THE ROLE OF TECHNOLOGICAL OPTIMISM IN INTERNATIONAL CLIMATE AGREEMENTS

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THE ROLE OF TECHNOLOGICAL OPTIMISM IN INTERNATIONAL CLIMATE AGREEMENTS

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ABSTRACT

The Role of Technological Optimism in International Climate Agreements

This research aims to explore the role of technological optimism in international climate agreements and how technological optimism affects the climate-related behaviors of countries. To this end, I built upon the dynamic game with stocks proposed by Harstad (2012, 2016), which takes emissions and green technology investments as contractible strategies. An R&D project that aims to invent a technology that will decrease the accumulation of greenhouse gases is introduced into the model. A comparison between my model, where the R&D dimension is exclusively considered, and the baseline model proposed by Harstad will capture how technological optimism may alter the behavior of countries. With the presence of an R&D project, emission levels and the greenhouse gas stock increase, and the global stock of green technology and its investments decrease for all countries in both the first-best (cooperative) and the business-as-usual (non-cooperative) outcomes. The effect of technological optimism increases when the R&D project is expected to invent a more robust technology to decrease greenhouse gas accumulation. My model explores how relying on a future technology affects the current action plan to tackle climate change, thus contributing to the literature on international climate agreements, dynamic games and technological optimism.

ÖZET

Uluslararası İklim Müzakerelerinde Teknolojik İyimserliğin Rolü

Bu araştırma, teknolojik iyimserliğin uluslararası iklim müzakerelerindeki rolünü ve ülkelerin iklim temelli davranışlarını nasıl etkilediğini araştırmayı amaçlamaktadır. Bu doğrultuda, Harstad (2012, 2016) tarafından geliştirilen, emisyonları ve yeşil teknoloji yatırımlarını kontratlanabilir stratejiler olarak ele alan dinamik oyunu kullandım. Bu modele, icat edildiği durumda gezegendeki sera gazı birikimini azaltacak, yatırıma açık bir Ar-Ge projesi eklendi. Ar-ge yatırımının mümkün olduğu benim modelim ile, Harstad tarafından kurgulanmış referans modelin karşılaştırmasının teknolojik iyimserliğin ülke davranışları üzerindeki etkisini göstermek mümkün olmaktadır. Bu karşılaştırma sonucu benim modelimde tüm ülkeler için emisyon seviyelerinin ve sera gazı stoğunun arttığı, yeşil teknoloji yatırımlarının ve küresel yeşil teknoloji stokunun ise azaldığı ortaya çıktı. Bu sonuçlar hem işbirlikli hem de işbirliksiz senaryolar için geçerli olmaktadır. Ar-Ge projesinin sera gazı birikimini daha fazla azaltmayı vaadetmesi durumunda teknolojik iyimserliğin etkilerinin arttığı görülmektedir. Modelim uluslararası iklim anlaşmaları, dinamik oyunlar ve teknolojik iyimserlik konularında literatüre katkı sağlarken, bir yandan da gelecekte icat edilme ihtimali olan bir teknolojiye duyulan inancın günümüzdeki iklim eylem planlarını nasıl etkilediğini keşfetmeyi amaçlıyor.

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To Arya

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CHAPTER 1

INTRODUCTION

“I know some of you and have met many new colleagues since I have arrived. Because the reality is, it is not common for Finance Ministers to attend a COP. In fact, I am the first U.S. Treasury Secretary to do so. The reason I am here is because climate change is not just an environmental issue. It is not just an energy issue. It is an economic, development and market-destabilizing issue and I would not be doing my job if I did not treat it with the seriousness warranted” (Janet L. Yellen, Glasgow, 2021).

It is almost traditional to start papers about climate change with a few sentences that represent the gravity of the situation. I thought none of my words could have given enough justice as the words of Janet L. Yellen, the current U.S Secretary of the Treasury. She made an opening statement at COP26 (Conference of Parties), the United Nations Climate Change Conference in Glasgow, between September 31 and November 12, 2021.[1] This was the 26th annual global climate summit organized by the United Nations. Climate change is now considered to be a very major problem threatening the planet earth by activists, advocates, scientists, and academics, and with an increasing number of ordinary people and in a related manner by nation-states. Yet the presence of Janet L. Yellen at COP26 really highlights the importance of the matter at hand in a way sentences cannot.

Climate change has been the subject of academic research for many decades. The main economic rationale behind the climate change problem is almost the same as any public good provision issue. While the benefit (or harm) of the public good (public bad in our case; greenhouse gases) are non-rival and non-excludable, its cost is private, which inevitably creates a free-riding incentive for everyone in the system and leads to strategic interaction between them. To solve this issue, the externality created by the agents (countries) should be internalized, which is the aim of any international environmental agreement.

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[1] United States Department of the Treasury (2021).

Even with two comprehensive and promising international attempts (the Kyoto Protocol and the Paris Agreement), it is safe to say that the international community has largely failed to reach global cooperation so far. Scholars prescribed many reasons for the lack of cooperation. Stern (2007) put forward the collective action problem as the overarching concept that hinders global cooperation and stated that its dynamics should be adequately understood. Nordhaus (2015) indicated that the lack of mechanisms to effectively punish defectors from, or non-signatories of, the climate agreement is the main reason. On the other hand, Barrett and Dannenberg (2012) suggested that the ambiguity over the threshold for global catastrophe gives rise to countries' non-cooperative and myopic behavior. These and many more are somewhat valid arguments.

While the cost of changing climate will mainly occur in the future, the cost of cutting down emissions is indeed in the present. Therefore, there is a tradeoff between combatting the climate crisis and continuing business-as-usual (thus free-riding in the meantime and risk facing the augmented effects of climate change in the future). The choice of this tradeoff depends on many determinants, such as the discount rates and comparative advantages of countries in terms of abatement. Although these issues are heavily researched, I believe there is one aspect not yet intensely scrutinized. Even though negotiations for restricting carbon emissions are ongoing, some might anticipate that new technologies will be invented in the future, which will make the problem of climate change redundant or radically less intense. Whether this is realistic or not holds little value since beliefs might affect behaviour, no matter how unreasonable they are. If there is such a belief, then it could be among the reasons governments of the world are having difficulties in sustaining collaboration to combat the climate crisis.

To identify and characterize the aforementioned belief, I will utilize the concept of "technological optimism". Although its meaning has transformed in time, the current connotation of technological optimism is the belief in technologies that have not been invented yet but could be the remedy to today's problems. From this perspective, relying on future technological improvement to solve the climate crisis falls into the realm of technological optimism, and if so, it might have a significant role in explaining the inability to sustain global cooperation.

To this end, I built upon the dynamic game with stocks approach proposed by Harstad (2012, 2016), which takes emissions and green technology investments as contractible strategies. I introduce a new investment channel of R&D, which aims to invent a technology that will dramatically decrease the accumulation of greenhouse gases. I believe a comparison between my model, where the R&D dimension is exclusively considered, and the baseline model proposed by Harstad will capture how technological optimism may alter the behavior of countries. The effect of technological optimism is embodied by the non-cooperative (business-as-usual) and cooperative (first-best) outcomes of both models. In both scenarios, with the presence of an R&D project, emission levels and the greenhouse gas stock increase, and the global stock of green technology and its investments decrease for all countries.

