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Cooperation on Carbon Emissions: a game-theoretic approach

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1. Introduction

The adverse effects of climate change are becoming increasingly visible and dangerous, bringing the problem of global warming to the attention of policy makers like never before.

Nonetheless, this phenomenon has been known since the end of last century, together with the fact that human activity has heavily contributed to altering the natural course of climate events. The consequences of climate change, discussed in the following section, are several and of various extent, and beside deeply affecting our natural ecosystem, they also have a high economic and social cost. Countries are affected differently and have different level of risks, but everyone agrees on one thing: we cannot afford to exceed the 2°C threshold. Indeed, the natural, social and economic consequences of the rising temperatures change drastically between an increase of 1.5°C and one of 2°C with respect to preindustrial temperatures. The main objective of international cooperation is to stay below the global average temperature increase of 2°C, avoiding catastrophic consequences. This result is achievable only through a serious cooperative commitment. However, so far, international cooperation efforts have failed, as described in section 3. The *Kyoto Protocol* has been subject to severe criticism for a number of reasons including its lack of obligations for developing countries and the fact that that failure to meet country-specific emissions-reductions targets carried no sanctions. Subsequently, the *Paris Agreement* required all 196 ratifying countries to commit to country-specific emissions reduction targets. Nevertheless, once countries set their national targets, there is no monitoring mechanism to ensure they meet those targets and thus the agreement is not giving the expected results. Strategic interaction among countries plays an important role in the failure of international agreement on emission reduction. The most significant issue is that climate change and greenhouse gas reductions are public goods: everyone can suffer from climate change and everyone can enjoy the benefits from emission reduction. This public-good nature has as main consequences the fact that it provides incentives to freeride — to enjoy the benefits while avoiding paying its share. The countries involved in negotiations are also very different among each other, further complicating the results of negotiation. In addition to those mentioned above, there are many other variables that determine the outcome of international agreements, including the frequency of interaction, the perception of future benefits and the ability of country to adapt to changes thanks to technological innovation. All these elements can be captured in a stylized model that is proposed and discussed in section 4. There is, thus, the necessity to find a way that takes into account and weakens these elements in order to promote cooperation and avoid catastrophic outcomes. A possible solution is described in the last section.

2. The Challenges of Climate change

In recent times, we have started to see the effects of climate change. This issue has recently been brought to the attention of everyone mainly thanks to movements such as Fridays for Future, but this phenomenon has been known since the end of last century. What was also known is the anthropogenic cause of climate change:

human activity has strongly contributed to altering the natural course of climate events, rendering such changes much more brutal and difficult to predict. The impacts of climate change are several and of varying importance, and scientists claim that the damages of rising temperatures will increase over time. Such effects, including sea level rise, increasing extreme weather events, droughts and floods, do not only impact the wildlife and our health but also represent an enormous cost for the economy and the society. Although difficult to precisely assess, the difference in damages caused by a further 0.5°C increase in temperature is known to be huge and it is one of the central purposes of international negotiations to avoid this scenario. In the following section, causes and consequences of the climate emergency are explained.

2.1 Climate Change Causes

The Intergovernmental Panel on Climate Change[1] (IPCC) defines Climate change as "a change in the pattern of weather, and related changes in oceans, land surfaces and ice sheets, occurring over time scales of decades or longer".[2] The causes of climate change are both natural and anthropic. Natural causes include internal movements — internal exchanges of water, energy and carbon between the Earth's surface and the atmosphere — and the impact of external factors such as changes in volcanic activity and solar radiation. The human impact on climate change is primarily attributable to variations in the composition of atmosphere — in particular increases in CO_2 and other greenhouse gases[3] (GHG) due to human activity — and land exploitation which changes the reflectivity of Earth's surface due to changes in the nature of land cover. Greenhouse gases are so called because they act as the glass in a greenhouse: they capture the Sun's heat and prevent it from returning to space. The CO_2 is responsible for 64%[4] of anthropogenic global warming. Its concentration in the atmosphere is currently 40% higher than it was at the beginning of the industrial age. Other greenhouse gases are emitted in smaller quantities, but they capture much greater quantities of heat compared to CO_2, sometimes a thousand times more. Methane is responsible for 17% of anthropogenic global warming, nitrous oxide for 6%. In the IPCC special report[5] on the impacts of global warming of 1.5°C, it is claimed with high confidence that human-induced warming reached approximately 1°C above pre-industrial levels in 2017, increasing at 0.2°C circa per decade. Due to anthropogenic emissions global temperatures will continue to rise for decades and so will the effects of global warming: sea level rise will continue beyond 2100 even if global warming is limited to 1.5°C in the 21st century. The IPCC estimates that, without implementing serious actions, the global average temperatures will increase, on average, of 3°C by the end of the century, but it warns that a temperature

[1] The Intergovernmental Panel on Climate Change established in 1988 jointly by the World Meteorological Organization and the United Nations Environment Programme.
[2] The timeframe considered is usually at least 30 years
[3] That include methane, nitrous oxide, fluorinated gases, plus some chemically manufactured greenhouse gases such as halocarbons
[4] Climate Action - European Commission. 2021. *Causes of climate change - Climate Action - European Commission*.
[5] Ipcc.ch. 2021. *Global Warming of 1.5 ºC*

rise of more than 4.5° C “cannot be excluded.” This scenario would give rise to temperatures that exceed the ranges of temperatures ever experienced by human civilization.

2.2 Climate Change Consequences

The consequences of climate change are several and of different types and dimensions, but scientists claim with confidence — based on evidence — that the net damage costs of climate change are likely to be significant and to increase over time**.** Climate change has not only devastating consequences on wildlife, biodiversity and human health, but it also represents an enormous cost for society and economy. Furthermore, the difference in consequences for a further 0.5°C increase in global temperatures is massive.

2.2.1 Natural Consequences of Climate Change

Climate change impacts all regions around the world in different ways: some regions are experiencing an increase in extreme weather events and rainfall while others are more affected by extreme heat waves and droughts. In general, sea level rise is an indicator that our planet is warming. It can happen for two main reasons, both linked to rising temperatures. When ice on land — glaciers or Polar ice shields — melts, the water contributes to the rise in sea level, and when our oceans get warmer the water expands, also making sea level higher. Sea level rise results in flooding and erosion of coastal and low-lying areas.

Heavy rainfall, droughts, heat waves and other extreme weather events are becoming more frequent, increasing floods and decreasing water quality and availability of water resources in some regions. Carbon Brief has recently mapped[6] every extreme weather attribution study published to date. The study reveals that over the past 20 years the literature is heavily dominated by studies of extreme heat (33%), rainfall or flooding (20%) and drought (17%) and the number of extreme events studied has grown substantially over the past 10-15 years. Furthermore, the analysis found that 70% of the 405 extreme weather events and trends included in the map have been made more likely or more severe by anthropic climate change.

Due to temperature spikes, warmer sea surface and increase in extreme weather events, climate change inevitably affects the habitats of several species, jeopardizing biodiversity. These species must either adapt or migrate to areas with more favorable conditions, but the change sometimes happens so fast to put their life at danger. According to a UN report[7] biodiversity is declining globally at rates unprecedented in human history and the rate of species extinctions is accelerating: around 1 million animal and plant species are now threatened with extinction, many within decades, more than ever before in human history.

[6] Carbon Brief. 2021. *Mapped: How climate change affects extreme weather around the world*.

[7] United Nations Sustainable Development. 2021. *UN Report: Nature's Dangerous Decline 'Unprecedented'; Species Extinction Rates 'Accelerating'*.

2.2.2 Social and Economic Cost of Climate Change

Besides being dangerous for the wildlife, climate change also represents a threat for the humankind. All over the world there has been an increase in the number of heat-related deaths[8] and we are already seeing changes in the distribution of water-borne diseases. Flood hurricanes and other extreme weather events destroy entire territories and infrastructures; these damages to properties, infrastructure and human health imposes heavy costs on society and the economy. According to the European Commission, between 1980 and 2011 floods by themselves affected more than 5.5 million people and caused direct economic losses of more than €90 billion. Generally speaking, sectors that rely strongly on certain temperatures and precipitation levels such as agriculture, forestry, energy and tourism are particularly affected by the climate emergency, but the extent to which climate change affects a certain economic sector depends also on the resources used and the locations in which companies are. Poorer developing countries like Puerto Rico, Pakistan, Philippines, Myanmar and Haiti have been among the most affected[9] by changes in climate in the 21st century. These countries suffered extreme weather events such as hurricanes and cyclones that have destroyed entire cities and killed thousands of people. People living in these countries often depend heavily on their natural environment and have the least resources to cope with climate related emergencies, therefore making the effects of such phenomena even more disruptive for the communities and the economy.

