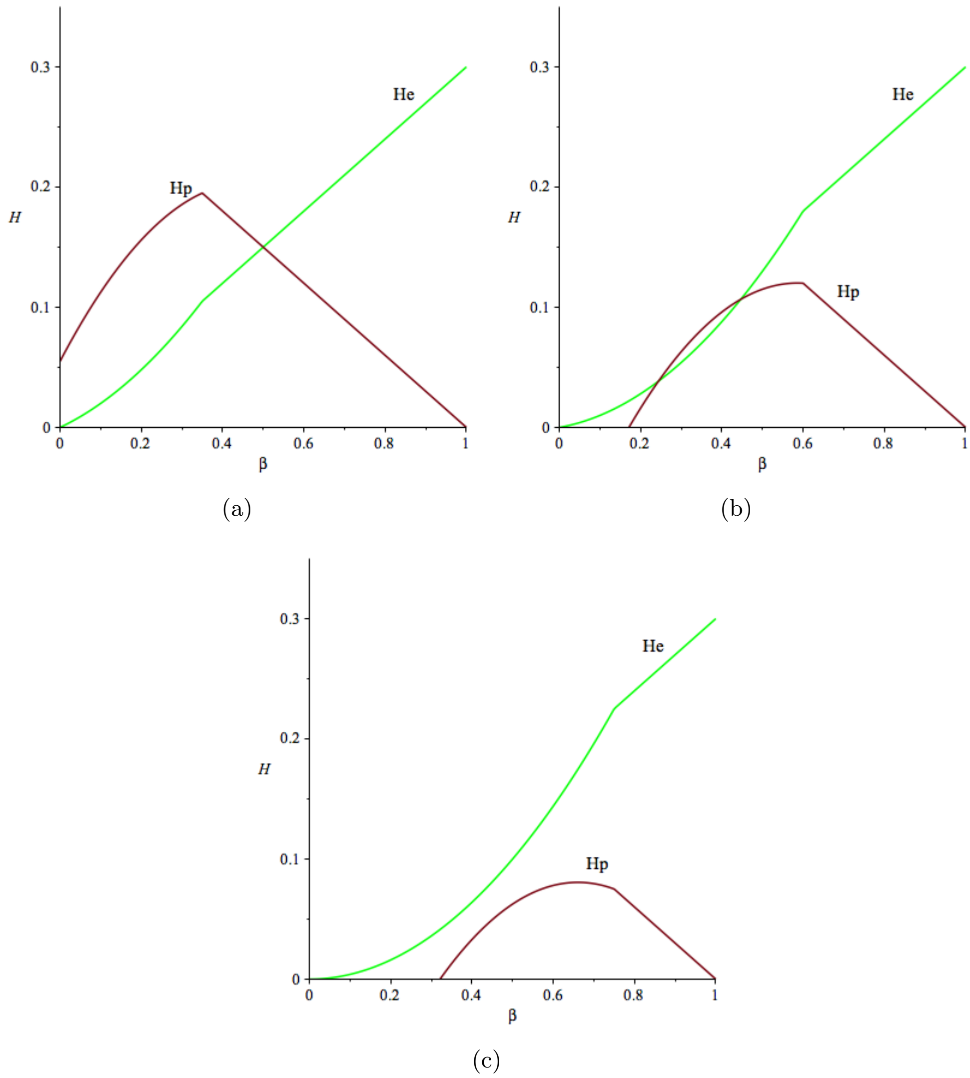


Figure 1: **Analysis of households equilibrium.** Green line shows the expected pay-off of green consumers, while the red curve shows the expected pay-off of polluting consumers. Panel (a) shows the case of single intersection (Δ_β =0), panel (b) the case of two interior equilibrium, while panel (c) the case of no intersection and no interior equilibrium (Δ_β <0).

If the environmental awareness is “sufficiently low” (i.e., $\delta < u$), there is a single intersection between H_E and H_P for any value of $\theta \in [0, 1]$. In case $\beta < min\{\beta_0^*, \beta_1^*\}$, the expected reward of the polluting strategy is greater than the green one, while if $\beta > max\{\beta_0^*, \beta_1^*\}$ the reverse holds. When $\theta > \theta_0$, the two curves – H_E and H_P – can be either secant ($\Delta_\beta > 0$), tangent ($\Delta_\beta = 0$), or without any point in common ($\Delta_\beta < 0$).