The remainder of the paper is organized as follows. The following chapter covers the literature regarding climate change and international environmental agreements focusing on technology and technological optimism. The third chapter provides the baseline model, the extended model with technological optimism, the equilibrium concept (Markov Perfect Equilibrium), the solution methods, and the subsequent results for the business-as-usual and first-best scenarios. Chapter four discusses the results and makes intuitive deductions. Finally, chapter five concludes.

CHAPTER 2

LITERATURE REVIEW

2.1 Fundamental works on climate change

Climate change is the deviation of Earth's climatic patterns caused by anthropogenic activities (Fawzy, Osman, Doran, & Rooney, 2020). The deviation towards a warmer climate results from increasing greenhouse gases (GHG), which are predominantly emitted from burning fossil fuels, deforestation, and changes related to land use (Stern, 2007, p. 3). From an economic perspective, emissions from production- and consumption-related activities are labeled as externalities, and countries contribute to the 'public bad' by emitting (Stern, 2007).

Parallel to the economic definition of externality, while the benefit of GHG emissions is public to the emitters in the form of national accounts of production and consumption, the associated cost is non-excludable and burdened on non-related parties. However, certain characteristics of GHG emissions differ from conventional externalities, which makes internalizing its costs even more difficult with policy implications. The resulting impacts are global and persistent, thus increasing its scale to all countries in terms of cost and damages. Moreover, it poses uncertainties and risks with a greater magnitude with the possibility of irreversible environmental, economic, social, and demographic effects (Stern, 2007, p. 23). Considering all the above, Nordhaus (2020) puts climate change in the cluster of hard international conflicts within a categorization consisting of easy, medium, and hard conflicts.

Despite the difficulty of the problem, a Pareto optimal scenario exists. Gradually moving the economy to a low-carbon path, especially with a transition to low-carbon energy systems, seems to be a remedy. Climate models prescribe the amount of emissions needed to be cut down in the short, medium, and long-run to remain in reasonable climatic conditions.[2] For the economic implications of abatement at prescribed levels, Integrated Assessment Models are the tools commonly used. They include economic impacts of climate change, the transition

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[2] For a detailed analysis, see IPCC (2018).

path to low-carbon energy systems, the costs and effects of transition on macro-level and sectoral basis, and the trajectory of GHG concentrations under different scenarios (Stern, 2007, p. 169).

If there is an achievable target that alleviates climate change, why the governments of the world would not undertake it? The answer is multifold, and there is not a strict consensus on which of the reason impacts the coordination problem the most. The common response is the collective action problem. To combat climate change, countries need to cooperate and act collectively, yet the free-riding incentive that arises from the public nature of the problem hinders that possibility (Nordhaus, 2015; Stern, 2007). Every country has a profitable deviation of increasing emissions. Knowing other countries also share this profitability, countries expect others to deviate, thus they also deviate. Meanwhile, a deviating country can still enjoy the decreased global emissions, which results in free riding. The aforementioned dynamics and other features impede cooperation, thus creating a collective action problem.

The asymmetry between countries in terms of marginal abatement costs and impacts of climate change is also among the reasons that make cooperation difficult. While more industrialized countries (notably the global north; Western Europe and North America) can transform their economies with relative ease, many developing and under-developed countries face difficulties in terms of lacking infrastructure, access to financial resources, and inadequate governance to facilitate their transition to a low-carbon economy and energy system (Stern, 2007, p. 211). Unless appropriately incentivized, there will be a reluctance to initiate the transformation to jeopardize their current economic well-being.

The above issue is also linked with the time-inconsistent behavior of decision-makers. If elected officials give more weight to another term in office instead of policies that will be beneficial for their country in the distant future, their preferences will have present-bias, thus preventing them from engaging in actions that will come into fruition in the future, such as the climate action (Harstad, 2020;

Hovi, Sprinz, & Underdal, 2009). Decision-makers endowed with time-inconsistent preferences hinder the possibility of reaching a global climate agreement a great deal. Barrett and Dannenberg (2012), on the other hand, came to a similar conclusion from a different underlying reason. They believe the ambiguity over the threshold for global catastrophe gives rise to countries' non-cooperative and myopic behavior.

The lobbying efforts for fossil fuel extraction are also considered one of the reasons for the lack of global cooperation so far. Decarbonization of energy sectors threatens the lucrative position of fossil fuel industries both in terms of market volume and the subsidies received from governments worldwide. Efforts related to maintaining their position through lobbying and rent-seeking lead to conflicts among decision-makers, thus prolonging the agreement on climate action (Stern, 2007, p. 278-279).

The heterogeneous impacts of climate change are not limited to the costs of mitigation and environmental damage. Empirically, not every country contributed to climate change equally. There is an ongoing debate on how the present and future costs of climate change should be distributed among countries. Which metrics should be considered to make this decision, such as historical emissions or current gross domestic product? The transition to low-carbon is even more costly for underdeveloped and under-industrialized countries as mentioned above. Who should support these countries financially and with which mechanisms? All of the questions related to the balance between the historical and present responsibility regarding climate action lead to a discussion of climate justice and decelerates global cooperation (Meyer & Roser, 2010; Schlosberg & Collins, 2014).

Last but not least, some people argue that technology not yet invented but will be available in the future, such as a feasible carbon capture and storage technology or solar geo-engineering, could make the problem of climate change obsolete. If decision-makers share such a technological optimist mindset, then a decisive climate action could be prevented or delayed. (Technological optimism and its effect on climate change will further be elaborated in chapter 2.3.)

In theory, despite all the reasons mentioned above, a global agreement has been met two times with the Kyoto Protocol and the Paris Agreement. Yet, the impact of these agreements turned out to be undesirable and inadequate. They relied on self-enforcing actions, which were insufficient to mitigate emissions as intended. Nordhaus (2015) believes self-enforcing agreements are doomed to fail, and they should have consisted of enforceable commitments with pre-determined punishments for defectors. Moreover, countries willing to sign an agreement should formulate a climate club and coerce non-signatories to participate.

The idea of climate clubs is a proposal based on game theoretical foundations. While the goals and benchmarks needed to be reached are designated by Integrated Assessment Models, the question of under which frameworks and strategies can achieve these goals can be analyzed within the game theory domain. The strategic interaction among countries lies in the center of understanding the dynamics that failed the global cooperation so far as well as the solutions how to overcome them (Stern, 2007, p. 449). Bearing the role of game theory in mind, the next subchapter reviews the literature for games of climate agreements.

2.2 Games of international climate agreements

A game-theoretical approach to climate agreements deepens the literature on climate change in two critical aspects. First, it makes the strategic interaction explicit between the countries represented in the modeling environment. Since the well-being of countries is affected by the emissions of all countries, it is perfectly natural to assume that any given country will formulate its strategies contingent on other countries' past and expected strategies. Second, it allows the negotiation procedures and defections from the agreement to be modeled. More explicitly, a game can show under which conditions a country signs an agreement, stays in or defects from the agreement, and how non-signatories would act when an agreement is met or not met. The game can be constructed according to the question desired to be answered.