2.2.3 Variation in Consequences between 1.5°C and 2°C

As anticipated, the natural, social and economic consequences of the rising temperatures change drastically between an increase of 1.5°C and one of 2°C with respect to preindustrial temperatures[10]. By 2100, global mean sea level rise is projected to be around 0.1 meter higher with global warming of 2°C compared to 1.5°C. This increase in sea level would expose 10 million more people to related risks[11]. Furthermore, a 0.5°C further rise in temperature would increases mean temperature in most land and ocean regions, extremes temperatures and heavy precipitation in several regions, the probability of drought and precipitation deficits in some regions. As long as concerns biodiversity, of 105,000 species studied, 6% of insects, 8% of plants and 4% of vertebrates are projected to lose over half of their climatically established habitat due to global warming of 1.5°C; with global warming of 2°C these figures would rise to 18% of insects, 16% of plants and 8% of vertebrates. Impacts associated with other biodiversity-related risks such as forest fires and the spread of invasive species are much lower at 1.5°C compared to 2°C of global warming

Climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5°C and increase further with 2°C. An increase of 2°C

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[8] According to World Health Organization (WHO), from 1998-2017, more than 166 000 people died due to heatwaves, including more than 70 000 who died during the 2003 heatwave in Europe.

[9] Iberdrola. 2021. *Which countries are most threatened by and vulnerable to climate change?*

[10] See footnote 5

[11] Based on population in the year 2010 and assuming no adaptation

would indeed result in higher reductions in yields of maize, rice, wheat and other cereal crops. Livestock are also subject to adverse effects due to rising temperatures with respect to feed quality, spread of diseases and resources availability. Speaking of economy, risks to global aggregate economic growth due to climate change impacts are projected to be lower at 1.5°C than at 2°C by the end of this century. Limiting global warming to 1.5°C compared to 2°C is thus fundamental in order to reduce the impacts on terrestrial, freshwater and coastal ecosystems and to retain more of their services to humans. This threshold would also guarantee a reduction in the number of people exposed to climate-related risks, change induced water stress and susceptible to poverty by up to several hundred million by 2050.

3. Why Cooperation is Essential and Why Cooperation Failed

In order to not exceed the critical threshold of 2°C, important mitigation actions must be undertaken. Greenhouse gases mixing globally in the atmosphere make anthropogenic climate change a global problem, therefore, this issue must be addressed with a global effort: international cooperation is *necessary* to significantly offset the effects of climate change. International cooperation has the potential to address several challenges: multiple actors that have different perceptions of the costs and benefits of decarbonizing the economy, emissions and mitigation sources that are unevenly distributed and climate impacts that are difficult to assess and distant in space and time. Besides being necessary, cooperative action to mitigate climate change is also beneficial. The economy would indeed be enhanced by technological innovation and many future costs —inherent to health care systems and natural detriments that will almost surely hinder certain sectors— would be avoided. Although necessary and beneficial, common agreements have not provided a reassuring foundation for fighting climate change. Since changing climate was publicly addressed for the first time — in the late 1980's — no agreement has been built in an effective manner, and no country has seriously committed to its pledges. The reasons for this failure are several, from the perception of the risk to the burden of transaction costs but what is most important, and has sometimes been underestimated, are the problems arising from strategic interaction among countries. In section 2.1 the benefits of cooperative action will be explained, section 2.2 will go over the most important international treaties in the matter of climate change, while section 2.3 will analyze the reason why climate agreements failed and examine some of the issues arising from strategic interaction among countries.

3.1 The Benefits of a Coordinated Action to Mitigate Climate Change

The IPCC defines *emission pathways* as patterns that, given current knowledge of the climate behavior, provide a $\frac{1}{2}$ to $\frac{2}{3}$ chance of a temperature increase either remaining below 1.5°C or returning to 1.5°C by around 2100, thus avoiding the catastrophic consequences of a warming of 2°C or more. All *1.5°C pathways* involve limiting cumulative emissions of greenhouse gases and substantial reductions in other climate forcers. Limiting cumulative emissions, in turn, requires either the reduction of net global emissions of greenhouse gases to zero before the cumulative limit is reached, or net negative global emissions (anthropogenic removals) after the limit is exceeded. Besides avoiding the extremely dangerous consequences of rising temperatures, a cooperative operation to decarbonize the economy — i.e., to work towards reaching net zero or negative cumulative emissions — would also generate important economic benefits. Most of the emissions reductions needed to decarbonize the global economy and thus to fulfill the *1.5°C pathways* can indeed generate economic benefits that outweigh the costs, even during the process itself, before the benefits of reduced climate change arise. First of all, it would mitigate air pollution that, on turn, would help to relieve pressure on healthcare systems globally. In 2010 in China, there has been 1.23 million air pollution-related deaths[12], which represented 9.7-13.2 % of the country's GDP. In the UK, the same year, these figures corresponded to 23000 deaths and around 7% of the GDP. An OECD's report[13] projects the number of global premature deaths due to air pollution to increase to 6-9 million annually in 2060. The estimated annual costs associated with the premature deaths from air pollution — calculated using estimates of the individual willingness-to-pay of reducing risk of premature death — are projected to rise from USD 3 trillion in 2015 to USD 18-25 trillion in 2060. A cooperative action to reduce carbon emissions would also increase innovation. Policies to reduce emissions would increase costs and thus reduce profits of emitting sectors and they would urge producers to research and develop new low-cost technologies to decrease emissions. That would also create a positive "knowledge spillover" of innovation in other industries. Climate mitigation policies would also be a source of jobs, offsetting the increase in unemployment due to the decline of some sectors. UNEP et al. (2008) define *green jobs* as 'work in agriculture, manufacturing, research and development, administrative and service activities that contribute substantially to preserving and restoring environmental quality.

In addition to relieve health care systems, foster innovation and create job opportunities, the transition to a zero-carbon system would make the economies more stable, productive and innovative, it would create more attractive and livable cities, and it would improve the quality and productivity of the natural environment. It would avoid enormous costs due to the loss of infrastructure through disasters like flooding, sea level rise and the difficulties in agriculture. If all countries take the low-cost climate crisis combating opportunities currently available, the total cost of mitigating would be 200-300 billion Euros per year by 2030 — nearly 1% of the projected global GDP in 2030[14]. Eventually, these efforts to decarbonize the economy would also save people and companies money over the medium and long term, considering that transitioning the global energy system to one based primarily on renewable energy would lead to trillions of dollars in financial savings. When considering these — and other — elements to assess the scale of the global and national economic benefit, it is difficult to explain why countries have not taken serious actions yet.

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[12] Hamilton, K., 2021. *Economic co-benefits of reducing CO2 emissions outweigh the cost of mitigation for most big emitters - Grantham Research Institute on climate change and the environment*.

[13] Lanzi, Elisa, and Rob Dellink. "Policy Highlights." *The Economic Consequences of Outdoor Air Pollution,* OECD Publishing, 2016.

[14] Mishra, D., 2020. "Op-Ed: The World Needs to Flatten the Carbon Curve Post COVID-19: Earth.Org - Past: Present: Future." *Earth.Org - Past | Present | Future*

3.2 International Agreements on Climate

Countries have debated how to combat climate change since the late 1980's with the *Montreal Protocol* (1987), which required ratifying countries to stop producing substances that damage the ozone layer, such as chlorofluorocarbons (CFCs).

In 1992 the *Rio de Janeiro Earth Summit* ended in some of the first international treaties on climate change, which become the foundation for following agreements. Among them, the *United Nations Framework Convention on Climate Change (UNFCCC),* ratified by 197 countries, was the first treaty to explicitly address the climate emergency. In this treaty, signatory countries, were not legally bound to reduce greenhouse gases, nor were given targets or timetable to do so, they only agreed on an annual international forum, known as the Conference of the Parties, (COP), aimed at stabilizing the concentration of greenhouse gases in the atmosphere. The third Conference of Parties (COP), in Japan, gave birth to the *Kyoto Protocol*[15]. The Protocol was adopted in 1997 and entered into force in 2005. It has been the first legally binding climate agreement: it requested developed countries to reduce their carbon emissions by an average of 5 percent below 1990 levels and established a system to control countries' progress. Nonetheless, *Kyoto* has been subject to severe criticism for a number of reasons including its lack of obligations for developing countries[16] — neither substantial emitters like India and China were obliged to respect the agreement — and, most of all, its lack of sanctions for noncompliance. Given that failure to meet *Kyoto*'s country-specific emissions-reductions targets carried no sanctions, there has been no incentive to comply with the Protocol. Canada, for instance, ratified the *Kyoto Protocol* in 2002, and committed to a 6 percent cut in its greenhouse gases emissions compared to 1990 levels, but continued to increase its emissions, with the result that in 2005 it emitted 25 percent more CO_2 than it did in 1990. In the following meetings, countries worked to find the successor of the *Kyoto Protocol* but could not find a common agreement. In 2011, the conference in Durban, South Africa, nearly crumbled after the world's three biggest polluters—China, India, and the United States—rejected an agreement proposed by the European Union. Eventually, they agreed to work on drafting a new legally binding agreement not after 2015. The countries also had to decide to extend the *Kyoto Protocol* until 2017 because it was set to expire in a few months from then.

In 2015 — as a result of COP21 — the *Paris Agreement*[17] was eventually stipulated. It represents the most significant global climate agreement yet concluded and requires all 196 ratifying countries[18] to commit to emissions-reduction targets. The so called nationally determined contributions — country-specific targets set by the governments — aim at preventing the global average temperature from rising 2°C above preindustrial

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[15] KYOTO PROTOCOL TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE
PDF: https://unfccc.int/resource/docs/convkp/kpeng.pdf

[16] This was a major reason for reluctance by the U.S. to commit to binding emissions reductions targets. The United States indeed signed the agreement in 1998 but never ratified it and in March 2001 withdrew its signature.