When $\theta_0 < \theta \leq \theta_1$ $(= \delta \leq \frac{c^2+4u^2}{4u})$, H_E and H_P have two intersections (see Figure 1(b)): the first one is β_0^* if $\theta_0 < \theta < \min\{1/2, \theta_1\}$, or β_1^* if $\max\{\theta_0, 1/2\} < \theta < \min\{1, \theta_1\}$. The second solution ($\beta_2^*$) is given by:

$$\beta_2^* = \frac{\theta(c+\delta) + \delta - \sqrt{\Delta_\beta}}{2(c+\delta)}. \tag{16}$$

In this case, if $0 \leq \beta < \beta_2^*$ and $max\{\beta_0^*, \beta_1^*\} < \beta \leq 1$ then the expected pay-off of the green strategy is greater than that of the polluting one, while for $\beta_2^* < \beta < \beta_{0,1}^*$ the reverse holds. Figure 1(c) shows a case in which there is no intersection between the two expected pay-off, to say the green strategy is always preferred for any value of β.

A.1.2 Firms

Figure 2 shows the resulting interceptions between F_E and F_P in the plane $\{\theta, \beta\}$. When $\beta > \theta$ there is an interior value of α (α_0^*), such that firms are indifferent between the two strategies, which does not depend on β. When instead $\bar{\beta} \equiv \frac{\gamma\theta - \pi_P}{\gamma - \pi_P} < \beta < \theta$, there is an interior value of α (α_1^*), such that $F_E = F_P$, but this value is an increasing function of β. Note that $\theta > \frac{\pi_P}{\gamma}$ is a necessary condition to induce at least one firm to deviate from the polluting convention (i.e., when $\alpha = 0$ and $\beta = 0$). More precisely, the two possible solutions are:

$$\alpha_0^* = \frac{\pi_P}{\pi_P + \pi_E}, \tag{17}$$

$$\alpha_1^* = \frac{\beta[\gamma(\theta-\beta) - (\pi_P + \pi_E)(1-\beta)] + \sqrt{\Delta_\alpha}}{2c[(\theta-\beta)(1-\beta)]}. \tag{18}$$

where Δ_α is always positive.[21]

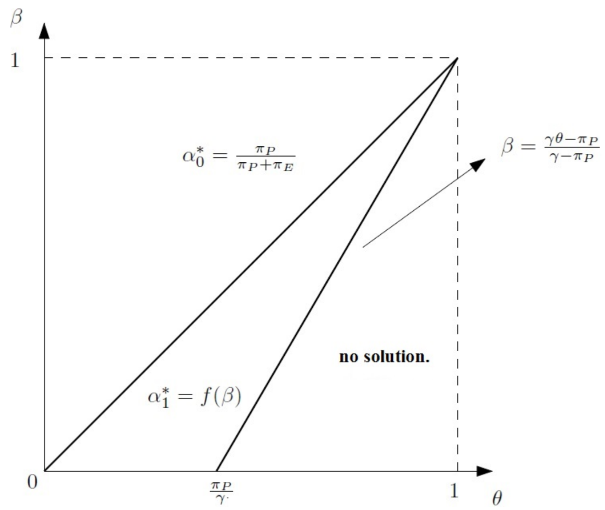


Figure 2: **Graphical analysis of firms' space of solutions.** The intersection between the expected payoff of green and polluting strategies in the plane $\{\theta, \beta\}$.

These results, combined with those of the previous subsection, determine analytically the equilibria of the evolutionary game. In what follows we establish under which conditions (*Regimes*) the dynamic system converges to an interior equilibrium and when it is (locally) stable.

[21] Note that the other solution in α of $F_E = F_P$ is always negative. Moreover $\Delta_\alpha = \beta^2\{(1-\beta)[2\gamma(\pi_P+\pi_E)((\beta-\theta)+(\pi_P+\pi_E)(1-\beta)]+4c(\pi_P-\gamma)(2\theta+\beta^2)+\gamma^2(\theta-\beta)^2\}+4c\{\beta\pi_P(\beta^2(2+\theta)-(\theta+\beta))+\gamma(\beta^2\theta^2-\beta-2\theta)-\theta^2\}$

A.1.3 Regimes

Households and firms change their behaviour according to the replicator dynamics described by Eq. (9) and (10). Given the discussion of Appendix A.1 and A.2, depending on the value of θ we get five *Regimes* (R_i) that qualitatively change the dynamic properties of the system. For the sake of clearness, we assume that the initial condition of the economy is in the polluting convention where $\beta = \alpha = 0$ and that the government establishes a certain level of environmental standard ($\theta > 0$). Figure 3 shows the phase diagram for each Regime. Note that the black circles indicate the (locally) stable equilibria and the dotted line the level of stringency of the environmental law (θ).