Two major types of games shine out among others. The first one investigates the number of countries willing to sign an international agreement. Typically, it is designed as a two-stage game where countries first decide whether or not they will sign an environmental agreement, and second if so, they decide on the strategies discussed in the agreement. The overall structure depends on the welfare-maximizing behavior of the countries involved. They will sign the agreement only if it is in their best interest. Hence, this type of game applies to the self-enforcing agreements and the variety of the accords we observe in real life. These games are called 'participation games'. Carraro and Siniscalco (1993) give the first example of such a game. In their model, each country decides to work individually or cooperatively in the presence of a global pollutant. Then, the coalition and the remaining singleton countries decide on their abatement levels to maximize their own welfare. The equilibrium is characterized by the coalition being stable. Accordingly, if a coalition is formed, there is no incentive for a signatory to defect, and there is no incentive for a non-signatory to join the coalition. This definition is derived from the cartel stability proposed by d'Aspremont and Gabszewicz (1986). Even though Carraro and Siniscalco (1993) did not explicitly formulate the model for climate change, it is easily applicable to our problem. It can thus be considered as the first example of a strand of games to analyze coalition formation for environmental and climate agreements, namely the participation games.

The second influential type of game aims to analyze the behavior of countries inside the coalition. Participation in the international agreement by a number of countries is a-priori assumed. The objects of interest are formulated as the negotiation procedures and the strategic behavior during the agreement. These games bypass the coalition formation problem of the participation games but make the strategic interaction repeated; hence we may name them 'repeated games'. The repeated interaction of the countries in terms of a given strategy (emission or abatement, for instance) detaches the structure from a static interaction and brings in real-life applicability. The solutions and results of the social planner's problem (first-best) in the game represent the outcome of the agreement. In contrast, the non-cooperative outcome (business as usual) describes a lack of an agreement.

The earliest example of such a repeated game is given by Barrett (1994). He formulated an infinitely repeated game where countries with identical net benefit functions designate their abatement levels in each period. There are several strict core assumptions and certain drawbacks of this formulation. The most important one is that, the only strategy of the countries is abatement, and their levels are instantly observable. Even though many studies have then incorporated new strategies in addition to emissions and abatements, the instant observability turned out to be a pretty necessary assumption to have a tractable model. Moreover, the pollutant in the model does not accumulate over time. Many authors also relaxed this restriction (Dutta & Radner, 2004, 2006, 2009, 2012; Harstad, 2012, 2016), and the games gained a dynamic character. Barrett (1994) also pointed out that the structure of the model does not allow for endogenizing the number of countries involved in the agreement and the decision to participate. Thus, the model needs to be renegotiation-proof if we say that it sustains a self-enforcing agreement. In the same paper, he proposed another approach to rectify these shortcomings with a participation game almost identical to Carraro and Siniscalco (1993). From this approach, he deduced that signatories might punish the defectors by decreasing their abatement levels and reward new signatories by increasing their abatement levels. Although the threats and the rewards are credible, their magnitude may not be enough to sustain a self-enforcing international environmental agreement (Barrett, 1994).

These two types of games paved the way for substantial research. Although the basic structure of the games persisted, many different studies introduced other strategies besides pollution (emission) or abatement. The rationale behind the proposed extensions is the same. When the desired outcome is either an environmental agreement with a sizeable stable coalition, or an aggregate level of greenhouse gas under a pre-determined threshold, the abatement alone in treaties fails to deliver the desired outcome (Barrett, 2006; Finus, 2003). The natural extension is to include other strategies that might affect abatement strategies. Carraro, Eyckmans, and Finus (2006) formulated a simulation game based on the aforementioned participation game. They propose an extension where countries choose their economic strategies that include emission abatement and capital investment at the game's second stage. Bayramoglu, Finus, and Jacques (2018) proposed an alteration, where adaptation to climate change is added in the second stage of the participation game as a strategy. They found that the addition of adaptation transforms the non-cooperative game into a cooperative (or coordination) game because the mitigation of different countries is no longer strategic substitutes but strategic complements. Another noteworthy extension is made by Dixit and Olson (2000), where the second stage of the participation game transformed into a bargaining stage between signatories.

Battaglini and Harstad (2016) extend the participation game as a dynamic game. They explored the complete and incomplete contracts of pollution and green technology investment. At the same time, the pollutant (greenhouse gas in their case) is a cumulative stock, which gives their game a dynamic component. They found that the free-riding incentive is alleviated when the contracts are incomplete. Even though incomplete contracts lead to a hold-up problem, the cost of preventing the hold-up problem decreases with the size of the coalition when the contracts are complete. Kováč and Schmidt (2021) found a similar result with a different mechanism. They alter the conventional one-shot participation stage with a dynamic membership option, where countries may suspend the participation negotiations and choose to continue negotiating in the next period. The possibility of continuing negotiations in subsequent periods allows countries to negotiate on stricter terms, leading to larger and more efficient coalitions.

On the other hand, Karp and Sakamoto (2021) suggested that even though the dynamic structure of the above models may lead to larger and more effective coalitions, these papers may have overestimated the easiness of forming such coalitions. They propose a negotiation process where the negotiators expect a few rounds of failures before reaching an agreement. They believe that if the negotiators have certainty over success or failure, the necessary compromises cannot occur. Therefore, the proposed extension might be a closer representation of the real-world negotiations since the outcome is uncertain and the negotiation process takes longer than formulated by Battaglini and Harstad (2016) and Kováč and Schmidt (2021).

Dynamic games of environmental agreements have fewer representations in the literature than participation ones. Dutta and Radner (2004, 2006, 2009, 2012) have several papers centered on dynamic games with stocks. Before them, many studies considered either a one-shot game or a repeated game where the state variable is static and identical throughout the periods.

The first model of Dutta and Radner (2004) formulates a game where the countries decide on their emission levels alone. The stock of GHG accumulates over time, the cost of climate change is linear, and the related cost of climate change for countries is also linear. The preferred equilibrium concept is Markov Nash Equilibrium since the payoff of countries is taken as associated with a dynamic stock, as commonly done in the literature. The paper focuses mainly on the equilibrium selection among various alternatives arising from the Markov Nash Equilibrium concept. In their following article, Dutta and Radner (2006) generalized their model by allowing population growth and endogenous technological change, followed by an empirical validation of the theoretical model through calibration exercises (Dutta & Radner, 2009). In their final paper, Dutta and Radner (2012) introduced exogenous capital accumulation to the model. They investigated whether retaliatory emissions are effective as a sanctionary mechanism from the perspective of China and India. The answer turned out to be 'no', because for the fast-developing countries, the loss they sustain from sanctions grows slower than the additional benefit they make from less abatement they make.

Harstad (2012, 2016) continues from the road paved by Dutta and Radner (2004, 2006, 2009, 2012) and provides examples of dynamic games with stocks. In both of his papers, countries repeatedly emit and invest in green technology.