[17] ADOPTION OF THE PARIS AGREEMENT
PDF: *https://www.un.org/ga/search/view_doc.asp?symbol=FCCC/CP/2015/L.9/Rev.1&Lang=E*

[18] Unlike the *Kyoto Protocol*, *Paris* requires nearly all countries—both developed and developing—to set emissions reduction goals.

levels and countries further increase their efforts to keep it below the critical threshold of 1.5°C. The agreement also aims at reaching the net-zero emissions target by the second half of the century. In order to assess the progress in climate change mitigation, countries have established an *enhanced transparency framework* (ETF) under which, starting form 2024, transparent information will be gathered on actions taken, adaptation measures and support provided or received. This information will constitute the *Global Stocktake*, which will assess collective progress towards long-term goals. However, once countries set their national targets, there is no monitoring mechanism to ensure they meet those targets. In November 2020, the former President Donald J. Trump withdrew the United States, the world's second-largest emitter, from the *Paris Agreement* saying that it was imposing "draconian financial and economic burdens" on the country. However, President Joe Biden re-entered the *Paris Agreement* on his first day in office. Only a few countries, namely Angola, Eritrea, Iran, Iraq, Libya, South Sudan, Turkey, and Yemen, have not formally signed the agreement. Nevertheless, according to some scientists, the Paris Agreement will probably not be enough. The countries' pledges are considered not to be enough and there is uncertainty on whether the countries will actually meet them. The Germany-based nonprofits Climate Analytics and NewClimate Institute developed a tracker[19] that projects current policies to result in an increase above preindustrial temperature of up to 3.9°C, while, if governments respect the pledges they have made under the agreement, it could still result in a 3.3°C rise.

3.3 Why Have International Efforts Failed

The traditional belief is that cooperation stems from the interests shared by all countries in the mutual problem of climate change. Failures in cooperation, therefore, are the result of some "market failure"—for example, the failure of countries to fully comprehend their interests, or the transaction costs associated with assembling many nations in order to negotiate. International institutions—such as treaties, organizations, and behavioral norms— facilitate cooperation by reducing those transaction costs, focusing efforts on specific issues and creating reputational risks for failure. Nevertheless, the efforts made so far to find proper global agreements have been shown to not be enough despite the role of international institutions.

The question at this point is, why have international efforts in negotiations produced such flawed efforts?

Before examining some possible explanations, we need to consider a number of issues that characterize the climate change problem. The first aspect is the increasing capacity of countries to "climate proof" themselves. Human capacity of adapting to changing weather — such as by building dikes, glasshouses for agriculture and irrigation systems— has risen sharply in the last century and shows no sign of abating. Those countries that have the greatest adaptation capabilities climate change and which are also, in general, the largest emitters are those most proofed against unpredictable climate, and have, therefore, less interests in cooperating to reduce emissions. Another aspect of climate science is that some nations may benefit from a small dose of changing climate. The most glaring example is Russia, where agriculture and forestry—being the most climate-sensitive

[19] "The CAT Thermometer." *The CAT Thermometer | Climate Action Tracker*

of economic activities—would probably gain from longer growing seasons that follow warmer weather. The third aspect of climate emergency is that there is one scenario that all countries want to categorically avoid: catastrophic effects of climate change, that are likely to happen if the increase in temperature reaches 2°C or more. Even the most "climate proofed" countries will struggle responding to such abrupt change. All these aspects are universal truth that contribute to the following possible economic explanations to failed negotiations.

The first valid explanation for the failure of international climate agreements is that climate change is a massive collective action problem, and the transaction costs of negotiations among countries on greenhouse gas emissions reductions are too great. From an economic point of view emitting greenhouse gases can be considered an over-supplied activity: the benefits of emitting greenhouse gases are internalized within a country, but the costs are distributed among all countries. The cost of organizing negotiations and of actually respecting the agreements is the main challenge when trying to correct the oversupply problem. Nevertheless, this explanation seems to be insufficient as the *Kyoto Protocol* and the *Paris Agreement*, although flawed, reduced the transaction costs of negotiations. A convincing political economy explanation focuses on domestic politics for emission reduction. The difficulties in finding a common agreement on the internal policies within a country — thus in defining the country-specific targets and how to reach them — can greatly complicate the international negotiations. As it happens among countries, also within a country there can be considerable differences among regions in their activities and reaction to climate change, with the consequence that speaking with one voice when deciding which actions to undertake becomes very difficult. China, for instance, is divided between rich regions vulnerable to the effects of climate change and poor regions concerned only about production and economic growth and this has given rise to conflicting opinions on how intensely the country should pursue greenhouse gas reduction policies. Nonetheless, the threats of climate change are global, and the consequences will affect all countries. It may be true that a cost-benefit analysis of undertaking greenhouse gas mitigation actions is country-specific and differ for differently featured individuals all over the world, but climate change is not a trivial matter for anyone. Yet, the way some countries seem to cope with the issue shows that some still think that the impact will not affect them. Another possible explanation emerges at this point, concerning the psychological aspect of climate change and the perception of risks which suggests that many might not believe that climate change is a real problem. The fact that climate effects have long time horizons does not help the cause. The calculation of hesitant countries could be considered rational. Fighting global warming would require them to sustain an important cost in reducing emissions today for uncertain benefits, or uncertain avoided costs, in the future. On the contrary, they could invest the same resources in economic growth, which will improve their future capacity to adapt to climate change. A proper response would include a set of public policies intended to raise public awareness, diminishing the gap between what scientists know and what the public knows. As long as concerns national leaders and international negotiators, either they believe it or they do not, but if the problem is the public psychology and perception of risk, the current is not a proper response.

None of these explanations for the failure of negotiations to reach an international solution takes into account the strategic interactions among countries as individual players. Yet, the problem that seems to slow down the active response of the countries is countries waiting to see what other countries will do, because what countries do deeply affects others' decisions. In international relations theory, realism assumes that states are self-interested rational actors and will do what is in their best national interest. Although this theory has been challenged by more complex theories that add elements to the puzzle, including a "constructivist" doctrine that focus on non-state actors that influence major international events and politics, we should consider it valid when making assumptions on the strategic interaction of countries. An appropriate model of international climate negotiations should address a number of issues concerning the nature of the climate change problem and individuals' strategic actions during negotiations. These issues are summed up in the following.

1. *Differences in players' features*

When constructing a game theoretical model, we cannot consider all the countries signatories of the agreement as players with the same characteristics. Countries have different backgrounds, different needs and resources and we cannot treat them as their strategic decision making was the same. For sake of simplicity, we can divide countries and geographic areas in three categories: the producers, the mitigators and the researchers. Producers are those — either developed or developing — geographical areas that leverage on economic growth and are not careful about emissions. Producers are also more efficient than others in production, which means that for a certain amount of value created they emit less than other countries that create the same value. This macro-group includes North America, East Asia and the Indian subcontinent.
The mitigators are mainly poor — not developed or developing countries — that are very rich in biodiversity and natural heritage and can carry on mitigation projects such as reforestation. However, when they produce, they emit more than areas in the previous and in the following categories. Mitigators include Latin America, Africa and Southeast Asia.
Eventually, researchers are countries or geographical areas that invest heavily in research and development and are the most likely to make progress in finding technological solutions to mitigate. As long as concerns production efficiency, they are located in the middle after producers but before mitigators. This category includes Europe and Oceania.

2. *Greenhouse gas reductions has a public-good nature and free-rider effects of mitigation*

The greenhouse effect offers a clear example of a public goods problem. Public goods are non-excludable (once the good is supplied to one person it is necessarily supplied to everyone) and non-rival in consumption (the good can be consumed by one consumer without preventing simultaneous consumption by others). Reductions of greenhouse gas emissions are perfectly non-excludable and non- rival. The cut on emissions by one individual player — either one emitter or one country — is inevitably to the benefit of all the players, in the form of avoided damages and prevented risk of climate change. Consumption of this benefit is necessarily enjoyed by everyone and one country cannot prevent the others from enjoying it. Global public goods are most easily provided when a single dominant country, or a small group, is able to take the lead. In the context of climate change, however, no country or group can readily take on that role. Public goods are typically underprovided in the absence of such governing authority, because each actor has an incentive to freeride — to enjoy the benefits while avoiding paying its share. Free-riding may take several forms. One can be avoiding costly mitigation actions while making others undertake them, another may be avoiding the costs of research and development of innovative technologies to reduce greenhouse gas emissions and eventually taking advantage of others' findings. A bothersome aspect of the free-riding problem in the climate change context is that the greater the amount of mitigation actions undertaken by a country or a group of countries, the greater the incentives for other countries to free- ride. Besides enjoying the co-benefits without embarking on costly actions, free riders will also benefit from reduced fossil fuel's price. Countries that cut their emissions will almost certainly reduce fossil fuel consumption, and thus reduce the global price of fossil fuels, which in turn encourages other countries to increase the use of fossil fuels, nullifying to some extent the emissions reductions achieved by the first countries. To further worsen the free-riding problem is a harsh reality: if one country waits to cut emissions, other countries will also pay for the delay. If countries like China continue to erect coal-fired power plants, the future costs of retiring will not be borne by those countries alone. The implication of the free-riding problem is that action to reduce emissions needs to be global: cooperative action is fundamental.