R_1: when $0 \leq \theta < \min\{\frac{u}{\delta}, \frac{\pi_P}{\gamma}\}$, the isoclines and the phase diagram of the system are shown in Figure 3(a). In this case there is no interior (locally) fixed points. The introduction of an environmental law ($\theta > 0$) is not sufficient to induce the system to detach from the polluting productive convention. The possible explanations of the failure of the policy (θ) can be found in: (i) consumers are not enough aware of the potential environmental damages (δ low), (ii) high level of utility from material consumption (u high), and (iii) high gap between green and dirty production ($\pi_P - \pi_E$ high) that induces the polluting firms to pay for the environmental damages instead of converting their production toward renewable energies.[22]

R_2 includes two cases: ($R_2\!-\!I$) when $\frac{\pi_P}{\gamma} < \theta < \frac{u}{\delta}$, the polluting convention becomes unstable because the environmental law is high enough to induce the start-up of new green firms as long as $\beta < \bar{\beta}$, that is the condition for which $F_E > F_P$. If $\bar{\beta} < min\{\beta_0^*, \beta_1^*\}$, then all the trajectories departing from the polluting convention converge to the fixed point with coordinates ($\alpha^* = 0$, $\beta^* = \bar{\beta}$). This is a corner solution (Figure 3(b)) that signals the imbalance between the high cost for polluting firms and the low awareness of households to environmental concerns.

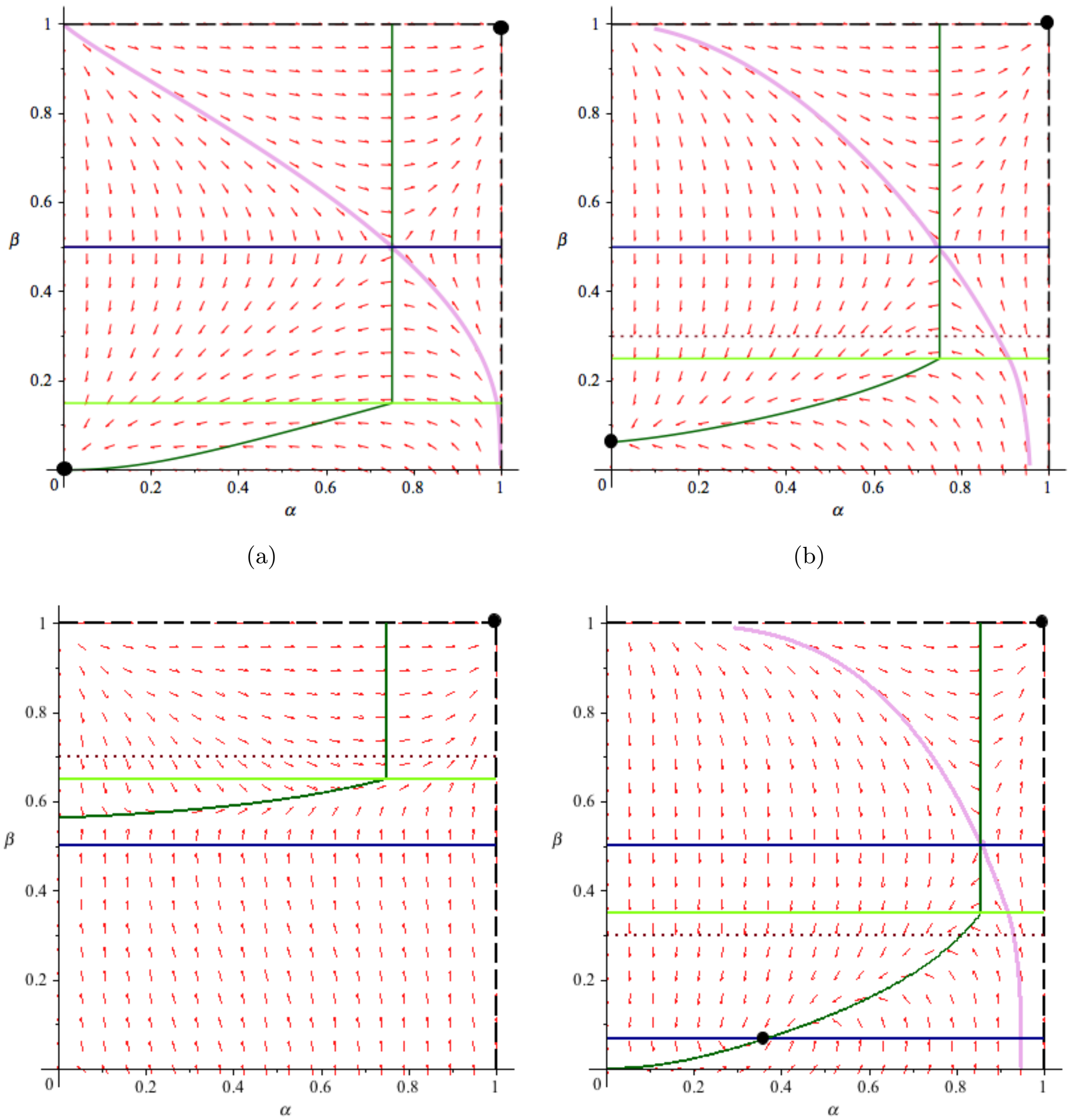
($R_2 - II$) If $\gamma < \pi_P$ and $\bar{\beta} > max\{\beta_0^*, \beta_1^*\}$ the system detaches from the corner solution. As long as β increases the households prefer to choose the green production. This process ends up when $\alpha = \beta = 1$. Thus the only globally stable equilibrium is the green convention (see Figure 3(c)).