Additionally, investments aggregate over time and become a green technology stock for each country. Like in Dutta and Radner (2004, 2006, 2009, 2012), the equilibrium concept is Markov Perfect Equilibrium (MPE). Contrary to the single global GHG stock, the green technology stock is country-specific, thus causing an increase in the number of stocks. Nevertheless, the model is tractable, and a unique symmetric MPE exists. Harstad (2012) sets up benchmarks with the first-best and business as usual outcomes, then analyzes different contracting environments with incomplete contracts and renegotiations. When only the emissions are contractible, the level of investments is quite sensitive to the length of the contract. Harstad (2016) adds technological spillovers and a stochastic component to the GHG stock, generating different results than Harstad (2012). He states that the weakness of intellectual property rights affects the duration of the climate agreement and requires a longer contract to obtain optimal emission and investment levels.

The concept of technological optimism has not been worked alongside with a game theoretical analysis of climate agreements so far. Therefore, the next subchapter probes the history and connotations of technological optimism, with an intent of clarifying its use for the remainder of this paper.

2.3 Technological optimism

The emergence of technological optimism as a term in the literature coincides with the discussion regarding the possibility of everlasting economic growth. It is first mentioned in Meadows, Meadows, Randers, and Behrens III (1972). Their book aims to highlight and discuss how economic growth is interconnected with particular and important exponentially growing factors (population, food production, industrialization, pollution, and consumption of nonrenewable natural resources), which either have physical limitations or are inversely proportioned with growth. Even though the famous Malthusian predictions, namely the inevitable inability to feed the increasing human population (Malthus, 1872), seemed to be invalidated by the discovery of new lands and the increasing productivity, our world is still a closed system that is bound by its physical boundaries and limited natural resources (Meadows et al., 1972). This is not a groundbreaking observation by itself, as all involved parties are aware of such limitations. However, some believe that a growing number of technological improvements in vital areas such as energy, food, and environment will be able to bend the physical limitations of Earth into the will of its increasing inhabitants. This mindset came to be known as technological optimism (Meadows et al., 1972).

Meadows et al. (1972) certainly stirred the academic and scientific community. While the majority believed the skepticism regarding the future of growth is ill-founded, some shared the authors' concerns and highlighted the potentially detrimental effects of blindly pursuing growth.[3] The ensuing discussion put the concept of technological optimism into a perspective and laid the ground for its environmental connotations.

The main argument for the book's critics is that somehow authors neglect to take the apparent exponential growth of technological advancements into consideration. Krier and Gillette (1985) believe this is precisely what technological optimism is, the expectancy of growing numbers of scientific and technological breakthroughs to alleviate society's present limitations and challenges. The solution does not have to be imminent; it simply needs (and is expected) to come in the foreseeable future. The temporal break between the emergence of the problem and its probable solution is the tolerable imperfection of the technological optimist worldview (Krier & Gillette, 1985). This statement gains even more importance from the perspective of current debates on how decision-makers should determine the severity and timing of climate action. One might expect that the opportunity cost of taking and not taking a swift and considerable action towards climate change differentiates with their position vis-à-vis technological optimism.

Ultimately, the technological optimism began to prevail in every layer of the society, and environmental discussions had their fair share. As a society, we have

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[3] See Basiago (1994) for the most prominent for and against arguments back in the day.

relied too much on technology to foster the next cycle of economic growth, which inevitably decoupled the notion of growth from environmental limitations and concerns (Grossmann et al., 2021). Perhaps the main reason for this tendency is the viewpoint of decision-makers. Natural scientists and policymakers who are predominantly technological optimists characterized environmental problems as mere technical problems. From their perspectives, the challenges posed by environmental limitations simply call for further innovation and breakthroughs (York & Clark, 2010). This current dominant view is visible in earlier discussions as well. ”If environmental quality is threatened, more effective pollution control technology can be developed to deal with the problem. If fossil fuels are growing short, technology can reduce the costs of discovery and extraction. It can also provide fuel substitutes, natural or synthetic” (Krier & Gillette, 1985, p. 407). Inevitably, the contemporary discussions on tackling the climate crisis are dominated by technical solutions, while the social and political alternatives left little room to blossom (York & Clark, 2010).

Among the risks pointed out by the critics of technological optimism, two come to the forefront. First, the critics argue that the technological aspect of climate policy is delegated to the experts who might tend to overlook the potential challenges in the invention process of new technologies. Tichy (2004) indicates that top experts tend to neglect or underestimate the difficulties specific to their field, even if the said difficulties are vital to the success of realization. Consequently, the forecast of those experts was found to be unexact as they tend to underestimate the period of realization. Moreover, Brandes (2009) retrospectively investigates the technological foresight accuracy of European experts from their technological Delphi[4] surveys. He finds short-range optimism at least and warns the decision-makers not to limit their circle of advice to the experts on a subject. The subconscious optimism towards new technologies creates a discourse in which swift and severe climate action is de-emphasized and consequently delayed (Stephenson, 2022).

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[4] Surveys based on statements trying to assess current technological position of a country and attempts to forecast its future scenarios (Czaplicka-Kolarz, Stańczyk, & Kapusta, 2009).

The other point made by critics is that as the issue needed to be handled gets bigger, the solution technological optimists put forwards gets riskier and more complex. This is characterized by Rosner (2004) and used by many others (Stephens & Markusson, 2018; York & Clark, 2010) with the term ‘technological fix’, a solution for all proposal that does not tackle the issue head-on and therefore offers only partial remedies or has the potential to cause intended consequences. The appeal of technological fixes is to avoid systemic changes and maintain the status quo. Many believe that current efforts of geo-engineering and solar geo-engineering could be considered as such. Stephens and Markusson (2018) label carbon capture and storage (CCS) technologies under this division. They believe the amount of additional energy needed to capture and store one more unit of carbon dioxide should be seen as a significant threat to the shared optimism. ”The magnitude of this energy penalty (including even the lower estimates) is so high that it is difficult to imagine a future scenario in which generating and then consuming this much additional energy to enable CCS would actually make sense” (Stephens & Markusson, 2018, p. 19).

In terms of cost-efficiency, solar geo-engineering seems more desirable than CCS technologies. Barrett (2008) and Weitzman (2015) indicate that solar geo-engineering options that prevent a portion of solar radiation from arriving on Earth and infused by its climactic system offer considerably cheaper alternatives. Some options are so affordable that a single country may decide to take up unilateral action if they suffer more due to asymmetric climate damages or desire to take a strong position in climate leadership (Weitzman, 2015). Barrett (2008) also believes such options are possible, but they pose their own issues. Even though the free-rider problem can be circumvented, it will be replaced with governance problems due to a lack of governmental bodies to oversee such unilateral action and maneuver away from resulting issues (Barrett, 2008).

A collection of technological fixes and a technological optimist mindset is highly praised by Bill Gates. His new book (Gates, 2021) advocates innovation in ideas both in terms of technology and policy.[5] However, Acemoğlu (2021) criticized the nudge of Gates into solar geo-engineering. He stated that the optimism uncovered by solar geo-engineering might undermine the potential benefits of current policy remedies such as carbon tax and emission trading schemes. Also, the unintended consequences and potential calamities are always in question since solar geo-engineering may cause even more climatic variability. He concluded by emphasizing the importance of tried and tested policy mechanisms such as carbon taxing and describes the ways geo-engineering may hinder conventional efforts. This statement is in parallel with Acemoglu and Rafey (2019), where they showed that without future commitments to tax policies, any discussed tax rate above the benchmark[6] risk being revised depending on the developments in geo-engineering, thus resulting in underinvestment in clean technology. Moreno-Cruz (2015) deduces similar results by stating geo-engineering efforts may lead to substitution away from mitigation within policy portfolios.