3. *Uncertainty regarding damages and adaptation costs and the discounting factor*

It is not certain which, when and where the effects of climate change will occur. It is difficult to clearly assess the relation between concentrations of greenhouse gases to specific global temperature increases. This uncertainty makes it difficult for present governments to understand the future impacts of climate change, nor to communicate the risk to its citizens and plan for the future of young generations. The main consequence of the uncertainty is that a country's perception of its vulnerability may change when the information changes, making the planning of a long-term strategy even more difficult. Yet, if a country adopts a cost-benefit analysis for deciding whether or not to undertake greenhouse gas emissions mitigation, this information seems necessary. The future effects of climate change imply that a cost-benefit analysis is extremely sensitive to the discount rate chosen. The discount rate varies deeply according to the piece of information currently possessed, to the perception of the risk someone has and to the predictions made. Furthermore, delayed action, allowing concentrations of greenhouse gases to increase before drastic reductions are undertaken, poses some risks of irreversible ecological damages that are often disregarded.

4. *The savings in mitigation costs of coordinated early action*

Once emissions rise to a certain level, the emissions reductions to lower greenhouse gas concentrations to reasonable levels become exceedingly costly. Furthermore, early action by only one country is more costly because it makes lose opportunities to embark on early coordinated mitigation and prepare for transition into a less carbon-dependent economy. It is evident that efforts to reduce greenhouse gas emissions that are made globally will be more effective than those made by single countries or small groups of countries. This is true especially when the challenge is to find innovative solutions: some research and development efforts might benefit from economies of scale. For instance, although very efficient, carbon capture, utilization and storage (CCUS) technology is not yet considered a very cost-effective emissions reduction measure. However, thanks to economies of scale, CCUS' price has decreased drastically, the cost of CO_2 capture in the power sector has come down by 35%[20] from the first to the second large-scale CCUS plant, and this trend is expected to continue as the market further expands. If the costs are shared among several players, it is easy to undertake such efforts and to bear the costs of research, facilitating the creation of co-benefits for everyone. In conclusion, the above mentioned and other gains from early coordinated action produce reductions in mitigation costs. Conversely, a lack of coordination is more costly.

5. *The role of technology*

The rate of technological innovation is another element that must be taken into account when modeling the optimal path of mitigation. Besides its role in reducing emission or capturing emissions, technology has a fundamental role when it comes to adaptation. How countries adapt to climate change, may profoundly affect how they currently face the problem. Furthermore, adaptation research has the potential to detract from the mitigation mission and take resources away from mitigation efforts. As long as technological innovation is concerned, there is indeed a tradeoff between emission reduction and adaptation, and countries need to choose how to allocate resources, even compromising international negotiations when countries' decisions go in opposite directions.

6. *International climate negotiations and mitigation actions take place over many time periods and defy traditional game-theoretic models*

International climate negotiations are so complex that it is difficult to characterize them using labels traditionally used by game theoreticians to determine model structure. They can certainly be sketched using finite and infinite repeated games, but the complexity of strategic interactions in international climate negotiations poses challenges for the modeler. Communication among countries, which could take the form of a costly commitment to reduce emissions, take place over many time periods and can also have the effect of lowering future mitigation costs for everybody. The complex nature of climate change suggests that it should be modeled as a repeated game where actors have the possibility to cooperate or deviate from

[20] Baylin-Stern, A., and Berghout N., 2021, "Is Carbon Capture Too Expensive? – Analysis." *IEA*, IEA.

cooperation, but in which certain parameters are inserted to take into account the above-mentioned features of strategic interactions in negotiation on climate change.

4. A Stylized Model of International Negotiations on Carbon Emissions

Taking into account all the considerations made above on strategic interaction among countries, the following section will propose a game-theoretic model for international negotiations on carbon emissions. The model proposed is a repeated Prisoner's Dilemma with 2 players, this model accurately capture the nature of countries decisions taking concerning reduction of carbon emissions. In particular, in a static Prisoner's Dilemma, each player is incentivized to deviate from cooperation (i.e., deviation is each player's dominant strategy), but the payoffs if both countries deviate are lower than the payoffs resulting from cooperation, thus underlying the importance of a coordinated action. However, the phenomenon of decision making for mitigation actions is better described by a dynamic game. Countries indeed negotiate over a potentially infinite period of time and their action to reduce carbon emissions are assessed periodically. The strategy that better captures negotiations, in this case, is Grim Trigger strategy. Although countries might be able to reconsider their decision on whether to cooperate or not, significant technological investments costs exist, and the nature of such investments is the one of sunk cost thus making it difficult to decide, from time to time, whether to reduce carbon emissions or not.

In the first place, results of negotiations will be described using a simple matrix, which will be enriched and complicated to resemble reality as much as possible.

4.1 The Basic Model

Consider the payoffs matrix below described

P2 → P1 ↓	Deviation	Cooperation
Deviation	(0; 0)	$(\alpha B_L; (1-\alpha)B_L - c)$
Cooperation	$((1-\alpha)B_L - c;\ \alpha B_L)$	$(\frac{B_G}{2} - c;\ \frac{B_G}{2} - c\ )$

Where:

- c = cost for emissions abatement

- B_G is the benefit accruing to the whole world (= 2 countries) when each country makes its contribution to emissions abatement. In this case, the global benefit is evenly split between the countries.
- B_L is the benefit accruing to the whole world when only one country makes emissions abatement investments, with $B_L < B_G$. When only one country makes the costly investment then benefits are asymmetrically distributed. We assume that $\alpha < \frac{1}{2}$

If

$$\alpha B_L > \frac{B_G}{2} - c > 0 > (1-\alpha)B_L - c$$

the game becomes a Prisoner's Dilemma.

In a static game, each player would choose to deviate. However, if both deviate from cooperation their payoffs are lower than if they both cooperate: $\frac{B_G}{2} - c > 0$

In the repeated game, considering the Grim Trigger Strategy the payoffs are:

$$V_i^C = (\frac{B_G}{2} - c)(1 + \delta + \delta^2 + \cdots)$$

$$\Leftrightarrow V_i^c = \frac{(B_G - 2c)}{2(1-\delta)}$$

And

$$V_i^D = \alpha B_L + 0(\delta + \delta^2 + \cdots) = \alpha B_L$$

Thus, cooperation is convenient if:

$$V_i^c \geq V_i^D$$

$$(1) \Leftrightarrow \frac{(B_G - 2c)}{2(1-\delta)} \geq \alpha B_L$$

$$\Leftrightarrow (B_G - 2c) \geq \alpha B_L 2(1-\delta)$$

$$\Leftrightarrow 2\alpha B_L \delta \geq 2\alpha B_L + 2c - B_G$$

$$\Leftrightarrow \delta \geq \frac{2\alpha B_L + 2c - B_G}{2\alpha B_L}$$

$$\Leftrightarrow \delta \geq \delta^* = 1 - \frac{B_G - 2c}{2\alpha B_L}$$

Considering that:

$$\frac{B_G}{2} - c \geq 0 \Longrightarrow \frac{2c - B_G}{2} = -\left(\frac{B_G}{2} - c\right) \leq 0$$

and

$$\frac{B_G}{2} - c < \alpha B_L$$

The discount factor δ must be higher than 1-x (where x=$\frac{B_G-2c}{2\alpha B_L}$) for cooperation to be convenient.

4.2 Frequency of Monitoring: decision making every period T (T> 1)

The first consideration that must be done is that decision making happen in a dilated time and negotiations and monitoring do not occur every year. In the case of *Paris Agreement*, the first global stocktake, to assess collective progress, will be in 2023[21] and every five years thereafter, unless otherwise decided by the CMA[22]. This means that — despite production and emissions are continuous factors over time — assessment is done only over a time period T > 1 (T=5 in the *Paris Agreement*). In this situation, the payoff from cooperation changes accordingly to the change in the period of time.

$$V_i^C = (\frac{B_G}{2} - c)(1 + \delta^T + \delta^{2T} + \cdots)$$

$$\Leftrightarrow V_i^c = \frac{(B_G - 2c)}{2(1 - \delta^T)}$$

While the payoff from deviation stays the same, as they are not affected from future discounting (i.e. payoffs after period 1 are always null).

This consideration changes (1) into the following:

$$(2)\ \frac{(B_G - 2c)}{2(1 - \delta^T)} \geq \alpha B_L$$

Thus, computing the condition for cooperation becomes:

[21] "Global Stocktake (Referred to in Article 14 of the Paris Agreement)." *Unfccc.int*, United Nation Climate Change.

[22] The Conference of the Parties, the supreme body of the Convention, shall serve as the meeting of the Parties to the Paris Agreement. All States that are Parties to the Paris Agreement are represented at the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement (CMA), while States that are not Parties participate as observers. The CMA oversees the implementation of the Paris Agreement and takes decisions to promote its effective implementation.

$$(3)\delta \geq \delta^* = \left(1 - \frac{B_G - 2c}{2\alpha B_L}\right)^{\frac{1}{T}}$$

As long as the time period T increases, the critical discount factor δ^* increases as, making cooperation more difficult. Indeed, when countries interact, and are monitored, less frequently, cooperation becomes more difficult because the perceived future cost of retaliation is further discounted.