R_3: When $\frac{u}{\delta} < \theta < \frac{\pi_P}{\gamma}$, households prefer to choose the green strategy so that they induce the firms to supply more green goods and services. The dynamical system is characterized by two locally stable fixed point, an interior point ($\alpha^* > 0$, $\beta^* > 0$) and the clean convention ($\alpha^* = 1$, $\beta^* = 1$). In this case all the trajectories departing from the polluting convention join the interior equilibrium where $\beta^* \leq \theta$ (see Figure 3(d)). The environmental policy has only a partial effect because θ is not strict enough to induce the expected share of firms to shift their production from the polluting convention. Its impact is indirect and simply stands on the stimulus from the demand side.

R_4: When $\max\{\frac{u}{\delta}, \frac{\pi_P}{\gamma}\} \leq \theta < \min\{\theta_1, 1\}$, households and firms prefer to choose the green strategy. The dynamical system defines two locally stable fixed points, the interior one and the green convention. In this regime, all the trajectories departing from the polluting convention end up to the interior equilibrium where $\beta^* \leq \theta$ (see Figure 3(e)), accordingly the same considerations of the previous regime holds true here.

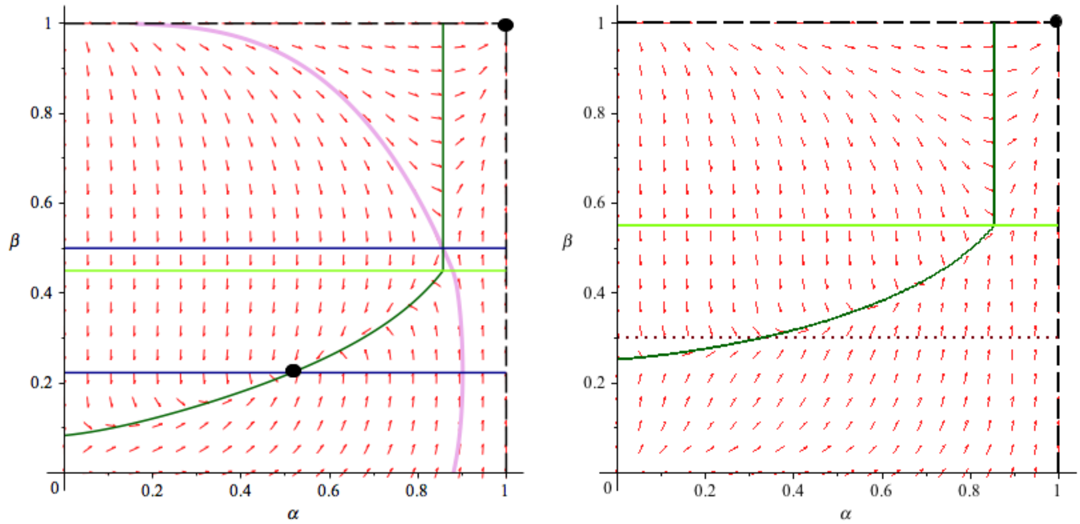
[22] Note that given θ an increase in δ or γ may induce the system to depart from R_1 and to follow one of the other regimes.