2.4 Climate change and technology

Regardless of the position on technological optimism, technological advancements are recognized as an essential tool for the fight against climate change. In the broadest sense, both new forms of renewable energy production and projects fueled by geo-engineering are technological advancements. Stern (2007) emphasized the importance of technology and innovation by stating how climate change induces an unprecedented risk and uncertainty that could perhaps only be mitigated by low-carbon technology options. He indicates that the scale required to combat climate change requires a technological transformation in key sectors and collaboration between the private sector, the industry, and the government. A joint strategy could stimulate increasing R&D and technology diffusion. Moreover, Barrett (2009) indicates that while existing technologies could reduce the current emissions

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[5] Reference is from an interview made by Hedegaard (2021) with Gates regarding the ideas in his new book.

[6] ”Pigovian benchmark where the carbon tax equals the marginal damage from one more unit of carbon” (Acemoglu & Rafey, 2019, p. 2).

significantly, a technological revolution is necessary if we hope to stabilize the GHG concentrations in the atmosphere. The nature of this revolution is yet to be seen, but it will be shaped by the institutions tasked with challenging the climate crisis.

The Kyoto Protocol and the Paris Agreement recognize the role and importance of technology. Even though R&D investments for green technologies and low-carbon alternatives are identified with utmost priority, investment on technology itself has not been a contractible strategy in either of the agreements (Barrett, 2006; Harstad, 2016). However, the exclusion is not caused by the lack of importance yet the difficulty of deciding what an investment is and then measuring them. Therefore, the treaties decided that even though the contribution to green investment has the utmost importance, the levels should be nationally determined (Harstad, 2016).

The attention devoted to technology in policymaking and literature is not limited to green technology investments. Many scholars attempted to incorporate "breakthrough technologies" into the games of environmental agreements. Recent papers described the technologies breaking the ground in the sense of decreasing the cost of abatement and the cost of adaptation to the adverse effects of climate change. Some even argued that a model that does not incorporate technology somehow is doomed to be shortsighted. Barrett (2006) stated that a successful treaty must contribute mitigation and technological knowledge as public goods. He proposes a participation game where the usual setup is reversed. In this case, the R&D effort precedes the participation decision. The paper's primary conclusion is that the R&D venture does not facilitate self-enforcing agreements, and the performance of coalitions only swells when the breakthrough technology generates increasing returns to scale.

Hoel and de Zeeuw (2010) investigate the coalition stabilizing properties of technology adoption and the relevant R&D effort with a similar model. They reversed the participation game to its usual order and started the game with the decision to sign the agreement. When the R&D effort is a joint venture, and the adoption of resulting innovation is bargained over, an increase in the average welfare (characterized by decreasing costs of adoption) and larger stable coalitions are possible. Finally, de Coninck, Fischer, Newell, and Ueno (2008) approach the subject of climate agreements as a policy portfolio. They found that technology-oriented climate agreements aimed at R&D, knowledge sharing, and coordination could increase the stability and efficiency of agreements. Yet, their role should be complementary since they yield environmental protection on their own.

So far, I have reviewed the literature from four different angles which are complimentary to each other. Chapter 2.1 summarizes the economic rationale behind climate change and the probable causes of the lack of effective global cooperation to tackle it, which includes technological optimism as well. Chapter 2.2 examines the frontier of game theoretical analysis regarding the climate change, since game theory has been identified as a valuable tool to understand the mechanisms behind the failure of global cooperation. The review in this chapter constitutes the backbone of my research and my model as well. Although technological optimism attracted some academic attention, it has never been studied within a game theoretical framework. Recognizing this gap in the literature, chapter 2.3 conceptualizes the term technological optimism and bridges it into the model that I am going to introduce in the next chapter. Finally, chapter 2.4 touches upon the games of climate change related to technology, with a focus on “breakthrough technologies”. The technology introduced in my model characterizes a ground breaking invention analogous to the breakthrough technologies literature, thus their mention in here is noteworthy.

CHAPTER 3

MODEL

3.1 Baseline model

The baseline model is the one formulated by Harstad (2012, 2016). His model serves as a benchmark for the extensions I am going to propose in the next subsection. In this subsection, I simply present Harstad's model.

The players of the game consist of countries $i \in N = \{1, \ldots, n\}$, where they contribute to the stock of public bad, stock of greenhouse gases (will be referred to as GHG from now on) by emitting, while also investing in green technology at periods $t \in T = \{1, 2, \ldots, \infty\}$. Consequently, the decisions made by a country in a given period t are the amount of emissions ($g_{i,t}$) and the investment to green technology ($r_{i,t}$).

The stock of public bad at period t, G_t, depreciates with a rate of $1 - q_G \in [0, 1]$. In other words, q_G fraction of the stock from the previous period survives to the next period. The emissions of all countries contribute to the stock in an additive manner, characterizing the accumulation of the GHG stock over time as follows:

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

where G_{t-1} represents the stock of public bad from the previous period and G_0 is exogenously given as a constant.

In addition, each country may invest in their stock of green technology. The stock from the previous period depreciates with the same constant rate of $1 - q_R \in [0, 1]$ for each country. Consequently;

$$R_{i,t} = q_R R_{i,t-1} + r_{i,t}. \tag{2}$$

Similar to the GHG stock, q_R represents the fraction of stock that survives for the next period, $R_{i,t-1}$ is the stock from the previous period, and $r_{i,t}$ is the contribution to the stock by country i in the current period. There are no initial green technology stocks for any countries, $R_{i,0} = 0$ for all i.

While there is an identical per unit investment cost for each country, $k > 0$, the cost of emission is not a per-unit cost. Each country receives a disutility from the accumulation of GHG in the atmosphere, which is represented by an increasing and convex environmental cost function; $C(G_t)$. Note that this cost depends on the level of aggregate stock, not on the individual contribution to the stock.

Harstad (2012) does not specify the functional form of the environmental cost function. However, Harstad (2016) imposes a quadratic function as follows, which I will utilize in the following sections:

$$C(G_t) = \frac{c}{2} G_t^2 \tag{3}$$

where the parameter $c > 0$ implies the severeness of climate change.

Finally, the benefit of energy consumption, which is denoted by $(y_{i,t})$, is represented by an increasing and concave function $B_i(y_{i,t})$. Again, Harstad (2012) does not specify the functional form of the benefit function besides its concavity, yet Harstad (2016) proposes a quadratic benefit function as follows:

$$B_i(y_{i,t}) = -\frac{b}{2}(\overline{y_i} - y_{i,t})^2 \tag{4}$$

The benefit function is thus concave and increasing up to the ideal energy level for country i, which is represented by its bliss point $\overline{y_i}$. It is the optimal amount of energy consumption if the production process is not polluting. The reason for the optimal point not going to infinity is the other implicit costs of generating and transporting energy (Harstad, 2016). In addition, $b > 0$ is a parameter that reflects the importance of energy.