4.3 What if negotiators are not alike?

As explained in the previous section, we cannot consider all the countries signatories of the agreement as players with the same characteristics. Due to different backgrounds, different needs and resources, we cannot treat countries as their strategic decision making was the same. The three categories — the producers, the mitigators and the researchers — have different levels of production efficiency and of emissions abatement costs. Consider the producers: producers have a high level of production efficiency and their emissions for a certain level of production are less compared to the other two groups. This feature can be described by assessing the extent of benefits generated when such countries make emissions abatement investments by their selves (B_L). Due to the high efficiency, if producers make these investments or start to produce less, benefits accruing to the whole world (B_L) are higher than if the same investments are made by researchers. Benefits accruing to the whole world when researchers cut production are in turn higher than the one of mitigators, which would need to drastically reduce their production or make more substantial investments to reach the same level of emissions mitigation. Therefore $B_L^P > B_L^R > B_L^M$ when taking into account the same level of decrease in production.

For this reason, an asymmetry arises in the assessment of the threshold over which countries would decide to cooperate. We thus need to consider three different discount factors.

For producers

$$\delta^P \geq \delta^{P*} = \left(1 - \frac{B_G - 2c}{2\alpha B_L^P}\right)^{\frac{1}{T}}$$

For researchers

$$\delta^R \geq \delta^{R*} = \left(1 - \frac{B_G - 2c}{2\alpha B_L^R}\right)^{\frac{1}{T}}$$

And for mitigators

$$\delta^M \geq \delta^{M*} = \left(1 - \frac{B_G - 2c}{2\alpha B_L^M}\right)^{\frac{1}{T}}$$

All rest equal and considering that $B_L^P > B_L^R > B_L^M$, the critical δ for producers is higher than the one for researchers, which is in turn higher than the one for mitigators ($\delta^{P*} > \delta^{R*} > \delta^{M*}$) meaning that producers are less incentivized to cooperate for emissions reduction than both researchers and mitigators. Sticking to a 2-countries-world, we can say that whenever producers are involved into negotiations, cooperation becomes more difficult. The easiest form of cooperation is the one between two mitigators countries.

Another element that must be examined when distinguishing among the three groups is the cost for emissions abatement: *c*.

Due to the nature of researcher countries, their investments cost can be considered to be smaller than the one of both producers and mitigators. Researchers have indeed more capabilities to undertake an efficient investment in technology that reduce carbon emissions. Producers can be found in the middle, while mitigators which are mainly developing or developed countries, would incur in higher costs if they invest in R&D. Therefore, $c^M > c^P > c^R$ and also in this case, an asymmetry appears.

For sake of simplicity, consider all the benefits accruing to the whole world when countries undertake mitigation actions to be the same for the three groups. In this case, the higher the cost, the more difficult is for countries to cooperate.

Discount factors in this case become the following:

For producers

$$\delta^P \geq \delta^{P*} = \left(1 - \frac{B_G - 2c^P}{2\alpha B_L}\right)^{\frac{1}{T}}$$

For researchers

$$\delta^R \geq \delta^{R*} = \left(1 - \frac{B_G - 2c^R}{2\alpha B_L}\right)^{\frac{1}{T}}$$

And for mitigators

$$\delta^M \geq \delta^{M*} = \left(1 - \frac{B_G - 2c^M}{2\alpha B_L}\right)^{\frac{1}{T}}$$

All else equal and considering $c^M > c^P > c^R$, the critical δ for mitigators results higher than the one for producers, which is in turn higher than the one for researchers ($\delta^{M*} > \delta^{P*} > \delta^{R*}$). Thus, in this case, when mitigators are involved in the game, coordination becomes more difficult, while two researcher countries can reach a cooperative outcome more easily.

These two elements — production efficiency and cost of investments— should be combined to better analyze the situation. To perform an accurate assessment, country specific characteristics should be taken into account and a comparison between each country's benefit provided and cost of investments is necessary. However, a general consideration can be done in this regard. Considering both elements together and given the results of the analyses above, we can say that researchers are the countries that would most probably cooperate. These finding is supported by the current situation: Europe — a quintessential researcher— is one of the leading parties[23] of the transition to a green economy.

4.4 Free Riding

Due to the fact that greenhouse gas reductions have a public-good nature, the free riding effect is almost unavoidable. Free riding has a triple nature: countries can enjoy the co-benefits without embarking on costly actions, free riders will also benefit from reduced fossil fuel's price or they can avoid the costs of research and development of innovative technologies to reduce greenhouse gas emissions and eventually take advantage of others' findings. The possibility to enjoy such benefits without making substantial investments, not only makes deviation convenient for some countries, but also disincentives the others due to the fact that the benefits arising from their costly action are spread, although asymmetrically, also to other countries, somehow diminishing the cooperative countries' benefits. This aspect is captured in the model by the coefficient α, which determines to which extent the benefits produced by one country can be enjoyed by another country which do not undertake mitigation actions. For the nature of our model, free riding, that is deviating when the other player cooperate, gives the most profitable outcome and make deviation the most appealing (dominant) strategy in the static game.

$$\alpha B_L > \frac{B_G}{2} - c > (1-\alpha)B_L - c$$

The coefficient α also plays an important role when taking into account the repeated version of the Prisoner's Dilemma. Recalling the results derived in 3.2:

$$(3)\delta \geq \delta^* = \left(1 - \frac{B_G - 2c}{2\alpha B_L}\right)^{\frac{1}{T}}$$

It becomes clear that the smaller is α $(0 < \alpha < \frac{1}{2})$, the smaller is δ^*, in words: the less a country can benefit from other's actions (freeride) the more likely is cooperation. The coefficient α may vary according to some factors. First of all, when considering free riding as taking advantage of others' findings in technology research and development, we must assume that the free rider is able to replicate such technology, and this imply that the level of technological progress is high enough. In this sense, α can be considered as a technology driven parameter as it becomes higher as the free rider country is more technological advanced. Then, we must consider that distance among countries makes this factor vary as well. Although it is true that

[23] Recently (21 April 2021) an agreement was reached between the European Parliament and the Council on the climate law. In Brussels, negotiators closed the deal, which prioritizes the reduction of climate-changing emissions in meeting the target of reducing them by 55% by 2030 compared to 1990 levels.

CO_2 emissions mix up in the atmosphere and create a global damage, it is undeniable how pollution produced by a certain country affects more neighboring countries than faraway countries.[24] The coefficient α therefore also depends on the distance among the two players: the closest those two countries are, the higher is the benefit that the free riding country will receive.

4.5 Perception of Future Benefits

Countries have different perception of the extent of future changes in climate and consequently they perceive future costs differently. The nature of the phenomenon — almost undetectable on a daily basis— makes climate change more difficult to be understood and somehow feared with respect to other phenomena such as the impetuous Covid-19. For this reason, beside some exceptions, what influences public opinion and political decisions is the country ruling class belief about the dangerousness of the issue and the urgency with which it should be addressed. In the countries where Fridays For Future and other movements arrived, this process is starting to work also the other way round — people are demonstrating to politicians how much they care to quickly solve the problem of climate change. Inevitably some countries are more affected by the impacts of extreme weather events than others[25], risking more lives and losing more money, and are thus more conscious of the benefits a mitigation action would bring them. There is indeed a certain degree of variation when it comes to perception of future benefits, that radically change how countries strategically interact. Suppose the initial matrix changes in the following way

P2 → / P1 ↓	Deviation	Cooperation
Deviation	(0; 0)	$(\alpha B_L;\ (1-\alpha)B_L - c)$
Cooperation	$((1-\alpha)B_L - c;\ \alpha B_L)$	$(\beta_1 \frac{B_G}{2} - c;\ \beta_2 \frac{B_G}{2} - c\ )$

Where β_1 and β_2 capture the sensibility of respectively country 1 and country 2 to estimate future benefits, and the following relation holds:

$$\alpha B_L > \beta_i \frac{B_G}{2} - c > 0 > (1-\alpha)B_L - c$$

[24] : Samreen, Isma; Majeed, Muhammad Tariq (2020) : Spatial econometric model of the spillover effects of financial development on carbon emissions: A global analysis, Pakistan Journal of Commerce and Social Sciences
[25] Eckstein, David, et al. "GLOBAL CLIMATE RISK INDEX 2021 Who Suffers Most from Extreme Weather Events? Weather-Related Loss Events in 2019 and 2000-2019." *Germanwatch E.V.*, Jan. 2021.