R_5: When $\theta_1 < \theta < 1$ the only globally stable equilibrium is the green convention (see Figure 3(f)) because the environmental law is sufficiently high to induce every agent to prefer the ecological strategy. Note that in this case the environmental standards have not to be necessarily strict to obtain the green transition, rather its success is strictly tied with the economic structure of the country, and with the level of environmental awareness, in particular.



(a) (b)

(c) (d)



(e) (f)

Figure 3: **Phase diagram of the dynamical system.** The red arrows show the directions of the trajectory. The isocline of the share of green firms (β) is given by the dark green curve. The isocline of the share of green households (α) is given by the horizontal dark blue line(s). The value of θ is the light green horizontal line. The dot horizontal line is the value of u/δ. The magenta curve shows the basin of attraction of the two convention if applicable.

A.2 Analytical comparative analyses of international environmental standards (θ)

Given the non-linearity of Eq. 5 and 7, we apply a comparative analysis (*ceteris paribus*) to establish under which conditions $\theta_N^{CO} > \theta_S^{CO}$ and when $\theta_i^{CO} > \theta_i^{NC}$ for all $i = \{N, S\}$. In other words, we define the conditions under which a country behaves as the bottleneck of the international agreement – to say when the country establishes the smallest common denominator – depending on the benefit-risk ratio. We compare the results under the hypothesis that countries differ only either in the opportunity costs ($b_i \neq b_j$) or in the risk to suffer economic losses from climate change and global pollution ($a_i \neq a_j$). We assume that both green and polluted profits of the former country follow the same proportion with respect to those of the second country, that is $\pi_{P,N} = m \cdot \pi_{P,S}$ and $\pi_{E,N} = m \cdot \pi_{E,S}$, with $m > 1$, and that the green profits are $\pi_E = n \cdot \pi_P$, with $n \in (0,1)$, in both country. Obviously N is richer than S because $m > 1$, which is a measure of income and technological inequality.

A.2.1 Non-Cooperative Game

Case I - **different climatic risks**: let us assume that both countries have the same marginal benefits, $b_N = b_S = b$ and $d_N = d_S = d$, but different climatic risks: $a_N = \tilde{z} \cdot a_S$, with $\tilde{z} > 0$. Differences in a might be due to different weights put to the environment – which can be related to the economic development of a region – or to the geographical location (e.g., Italy may suffer more from sea level rise than Russia). Country i will be the bottleneck (i.e., if $i = S$

and $\theta_N > \theta_S$, then it results that $\theta^* = \theta_S$) of the IEA game inasmuch as:

$$\tilde{z} > \bar{z}^{NC} \equiv 1 + \frac{b}{a_S}\frac{(1-m)}{(1+m)} \qquad \lim_{m\to+\infty} \bar{z}^{NC} = 1 - \lambda_S \tag{19}$$

where $\frac{b}{a_S} = \lambda_S > 0$ is the benefit-risk ratio of country S given by the benefit of local production and potential losses from global emissions. The threshold $\bar{z}^{NC}$ depends on both the income (and historical) inequality (m) and λ_S. Given that N is richer than S then, independently from λ_S, if country N is more risky ($\tilde{z} > 1$) it prefers a higher joint emission reduction, however the convention will be dictated by country S (i.e., $\theta^* = \theta_S$). The same result holds even when $\tilde{z} < 1$ if $\lambda_S > 1$ and if the level of inequality is sufficiently high ($m \gg 1$). A typical example is given by China which is likely to suffer from extreme climate events (e.g., desertification) but it prefers to further develop the industrial production and it is thus less concerned about emission reductions.