The energy consumption in the model may come from two sources. Either a country can emit (burn up fossil fuel) $(g_{i,t})$ and contribute to the public bad or it can invest in green technology and meet the energy requirement from renewable sources.

The individual green technology stock of a country ($R_{i,t}$) represents the amount of energy produced from renewables. Therefore, the energy consumption of a country could be represented in the following additive form:

$$y_{i,t} = g_{i,t} + R_{i,t} \tag{5}$$

One should notice that while the energy consumption depends on the amount of emissions in a given period, the impact of green technology is on the basis of the entire stock. Harstad (2012, 2016) explains this as the stock of green technology amounts to the renewable capacity of a country, whereas consuming fossil fuel does not require such a capacity building. An alternative explanation is again made by Harstad (2012, 2016), where $R_{i,t}$ can be thought as the abatement technology of country and $y_{i,t}$ is the energy production of country i at time t. If the energy production is pollutive by itself and the stock of abatement technology is used to clean up the production process, then we end up in the same additive representation given by the equation (5).

Then the utility in a given period is:

$$u_{i,t}(y_{i,t}, g_{i,t}, r_{i,t}) = B_i(y_{i,t}) - C(G_t) - kr_{i,t} \tag{6}$$

While the benefit from energy consumption is private, the environmental cost of the public bad is, by definition, public and exactly the same for each country.

Each country aims to maximize the following continuation value V_i measured as the beginning of period t, which is the present discounted value of future utilities, where δ denotes the common discount factor for all countries.

$$V_{i,t} = \sum_{\tau=t}^{\infty} u_{i,t}\delta^{\tau-t} \tag{7}$$

Countries invest in green technologies ($r_{i,t}$) and emit ($g_{i,t}$) in sequence within a period. Countries invest simultaneously at the beginning of the period. Once the investment stage is complete, amounts of investments made by countries (consequently, individual and global stocks of green technology) become common knowledge, and then the emission stage begins. Again, countries emit simultaneously, and subsequently, the amounts of emissions and the new stock of GHG become common knowledge. Then the period ends. Harstad (2012, 2016) claims that alternating timing of the strategies within a period is essential to have a tractable model.

3.2 The model with technological optimism

My model introduces a second investment channel, an R&D project that will increase the depreciation rate of the GHG stock if successfully invented. We can think of it as carbon capture or carbon storage technology that will technologically boost Earth's natural ability to dissolve and decompose a portion of the carbon in the atmosphere. The increased depreciation rate will lead to smaller GHG stocks and ceteris paribus lower environmental costs.

Investment in R&D project accumulates in a similar fashion to other stocks in the model. X_t represents the global stock of R&D investments at period t:

$$X_t = q_X X_{t-1} + \sum_{i \in N} x_{i,t} \tag{8}$$

where $q_X \in [0, 1]$ represents the fraction of R&D stock that survives to the next period, X_{t-1} is the global stock of technology from the previous period, and $x_{i,t}$ is the contribution to the project by country i in period t.[7] The project starts with no stocks from before, $X_0 = 0$. In this model, there are n + 2 stocks.

The successful realization of the R&D project is a random variable $\psi_t \in \{0, 1\}$ where $\psi_t = 0$ indicates that the technology fails to be invented and $\psi_t = 1$ indicates the technology is successfully invented. The probability of successful realization of the R&D project is ex-ante linked to the total amount of investment made by all countries.

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[7] The global R&D investment stock may instead be country-specific, as the green technology stock. Nevertheless, if we assume the perfect knowledge sharing between countries, we end up in the same equation as (8).

Once the R&D project becomes successful, countries no longer invest in R&D since the new technology is already invented. The accumulated X_t stock is used up entirely in the development of the technology and no longer plays a part in the model.[8] Without the ongoing R&D project, countries terminate the investment in R&D, yet continue to enjoy the higher depreciation rate of the GHG stock. To put it formally, if $\psi_t = 1$, then $\psi_{t+k} = 1$ for all $k = 1, \dots \infty$.

If the R&D project successfully develops the new technology in any previous or current period, i.e. $\exists \tau \leq t$ such that $\psi_{\tau-1} = 0$ and $\psi_{t+k} = 1$ for all $k = 1, \dots \infty$, then the period starting at t proceeds as in the baseline model with green technology investment stage and the emission stage taking place, respectively.

All in one, the conditional probability of success function can be expressed as

$$\begin{aligned}
&\text{prob}(\psi_t = 1 | \psi_\tau = 0 \quad \forall \tau < t) = p(X_t), \\
&\text{prob}(\psi_t = 1 | \psi_\tau = 1 \quad \text{for some} \quad \tau < t) = 1, \\
&\text{prob}(\psi_t = 0 | \psi_\tau = 0 \quad \forall \tau < t) = 1 - p(X_t).
\end{aligned}$$

For the rest of the paper, any state with $\psi_t = 0$ will be referred to as the Failure state and any state with $\psi_t = 1$ will be referred to as the Success state for simplicity.

Naturally, we would expect that with higher X_t, $p(X_t)$ should also increase. Also, probability of invention should be equal to zero if there is no investment made, and investing should become unfeasible when X_t goes to infinity (or sufficiently large). Thus, the probability of success function p is concave, twice continuously differentiable and should satisfy the following conditions.[9] For $X_t \geq 0$:

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[8] Installation and maintenance of the technology are assumed to bear no additional costs.

[9] An example would be $p(X) = 1 - e^{-X}$

$$\lim_{X_t \to \infty} p(X_t) = 1$$

$$\lim_{X_t \to \infty} p'(X_t) = p(0) = 0$$

$$\lim_{X_t \to 0} p'(X_t) = 1$$

$$p''(X_t) \leq 0$$

Harstad (2012, 2016) characterized the depreciation rate of the stock of GHG to be equal to $1 - q_G \in [0, 1]$. In my model, if the technology is successfully invented, the depreciation rate will become $1 - \alpha q_G$, where $\alpha \in [0, 1]$ and $1 - \alpha q_G \in [0, 1]$. The increased depreciation rate leads to a smaller portion of the stock surviving to the next period. The new GHG accumulation equation is

$$G_t = \begin{cases} q_G G_{t-1} + \sum\limits_{i \in N} g_{i,t} & \text{if } \psi_t = 0 \\ \alpha q_G G_{t-1} + \sum\limits_{i \in N} g_{i,t} & \text{if } \psi_t = 1. \end{cases} \tag{9}$$

Similar to the green technology investment, R&D has a per-unit investment cost of $e > 0$. Therefore, one period utility in my model, recalling that $\psi_t = 0$ indicates the failure of invention and $\psi_t = 1$ indicates the success of the invention, becomes:

$$u_{i,t}(y_{i,t}, g_{i,t}, r_{i,t}, x_{i,t}; \psi_t) = B_i(y_{i,t}) - C(G_t) - kr_{i,t} - (1 - \psi_t)ex_{i,t}. \tag{10}$$

Notice that the energy consumption equation ($y_{i,t}$) remains unchanged after R&D investment is introduced in the model. This is because the investment made for R&D has no direct link to energy consumption and the model does not have any budget constraint.