With *i*=1,2 and $\beta_i > 0$

The critical discount factor δ^* is affected by the factor β_i. Indeed, the payoff from cooperation becomes

$$V_i^C = (\beta_i \frac{B_G}{2} - c)(1 + \delta^T + \delta^{2T} + \cdots)$$

$$\Leftrightarrow V_i^c = \frac{(\beta_i B_G - 2c)}{2(1 - \delta^T)}$$

Considering the payoff from deviation remain the same, cooperation is convenient if:

$$V_i^c \geq V_i^D$$

$$\Leftrightarrow \frac{(\beta_i B_G - 2c)}{2(1 - \delta^T)} \geq \alpha B_L$$

$$\Leftrightarrow (\beta_i B_G - 2c) \geq \alpha B_L 2(1 - \delta^T)$$

$$\Leftrightarrow 2\alpha B_L \delta^T \geq 2\alpha B_L + 2c - \beta_i B_G$$

$$\Leftrightarrow \delta^T \geq \frac{2\alpha B_L + 2c - \beta_i B_G}{2\alpha B_L}$$

$$\Leftrightarrow \delta \geq \delta^* = \left(1 - \frac{\beta_i B_G - 2c}{2\alpha B_L}\right)^{\frac{1}{T}}$$

With β_i increasing, the critical discount factor decreases, making cooperation easier to achieve. This result is consistent with the meaning of β_i. When this parameter is sufficiently high, i.e. $\beta_i = 1$ or $\beta_i > 1$, the benefits from a collective action mitigation action —or in other words the costs arising from changes in climate— are correctly assessed or even overestimated, and the country is more inclined to cooperate with the purpose of reaching the beneficial condition. If β_i decreases under the neutral status 1, the country underestimates the effect of climate change and the benefits from cooperation, and it is thus less likely to undertake coordinated mitigation actions. This can give rise to a number of asymmetries, because countries are very unlikely to make the exact same evaluations, and when a country with a $\beta_i < 1$ is involved, cooperation becomes more difficult.

4.5.1 The *Russia Case*

The case of Russia, mentioned in the previous section, whose territories could benefit from an increase in average temperatures is noteworthy when discussing perception of future benefits. The fact that an increase in temperatures can benefit the economy of a country in the short term, not only concerns Russia, but also those countries that are in the status quo unable to exploit their territories for agricultural purposes due to the harsh climate. With global warming, if we only consider as a consequence the rising temperatures, northern countries could be able to produce goods that can only be produced in milder climates. In the strategic interaction this is captured by a higher payoff coming from deviation. If such countries deviate from the cooperative mitigation action they gain in terms of economic value. Suppose the payoff matrix is thus redefined in the following way:

P2 → P1 ↓	Deviation	Cooperation
Deviation	(1; 0)	$(\alpha B_L; (1-\alpha)B_L - c)$
Cooperation	$((1-\alpha)B_L - c;\ \alpha B_L)$	$(\beta_1 \frac{B_G}{2} - c;\ \beta_2 \frac{B_G}{2} - c\ )$

Where player 1 is Russia, or any other country that could benefit from a warmer climate and $\beta_1 \frac{B_G}{2} - c > 1$ so that the game remains a Prisoner's Dilemma.

In this scenario the expected payoffs would be the following

$$V_i^C = (\beta_i \frac{B_G}{2} - c)(1 + \delta^T + \delta^{2T} + \cdots)$$

$$\Leftrightarrow V_i^c = \frac{(\beta_i B_G - 2c)}{2(1-\delta^T)}$$

Where *i*= 1,2

$$V_2^D = \alpha B_L + 0(\delta^T + \delta^{2T} + \cdots) = \alpha B_L$$

And

$$V_1^D = \alpha B_L + 1(\delta^T + \delta^{2T} + \cdots) = \alpha B_L + \frac{\delta^T}{(1-\delta^T)}$$

The critical discount factor therefore differs between the two countries:

$$\delta_2 \geq \delta^* = \left(1 - \frac{\beta_2 B_G - 2c}{2\alpha B_L}\right)^{\frac{1}{T}}$$

While for country 1

$$V_1^c \geq V_1^D$$

$$\Leftrightarrow \frac{(\beta_1 B_G - 2c)}{2(1-\delta^T)} \geq \alpha B_L + \frac{\delta^T}{(1-\delta^T)}$$

$$\Leftrightarrow (\beta_1 B_G - 2c) \geq \alpha B_L 2(1-\delta^T) + 2\delta^T$$

$$\Leftrightarrow 2\alpha B_L \delta^T - 2\delta^T \geq 2\alpha B_L + 2c - \beta_1 B_G$$

$$\Leftrightarrow \delta^T \geq \frac{2\alpha B_L + 2c - \beta_1 B_G}{2\alpha B_L - 2}$$

$$\Leftrightarrow \delta_1 \geq \delta^* = \left(\frac{2\alpha B_L + 2c - \beta_1 B_G}{2\alpha B_L - 2}\right)^{\frac{1}{T}}$$

The denominator decreases and the critical threshold is thus higher than the one of country 2, and it give rise to an asymmetry. The critical discount factor for which country 1 and country 2 cooperate is thus the following:

$$\begin{cases} \delta \geq \delta^* = \left(\frac{2\alpha B_L + 2c - \beta_1 B_G}{2\alpha B_L - 2}\right)^{\frac{1}{T}} \\ \delta \geq \delta^* = \left(1 - \frac{\beta_2 B_G - 2c}{2\alpha B_L}\right)^{\frac{1}{T}} \end{cases}$$

$$\Leftrightarrow \delta \geq \delta^* = \left(\frac{2\alpha B_L + 2c - \beta_1 B_G}{2\alpha B_L - 2}\right)^{\frac{1}{T}}$$

Furthermore, we must consider that the future benefits of country 1 are probably underestimated and β_1 is likely to be very small if not approximately zero, further increasing the critical discount factor and making it more difficult to achieve cooperation. Undoubtedly a country that believes that its economy would benefit from climate change has as its wisest strategy the one to deviate from cooperation and somehow facilitate climate change, or at least do nothing do nothing to prevent it from happening.

4.6 Technological Adaptation

The rate of technological innovation is another element that must be considered when creating a model for the optimal path of mitigation. What must be taken into account is that technology has a fundamental role when it comes to adaptation. How countries are able to adapt to climate changes, profoundly affect how they currently face the problem, altering their willingness to cooperate. Furthermore, adaptation research may take resources away from mitigation efforts. This element is extremely important because is able to change the results of negotiation efforts and must be included in the model. Consider modeled world with two countries where, with probability ρ, one of the country (either one, with equal probability) can innovate and increase adaptation and V^I is its corresponding expected payoff. As long as no innovation arises, each country gets an expected payoff given by the following:

$$V_i^C = \left(\beta_i \frac{B_G}{2} - c\right) + \delta^T \left[\left(\frac{\rho}{2} \times V_i^I + \frac{\rho}{2} \times 0\right) + (1-\rho) \times \left(\beta_i \frac{B_G}{2} - c\right)\right]$$
$$+ \delta^{2T}(1-\rho)\left[\left(\frac{\rho}{2} \times V_i^I + \frac{\rho}{2} \times 0\right) + (1-\rho) \times \left(\frac{\beta_i B_G}{2} - c\right)\right] + \cdots$$
$$\Leftrightarrow V_i^c = \frac{(\beta_i B_G - 2c)}{2(1-\delta^T)(1-\rho)} + \frac{(\delta^T \frac{\rho}{2} V_i^I)}{(1-\delta^T)(1-\rho)}$$

Where $\frac{\rho}{2}$ = Prob(Country 1 is the innovator)= Prob(Country 2 is the innovator).

In the absence of innovation, each country gets the cooperative profit $\beta_i \frac{B_G}{2} - c$. Then, in the following periods one county obtains innovation with probability $\frac{\rho}{2}$ and no innovation occurs with probability $1-\rho$. For what concerns the deviating country, if we consider the probability of innovation, the payoff becomes the following

$$V_i^D = (\alpha B_L) + \delta^T \left[\left(\frac{\rho}{2} \times V_i^I + \frac{\rho}{2} \times 0\right) + (1-\rho) \times (0)\right] + \delta^{2T}(1-\rho)\left[\left(\frac{\rho}{2} \times V_i^I + \frac{\rho}{2} \times 0\right) + (1-\rho) \times (0)\right] + \cdots$$
$$\Leftrightarrow V_i^D = \alpha B_L + \frac{(\delta^T \frac{\rho}{2} V_i^I)}{(1-\delta^T)(1-\rho)}$$

The deviating country gets zero profits in the periods subsequent to the first, unless it innovates (which can happen with probability $\frac{\rho}{2}$ in each of the periods following its deviation).

Cooperation is thus sustainable if $V_i^c \geq V_i^D$, which computing becomes

$$\delta \geq \delta^* = \left(1 - \frac{\beta_i B_G - 2c}{2\alpha B_L(1-\rho)}\right)^{\frac{1}{T}}$$

This result is in line with expectations and captures the concept that as long as probability of innovation increases, and countries become more confident so that they might be able to adapt to changes in climate in the future, cooperation become more difficult to achieve.

4.7 Conclusive Remarks on the Model

With models like the one described above it is very difficult, if not impossible, to capture all the variables of this form of cooperation. In reality, decision making on climate mitigation do not happen just at the beginning of the process, but it is a continuous operation that constantly changes the fate of the game.