Case II - **different opportunity costs**: let us now consider the opposite case of equal climate damage, $a_N = a_S = a$ but different opportunity costs of abatement: $b_N = \hat{z} \cdot b_S$. In this case country S will determine the stringency of the IEA game inasmuch as:

$$\hat{z} < \bar{\bar{z}}^{NC} \equiv \frac{a\cdot(1+m)}{a(1+m) + b_S\cdot(1-m)} \qquad \lim_{m\to+\infty} \bar{\bar{z}}^{NC} = \frac{1}{1-\lambda_S} \tag{20}$$

where $\lambda_S = \frac{b_S}{a}$ is the benefit-cost ratio. A richer country proposes an higher environmental convention inasmuch as it faces lower opportunity costs and the poorer country expects low benefit-risk ratio. Assume that N has low opportunity costs ($\hat{z} < 1$) and that $\lambda_S < 1$, then $\theta_N > \theta_S$ always because the threshold is greater than 1. If $\lambda_S > 1$, and $m \gg 1$ then $\bar{\bar{z}}^{NC} < 0$ and thus country N will dictate the IEA. Indeed, country S, though poorer, faces a greater opportunity cost with respect to the same climate risk. Note that our results confirm the inverse relation between damage and opportunity costs; furthermore, we show that the level of inequality can lead to counter-intuitive results where, for instance, a riskier country prefers a lower level of emission abatement.

A.2.2 Coordinated Game

Case I - **different climatic risks**: let us assume that both countries have the same marginal benefits, $b_N = b_S = b$ and $d_N = d_S = d$, but different climatic risks: $a_N = \tilde{z}a_S$, with $\tilde{z} > 0$. In this case country S will always be the bottleneck of the IEA game because $m > 1$. It means that, independently from the level of climate risk, the poorest country always dictates the IEA. A possible explanation is that, in a context of coordinated maximization, S knows that, even when it is more risky ($\tilde{z} < 1$), the same percentage of emission reduction after the IEA has the same opportunity cost in both countries. However, in absolute values, N will reduce more because the amount of its polluting production is greater.

Case II - **different opportunity costs**: we assume that $\mathrm{b}_N = \hat{z} \cdot b_S$, then country S will be the bottleneck iff:

$$\hat{z} < \frac{2a(1+m)}{2a(1+m)+b_i(1-m)} = \bar{\bar{z}}^C \qquad \lim_{m\to+\infty} \bar{\bar{z}}_C = \frac{2}{2-\lambda_S} \tag{21}$$

thus the same reasoning for uncoordinated equilibrium holds here, where the only exception is represented by the fact that now the benefit-risk ratio is halved since that we are considering the aggregate welfare function. Moreover, in this case, the coordinated equilibrium is always higher than the uncoordinated, in both countries, for each $\hat{z} > 0$.

A.2.3 Games Comparison

Here we compare the stringency of environmental laws under the non-cooperative and the coordinated frameworks. We determine two thresholds ($0 < \zeta_i^C < 1 < \zeta_j^C$) which define the space where coordinated environmental standards are higher in both countries, that is:

$$\theta_i^{CO} > \theta_i^{NC} \qquad if \qquad \tilde{z} > \zeta_i^{CO} \tag{22}$$

$$\theta_j^{CO} > \theta_j^{NC} \qquad if \qquad \tilde{z} < \zeta_j^{CO} \tag{23}$$

$$\zeta_i^{CO} \equiv \frac{1}{2}\frac{\sqrt{b^2+4a_i^2}-b}{a_i} \qquad < 1 \qquad always \tag{24}$$

$$\zeta_j^{CO} \equiv \frac{\sqrt{a_i^2+a_ib}}{a_i} \qquad > 1 \qquad always \tag{25}$$

Hence, for $\tilde{z} \,\epsilon\, (\zeta_i^C, \zeta_j^C)$ both N and S find optimal to fix more stringent emission reductions under a coordination regime. Differently from what found in a large part of literature, here coordinated actions are not necessary more environmental friendly, but their success depends on the level of inequality, in terms of potential economic losses due to climate change. Notice that the space for which coordination leads to curb more emissions increases with respect to λ_i, in fact $\frac{\partial \zeta_i^C}{\partial a_i} > 0$ and $\frac{\partial \zeta_i^C}{\partial b} < 0$, furthermore $\frac{\partial \zeta_j^C}{\partial a_i} < 0$ and $\frac{\partial \zeta_j^C}{\partial b} > 0$.