In the baseline model, a period starts with the green technology investment stage, followed by the emission stage. In my model, there are two possibilities depending on the realization of the random variable ψ_t. If the R&D project fails to be realized until period t, i.e. $\forall\tau \leq t; \psi_\tau = 0$, then the countries still have the availability to invest in the R&D project. Consequently, a period consists of three successive and separate stages where the investment in an R&D project takes place between the green technology investment stage and the emission stage. Similar to other stages within a period, countries simultaneously invest in the R&D project as well.

All things considered; the game proceeds as follows. A period starts with the realization of the random variable ψ_t, whether the new technology is invented with the stock of R&D investment from the previous period. At the same time, countries observe the stocks from previous periods: G_{t-1}, R_{t-1} and X_{t-1}. If the invention is not successful ($\psi_t = 0$), then countries first announce their investment contribution ($r_{i,t}$) to their own green technology stock. After investment levels of all countries are chosen, new values of their own technology stock $R_{i,t}$ as well as the amount of global technology stock (R_t) are revealed and that information is common knowledge. Then the first period continues with the R&D investment stage where each country decides on how much they contribute ($x_{i,t}$) to the R&D project. The new stock (X_t) becomes common knowledge, yet whether the project is a success is to be seen until the beginning of the next period. At the final stage of the period, countries decide on how much to emit ($g_{i,t}$). After each country decides on its emission levels, the new stock of GHG (G_t) is revealed and that information is also common knowledge. Finally, consumption takes place.

With probability $p(X_t)$ on the other hand, the technology will be invented at the beginning of period t. In this case the game continues with two stages where green technology investment and emission decisions are taken respectively and there are no R&D investments.

Finally, the equilibrium concept of the game is Markov Perfect Equilibrium (MPE), where strategies are conditioned only on the payoff-relevant elements of the game. MPE prescribes the simplest notion of rationality by only taking payoff-relevant states as a function of strategy (Maskin & Tirole, 2001).

Consequently, my model, states that strategies depend are the values of stocks from the previous period.

MPE is a refinement of Nash Equilibrium. In an environmental agreement framework, Nash Equilibrium corresponds to a self-enforcing agreement where no country has an incentive to unilaterally deviate from the equilibrium strategy dictated by signing the agreement (Dutta & Radner, 2004). The Nash Equilibrium strategies are contingent on the entire history of the game, including the past strategies of other countries and the current state of the game, whereas MPE relaxes this restriction and allows equilibrium strategies to be stationary. A stationary strategy disregards the past strategies of the countries and maps the current state of the game to a strategy (Dutta & Radner, 2004, 2009; Maskin & Tirole, 2001). In my model, the equilibrium strategies are a mapping from current state of the game (previous stock values $G_{t-1}, R_{t-1}, X_{t-1}$), into current strategies $(g_{i,t}, r_{i,t}, x_{i,t})$.

It is quite common in the literature to use MPE in dynamic games (Fudenberg & Tirole, 1991; Harstad, 2012, 2016; Maskin & Tirole, 2001). The desirability of Markov perfect strategies comes from their simplicity. Since they do not condition histories in arbitrary ways, the analysis compared to Subgame Perfect Equilibrium is simpler (Maskin & Tirole, 2001). Harstad (2012, 2016) further defends this choice. There exists a unique symmetric MPE in Harstad's models, which is not very frequent to come up with. The existence of a unique equilibrium allows Harstad to make comparisons and derive intuitive results. My model will give a unique symmetric MPE as well.

In the game, countries aim to maximize the present discounted value of future utilities given by equation (7), as in the baseline model. In doing so, the strategy profile for country i is

$$\left(g_{i,t}(h_t, \psi_t), r_{i,t}(h_t, \psi_t), x_{i,t}(h_t, \psi_t) \right)_{t=1}^{\infty}$$

where h_t is the history at the beginning of period t and ψ_t is the realization of the random variable of invention, as explained earlier. Each strategy of country i depends on the history and the state of the game at that period. In the next section, I will show that countries do not take their individual green technology stocks (R_i's) into consideration when they decide on their strategies. Therefore, Markov perfect strategies only depend on aggregate stock variables from the previous period $(G_{t-1}, R_{t-1}, X_{t-1})$, and h_t should be represented in terms of these previous stock variables alone.

3.3 Preliminaries

From now on, I will drop the time subscript t for both the strategies and the stocks. The stocks from the previous period will be represented by underlined symbols (as in $\underline{G}, \underline{R}$ and $\underline{X}$), and current stocks will be shown simply by their respective symbols $(G, R,$ and $X)$. A similar adjustment is not necessary for strategies since any strategies besides the current one will not come up during calculations.

The first and most obvious challenge that needs to be tackled is the number of stocks in the model. Harstad (2012, 2016) avoided this challenge by assuming the perfect substitutability between current emission (g_i) and current stock of green technology (R_i), given by equation (5). This characterization allows us to reduce the number of stock from $n + 2$ to 3 by following the method used by Harstad as well.

Define the global stock of green technology, $R = \sum_{i \in N} R_i$. Then summing individual green technology stock given by (2) across countries, R can be expressed as follows:

$$R = q_R \underline{R} + \sum_{i \in N} r_i \tag{11}$$

Summing the consumption given by equation (5) across countries and using the previous identity of GHG stock, we get the following equation for the GHG stock:

$$G = \begin{cases} q_G\underline{G} + \sum_{i\in N} y_i - R & \text{if } \psi_t = 0, \\ \alpha q_G\underline{G} + \sum_{i\in N} y_i - R & \text{if } \psi_t = 1. \end{cases} \tag{12}$$

I already stated that Markov perfect strategies that constitute an MPE are contingent only on payoff relevant elements of the model. Equation (12) shows that individual green technology stocks (R_i's) are eliminated from the composition of GHG stock and they are no longer directly involved in any part of the countries' utility functions. R_i's become payoff irrelevant supposing that global technology stock (R) is known by all countries. Therefore, strategies should not be contingent on R_i's (Harstad, 2012, 2016).

One immediate result emerges. Since the strategies are contingent on the value of the stocks at the beginning of the period $(\underline{G}, \underline{R}, \underline{X})$, continuation values after the current period can be written contingent on the value of the stocks at the end of the period (G, R, X). Continuation values are calculated right after ψ is realized at the beginning of t. Thus there is two types of continuation values:

- $V_i^F(\underline{G}, \underline{R}, \underline{X}) = B_i(y_i) - C(G) - kr_i - ex_i + \delta\left[\left(1-p(X)\right)V_i^F(G,R,X) + p(X)V_i^S(G,R)\right]$
- $V_i^S(\underline{G}, \underline{R}) = B_i(y_i) - C(G) - kr_i + \delta V_i^S(G,R)$

where the superscripts F and S indicate realization of the state as Failure ($\psi_t = 0$) and Success ($\psi_t = 1$), respectively at the beginning of the period. Also, notice there is country subscript i at the continuation values because of the heterogenous bliss points ($\overline{y_i}$) in the benefit function.