Furthermore, decision making of a single country is complex and influenced by an infinite number of factors that most of the time are unpredictable and cannot be capture by the model. A clear example of the unpredictability of decision making is given the alternation of governments in the United States. The 44th President, Barack Obama, entered in the *Paris Agreement* and proposed in December 2015 the so-called *Climate Action Plan*[26], involving world leaders in the effort to address the threat of climate change. The following president, Donald Trump, announced the withdrawal of the US from the agreement in June 2017, but UN regulations meant that his decision only took effect in November 2020, the day after the US election. In January 2021, the current president Joe Biden has moved to reinstate the US to the Paris climate agreement just a few hours after he entered the White House. Such changes are unpredictable and can even ignite a spillover effect: a dominant power as the US can persuade other states to follow its modus operandi. These and other significant unexpected factors— as it can be, for instance, a further increase in extreme whether events that urges governments to take serious actions— are difficult to capture, leaving the model somewhat far from the complex reality. However, the model is a functional tool to understand how the factors examined in the previous section —frequency of monitoring, differences in countries' features, free riding, perception of future benefits and technological adaptation— can deeply influence cooperation among countries.

5 How to Promote Cooperation

The question is now "how can cooperation be promoted?" or in other words "how can we provide an agreement that avoids all the elements that are shown to encourage deviation?". A common commitment on carbon emissions reduction needs to be enforceable and enforced as any other commitment. Because deviating from cooperation will undermine the common agreement and jeopardize the efforts of other countries, a well-structured common commitment should automatically incorporate some kind of enforcement. The Kyoto negotiations properly focused on the research for a common pledge, but they demonstrated, after much time spent on searching, that no common quantity commitment can be reached. The result was an uncertain and powerless global cap and the misleading conclusion that a common international pledge is impossible to construct. The idea of seeking for a common international commitment was discarder on the way to the *Paris Agreement*. Indeed, the idea of Paris Agreement is to let every single country pledge to do whatever it wants (nationally determined contributions). This pledge-and-review approach has been shown to be unlikely to work: individually adopted targets do not change countries' self-interest. The main reason is that such agreements (Tokyo and Paris) are not in the form of "I will if you will"[27]. In fact, already under the Kyoto Protocol, many countries, including the United States, Canada, New Zealand, Japan, and Russian, have failed to meet their objectives, while the others continued in their efforts. These agreements work on the presumption that countries act altruistically, but there is no reason to suppose that altruism can solve the tragedy of the commons. Without a common pledge, any agreement would again result weak and fragile and not produce anything like a uniform price on carbon. There are some fundamental issues that must be taken into account,

[26] "Climate Change." *National Archives and Records Administration*, National Archives and Records Administration
[27] MacKay et al., chapter 2; Cramton et al., chapter 4, *Global Carbon Pricing: The Path to Climate Cooperation*. The MIT Press, 2017

which are shown in the previous section to deeply affect the results of negotiations. First of all, climate change is a global public good—all benefit from a good environment, and all suffer from the effects of climate change. As in the case of any public good, there is a problem of undersupply*:* every country would like to "free-ride" and enjoy the benefits arising from the efforts of others in supplying the good. Furthermore, in the case of global warming, we must consider that there are substantial differences among countries: some countries suffer more from the effects of climate change than others, the investments needed to avoid global warming are greater for some than for others, and the ability to undertake mitigating actions and adapt to the consequences are greater for some than for others. How can a common commitment be designed in order to enhance cooperation? In the next section some of important criteria are discussed and a possible solution is examined.

5.1 Quantity versus Price Commitment

In the report *Global Carbon Pricing*, the editors Peter Cramton, David JC MacKay, Axel Ockenfels, and Steven Stoft, and the several contributors, agreed that the most effective way to promote cooperation is to adopt a common pricing for carbon. Quantity agreements have been indeed shown not to be appropriate to address the climate change problem. The difference between the two types of commitment—price and quantity—has been unnoticed in part because in a world without uncertainty they can be economically identical. A global cap might be able to induces a common carbon price, and taxes on carbon at that price would limit emissions to that cap. However, for the purpose of reaching the agreements, the two targets are considerably different. Furthermore, although both quantity and price commitments results are uncertain, to some extent, for the period during which they apply (i.e., in between times of periodic monitoring), uncertainty takes different forms. With the cap-and-trade[28] system, total amount of emissions is known, but the price or cost is uncertain. Vice versa, with a carbon tax, the price or cost of carbon emissions is known, while total emissions are uncertain. On the basis of economic models of climate change that include uncertainty, carbon taxes outperform tradable permits, both theoretically and in numerical simulations.[29] A carbon tax has been argued to be more easily managed and to be more transparent than a cap-and-trade system, and this consideration is particularly valuable in an international context that include all major emitting countries. A global price can be seen as a common commitment, while a global quantity is only a common aspiration. Individual countries can actually implement the global price, and their commitment to the price is enforceable and monitorable, but no country can implement the global cap: an aspiration cannot be enforced. Additionally, the collected revenues from an internationally harmonized carbon tax remain within each country and could be used to reduce other taxes or even be redistributed internally. On the contrary, the revenues generated from an internationally harmonized cap-and-trade system flow as highly visible external transfer payments across

[28] In a cap-and-trade system, the government sets an emissions cap and issues a quantity of emission allowances consistent with that cap. Emitters must hold allowances for every ton of greenhouse gas they emit. Companies may buy and sell allowances, and this market establishes an emissions price. Companies that can reduce their emissions at a lower cost may sell any excess allowances for companies facing higher costs to buy.

[29] Martin L. Weitzman; chapter 8, *Global Carbon Pricing: the Path to Climate Cooperation*. The MIT Press, 2017

national borders, which might be less easily accepted by countries required to pay other countries large sums of tax-financed money to buy permits. In practice, the benefit of a price commitment is that it brings us closer to the final goals: it solves the problem of *who will do how much* for the climate, and it can help to reach the 2°C goal and other focal climate goals, without necessarily undermining the country's welfare. Generally speaking, whenever there are large externalities—as in the case of greenhouse gases—there are solutions that are Pareto superior, where all players would be better off compared to the status quo. The problem in this case is that these Pareto improvements would require developing countries making significant sacrifices that they can hardly afford in order to have developed countries continuing in their promiscuous production patterns—or to compensate developed countries for not continuing in such patterns. The understanding reasoning is that many of the developing countries, are likely to be hurt most by climate change or can more hardly invest in technologies to adapt to adverse effects. Inevitably, if an agreement has to be found, countries will have to decide on some allocation principles, captured by a formula. Therefore, also this circumstance is in favor of the idea that the transition to a decarbonized economy could be reached through the imposition of a moderate carbon tax. According to Joseph E. Stiglitz such carbon charge, for instance at the rate of $80 to $100 per ton, would raise substantial revenue and allow a reduction in other taxes. The reduction in other taxes would have generate net benefits to the society as a whole. Therefore, most countries would see their gains from reductions in emissions more than offsetting the costs that they would incur, so most would see the agreement as positive. However, within many countries, there would be large losers: in oil-producing countries, for instance, oil producers and owners of oil assets would definitely be worse off. In principle, the losers could more than compensated by the winners, but such compensation is rarely made. Thus, the fact that the country as a whole might gain does not necessarily mean that the government would actually encourage the agreement due to the fact that losers (the oil industry) may have a disproportionate power within the country. However, both in the case of a price and quantity commitment, an effective international treaty needs to be binding, which raises bitter questions on enforcement mechanisms and international sanctions.

5.2 Partial versus General Equilibrium

The aim of any global agreement on climate change is to reduce the demand for fossil fuels, which consequently would reduce the tariff associated with fossil fuels making the beneficiary of those tariffs worse off—even if we take into account the benefits they would directly receive from the reduction in the threat of global warming. For this reason, a fully voluntary global agreement among all countries is practically impossible to deliver results. Without any sense of global social responsibility, any country exporting a compelling amount of fossil fuels would be worse off. That is why an agreement would work better if the target was narrower: an agreement among countries without a large domestic fossil fuel sector, willing to cooperate. The combination of social consciousness and self-interest of citizens of other countries could then broaden the membership in this coalition until most countries joined it.

5.3 Voluntary versus Enforceable Agreements

Successful enforcement is a key element for successful cooperation. The current approach (of *Paris Agreement*) works on voluntary plans on emission reductions. Each country can present the actions it would take to reduce carbon emissions. There have been some reductions on this basis, and if all countries accomplish their goals, the results would be impressive, but still far from what is needed to remain under the 2°C threshold. In no other field voluntary action has represented a solution to the problem of under provision of a public good, especially when there are global public goods, and the benefits are shared by everyone in the world. Social consciousness works only to a limited extent. This is especially true when there are powerful groups within countries for whom the direct cost of taking action, for instance the loss in value of the fossil fuel assets, exceeds any direct gain from reduced emissions. Agreements must be enforceable, and in the absence of a global government able to impose direct punishments, the most effective enforcement instruments are trade sanctions. Cooperation based on a common commitment is relatively easy to accomplish because the common commitment set up a reciprocal relationship, which promote cooperation. A major advantage of monitoring and enforcement under a price commitment is that it happens annually rather than once-in-15- year, such as the Kyoto Protocol or once-in-5 year as in the case of Paris Agreement. Annual control limits free-riding and diffuses responsibilities among successive governments within countries and makes it more difficult to repair noncompliance. Furthermore, annual price commitments have the advantage that deviation can be easily detected and quickly corrected because full compliance can be achieved simply by increasing the carbon charge. In fact, the frequency of monitoring is known to be one of the most critical aspects of self-enforcing cooperation. Another main reason for which price commitment is more enforceable is that it reduces risks. Risks can produce strong incentives to leave or avoid a quantity commitment. Without such strong incentives to deviate, the needed size of the enforcement penalty is reduced. Several complementary mechanisms can further ease the enforcement of price commitments. A country that exceeds its commitment can even sell its excess performance to a country that falls short, this ensure that plans are met collectively but at the same time gives countries the flexibility to easily and efficiently react in an uncertain environment. Efficient resolution of deviations from plans greatly reduces risks, facilitates performance, and encourages participation.

5.4 Common and Differentiated Responsibilities: creating a Green Fund

The approach delineated previously does not, adequately take into account the differences among countries. Such differentiation was central to earlier approaches to climate change. It is inefficient and likely to be viewed as unbalanced for producers in developing countries to face a different carbon price from those incurred by firms in developed countries, giving rise to complaints of unfair competition. Furthermore, poor countries struggling to develop legitimately feel that the extra costs are withdrawing funds that could alternatively be used for advancing developmental objectives. The solution may be a global green fund. A global green fund could be guaranteed by allocating a percentage of the revenues from the carbon tax (or the equivalent mechanism) imposed in the most developed countries. Being the amount of these revenues proportional to carbon emissions of such countries, it would likely be an opportune way to raise financing for a global fund of such nature. The credit from the global green fund can then be used to help sustaining developing countries with their expenditures on technological adaptation and on the costs associated with reducing emissions. Additionally, the funds can also be used to help developing countries in carbon sequestration measures—for instance paying them to preserve forests, which would also raise global benefits in terms of biodiversity. Indeed, developing countries properly worry that, if they join an enforceable agreement regarding carbon emissions reductions, to meet those reductions they would further require paying developed countries a large sum of money to employ their technology. Developing countries are therefore reluctant to sign on to an international treaty that would see such result. In order to make the agreement acceptable for poorer countries, the fund should be generous enough to their choice of accepting the global carbon price. Furthermore, developed countries, which are in a better position to carry on research leading to technologies that reduce carbon emissions and to carbon storage systems at affordable costs, should provide developing countries with these technologies freely. Part of the costs might even be covered by the global green fund itself.

5.4.1 Equity Transfers Are Less Expensive with Price Commitments

Establishing a price as the indicator of global action enable a common commitment. However, as explained above, poorer developing countries, such as India, would need significant to satisfy certain conditions. Fortunately, equity transfers with a price commitment are relatively inexpensive.[30] India's carbon-pricing revenues would stay within the country, thus pricing India's 2 billion tons of emissions at $20 per ton will have a net cost to India of only about $2 billion if emissions were reduced by 10%—definitely less than the planned $100 billion per year of the current Green Climate Fund[31]. The common commitment should indeed include a Green Fund formula for providing assistance from richer, high-emission, developed countries to poorer, low-emission, developing countries. In such a way, the common pricing commitment would respect the UN's principle of "common but differentiated responsibilities", fostering the adhesion of developing countries. Furthermore, equity transfers are less expensive with price commitments because the risk to be covered is lower with respect to quantity commitments.

5.5 Choosing a Green Fund Formula

In the latest chapter of *Global Carbon Pricing* Peter Cramton, Axel Ockenfels, and Steven Stoft, affirm that by committing to a homogeneous global price, it is possible to confine the countries-differentiated-responsibilities problem by developing a proper formula for the Green Fund. The fundamental issue is, thus, to choose the Green Fund formula that maximizes global emissions abatement. The authors suggest a two-step design. The first step requires selecting the Green Fund formula and, only then, it is possible to choose the common price. This design is similar to many processes in which it is common to specify the payment and

[30] Cramton, Ockenfels, and Stoft; chapter 12, *Global Carbon Pricing: the Path to Climate Cooperation*. The MIT Press, 2017
[31] Green Climate Fund. *Green Climate Fund*, 13 Nov. 2020

benefit structure before deciding how much to spend on a program, as in the case of a school system. If voters are satisfied with the payment-benefit structure, they will be generous in their payments-decisions; if they are not satisfied, they will be less generous. This provision gives those designing the payment-benefit structure — in this case the Green Fund structure— a strong incentive to design a structure that please all countries whose support is needed. Furthermore, it guarantees to funders tranquility when they have to delegate authority to those designing the structure—first because they know that they can reject or minimize the suggested structure if it does not suit them, and second because they know the negotiator/designers will be well aware of this. The two-step approach for pricing carbon, instead, breaks the problem in two by first choosing mitigation efforts (P) and then negotiating equity transfers $\{G_i\}$, then it links the two parts so that the availability of the step-two price decision provides good incentives for the Green Fund design process, and the Green Fund is accurately designed to make the price negotiation successful. In order to decide on the common price, each country pledge its highest acceptable global price target, taking the step-one Green Fund formula into account. The highest acceptable price target to a consistent percentage of countries (population-weighted), then, determines the global price commitment. Only countries that have pledged at least that price sign the common-pricing agreement and participate in the green fund, this "club" of countries could then implement enforcement and consequently induce other countries to join. In reality, no simple formula will be sufficient to properly describe the Green Fund negotiations. However, what Cramton, Ockenfels, and Stoft illustrate will serve to demonstrate the value of looking for a common-commitment formula, even if the actual one needs to consider multiple relevant variables. The formula they propose as the most appropriate for Green Fund transfers comprises transfers that are proportional to a country's excess emissions— which are defined as emissions that are in excess of what the country would emit if it had world-average per capita emissions. Countries finance the fund in proportion to their excess emissions and get paid from the fund in proportion to their negative excess emissions. The formula also includes a generosity parameter (G) that determines the extent of transfers: how many dollars per ton of excess emissions will be transferred. The parameter must be well balanced. On the one hand, if the Green Fund formula is too generous, rich countries will hold down the global price to cut down payments. On the other hand, if the formula is too tightfisted, poor countries will hold down the carbon price to reduce the burden of carbon pricing. Only a well-thought compromise can lead to the highest agreed global carbon price and maximize emission abatement. In order to ensure that the generosity parameter of the Green Fund formula is established in a way which is proper to maximize climate ambition, the best solution, according to the authors, is to rely on countries that have the least interest in Green Fund payments. Those countries will base their recommendations on climate concerns rather than Green Fund considerations. Within the group, the median opinion should determine the outcome: not choosing the average prevents any one country from having too much influence. Under the agreement, countries are asked to commit to a maximum price equal to the one they nominate voluntarily with full knowledge of the generosity of the Green Fund; therefore, nothing is governed by other parties. Although the nature of this treaty is completely voluntary, the emerging agreement captures the "I will if you will" principles of common commitments that is able to modify self-interest within the agreeing group.

6. Conclusion

Climate change is the biggest threat humankind has to face nowadays. To avoid potentially catastrophic scenarios, all countries must join forces and fight global warming through a coordinated action. Nonetheless, agreements on climate change have failed to achieve the necessary results. The factors affecting cooperation on carbon emissions are infinite and very complex and is thus very difficult, if not impossible, to capture all of them in a stylized model as the one proposed above. However, the model clearly shows how the variables taken into account deeply affect the outcome of negotiations, rendering cooperation a hard-to-achieve result. Above all, the public-good nature of emission reduction and the different circumstances of countries involved in negotiations are the most determining variable. Quantity commitments, as the ones proposed by both *Kyoto* and *Paris*, do no not offset these factors. The quantity of emissions is indeed difficult to monitor, and poorer countries must make greater efforts and sacrifices compared to richer countries in order to achieve the same results. It is thus necessary to take a different path to reach the cooperative outcome. Cramton et al. take into account the factors mentioned above and provide a solution alternative to the quantity commitment, a price commitment, that foster cooperation among countries. A carbon tax has been argued to be more easily managed and to be more transparent than a cap-and-trade system, and this consideration is particularly valuable in an international context that include all major emitting countries. Individual countries can actually implement the global price, and their commitment to the price is enforceable and monitorable, and these characteristics address the free-riding problem. Furthermore, the creation of a Green Fund can ease the problem of the differences among negotiators. Developing countries, indeed, are more likely to be hurt by climate change or can more hardly invest in technologies to adapt to adverse effects. The global green fund can be created by allocating a percentage of the revenues from the carbon tax —or the equivalent mechanism of price commitment— imposed in the most developed countries. The credit from the global green fund can then be used to help sustaining developing countries with their expenditures on technological adaptation. Furthermore, developed countries, which are in a better position to carry on research leading to technologies that reduce carbon emissions and to carbon storage systems at affordable costs, should provide developing countries with these technologies freely. All these elements can reduce the differences among participating countries in terms of resources and incentivize developing countries to take part in the agreement. This solution would both promote the cooperation of signatories countries and encourage a significant number of countries to join the forces and fight against climate change. The efforts to decarbonize the economy are fundamental to avoid the catastrophic scenario of the temperatures increasing above the 2°C. All countries should actively participate in this fight to preserve future generations.

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