3.4 Equilibrium

The dynamic character of the game comes from the updated stocks each period. In an infinite-horizon dynamic game, it is impossible and unnecessary to characterize the strategies of many periods because each of them will be contingent on the stocks from the previous period. In each scenario, the objective function contains the continuation value as well. Therefore, simply solving the game for a representative period will suffice to make analytical comparisons.

At the equilibrium, countries do not negotiate their strategies and engage non-cooperatively, which gives business-as-usual (BAU) results. While the maximization at the Success state takes place with respect to green technology investment (r_i) and emissions (g_i), R&D investment (x_i) is added to the choice variables under the Failure state.

The optimal strategies come from backward induction since the choice variables are decided upon at distinct points within the period. This requires the interim continuation values to be defined since they will be the values maximized by a country in the middle of the period. Let

- $W_i^F(q_G\underline{G}, R, q_X\underline{X}) = B_i(y_i) - C(G) - ex_i + \delta\left[\left(1-P(X)\right)V_i^F(G, R, X) + P(X)V_i^S(G, R)\right]$
- $W_i^S(\alpha q_G\underline{G}, R) = B_i(y_i) - C(G) + \delta V_i^S(G, R)$
- $M_i^F(q_G\underline{G}, R, X) = B_i(y_i) - C(G) + \delta\left[\left(1 - P(X)\right)V_i^F(G, R, X) + P(X)V_i^S(G, R)\right]$

be the interim continuation values where W represents the interim continuation value just before the R&D investment stage and M represents the interim continuation value after the R&D investment stage and just before the emissions stage.

Note that defining M^S is redundant since there is no R&D investment stage in the Success state, which makes $W^S = M^S$. One final note is that all of the stocks depreciate when the first stage (green technology investment) is completed. That is why the state variables in the interim continuation values are the amount of stock that survived that period. This difference is particularly visible when W^S and W^F are compared.

The solution begins with the specification of the optimal amount of consumption (will be used interchangeably with emissions) by maximizing the interim continuation value (M^S or M^F depending on the state countries find themselves in). This will give the optimal consumption and optimal emission as a function of GHG stock where G can be represented in terms of $\underline{G}$ and R. This is chronologically sensible as well since the green technology investment stage and R&D investment stage (if present) occur prior to the emissions stage.

In the next step, the optimal amount of R&D investment will be determined by maximizing the second interim continuation value, W. Naturally, this step is only taken if the R&D project is yet to be successful and the countries still invest in R&D, i.e. if the game is in the Failure state. Under the Success state, this step does not exist.

In the final step, the countries decide on the amount of green technology investment at the beginning of the period by maximizing the complete continuation value, V^S or V^F. At this point, the results derived from the first step also come into play because optimal consumption is already formulated in terms of G, and consequently in terms of R_i and r_i. In the end, results from each three (or two) steps are combined and the strategies and stocks are written in terms of stocks from the previous period.

3.4.1 Success state

Equilibrium strategy of country i at the Success state is $\left(r_i^S, g_i^S\right)$. Since $\psi_t = 1$ and the entire R&D investment stock is used up, $\underline{X}$ becomes irrelevant for the future utilities as well.

At the Success state, country i decides only on its green technology investment, r_i and emissions, g_i in a given period. The problem of country i is:

$$\max_{r_i, g_i} V_i^S(\underline{G}, \underline{R}) = B_i(y_i) - C(G) - kr_i + \delta V_i^S(G, R)$$

However, the strategies are chosen at separate points within the period, which allows us to solve the problem by applying backward induction.

3.4.1.1 Emissions stage in the success state

At the emissions stage, a country will decide on the amount of consumption that maximizes the interim continuation value $M_i^S(\alpha q_G \underline{G}, R)$. Since the green technology investments are already made at the beginning of the period, it is acceptable to use y_i and g_i interchangeably at this stage, due to perfect substitutability of g_i and R_i on the consumption equation. Thus the problem of country i is:

$$\max_{y_i} B_i(y_i) - C(G) + \delta V_i^S(G, R).$$

In addition, we plug equation (12) into the above expression to get

$$\max_{y_i} B_i(y_i) - C(\alpha q_G \underline{G} + \sum_{i \in N} y_i - R) + \delta V_i^S(q_G \underline{G} + \sum_{i \in N} y_i - R, R).$$

Now I can take the derivative with respect to y_i and report the equation that will eventually give me the optimal consumption and emission levels.

$$B_i'(y_i) - C'(G)\frac{\partial G}{\partial y_i} + \delta\Big(\frac{\partial V_i^S}{\partial G}\frac{\partial G}{\partial y_i}\Big) = 0$$

From equation (12), $\frac{\partial G}{\partial y_i} = 1$. Then, the above expression could be written as

$$B_i'(y_i) - C'(G) + \delta V_G^S(G, R) = 0,$$

where $V_G^S(G, R)$ indicates the derivative of the continuation value with respect to the GHG stock in its own period.[10] This equality tells us that the value of V_G^S is needed in order to come up with complete results. Moreover, we observe that the above FOC allows y_i to be represented in terms of $\underline{G}$ and R alone.[11]

Second order condition is $B_i''(y_i) - C''(G) + \delta V_{GG}^S(G, R) \leq 0$. It holds due to $V_{GG}^S(G, R) = 0$, which will be shown at Lemma 1.

3.4.1.2 Green technology investment stage in the success state

At the beginning of the period, country i maximizes the continuation value $V_i^S(\underline{G}, \underline{R})$.

$$\max_{r_i} B_i(y_i) - C(G) - kr_i + \delta V_i^S(G, R)$$

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[10] That is, $V_G^S(\underline{G}, \underline{R}) = \frac{\partial V^S(\underline{G}, \underline{R})}{\partial \underline{G}}$.

[11] The country subscript i is omitted from V_G^S on purpose. It will be shown in Lemma 1 that first derivatives of continuation value with respect to GHG stock are identical across countries. The rest of the derivatives of continuation values will omit i by the same reason.

Similar to the problem at the emission stage, when equations (11) and (12) are plugged in, the above expression becomes

$$\max_{r_i} B_i(y_i) - C(\alpha q_G \underline{G} + \sum_{i \in N} y_i - R) - kr_i + \delta V_i^S(\alpha q_G \underline{G} + \sum_{i \in N} y_i - R, q_R \underline{R} + \sum_{i \in N} r_i).$$

Taking the FOC by applying the Envelope Theorem gives

$$-C'(G)\frac{\partial G}{\partial R}\frac{\partial R}{\partial r_i} - k + \delta\left(\left[\frac{\partial V_i^S}{\partial G}\frac{\partial G}{\partial R}\frac{\partial R}{\partial r_i}\right] + \left[\frac{\partial V_i^S}{\partial R}\frac{\partial R}{\partial r_i}\right]\right) = 0.$$

From equations (11) and (12), $\frac{\partial R}{\partial r_i} = 1$ and $\frac{\partial G}{\partial R} = -1$ respectively. The more compact version of the above expression is

$$C'(G) - k + \delta\left(V_R^S(G, R) - V_G^S(G, R))\right) = 0,$$

where $V_R^S(G, R)$ indicates the derivative of continuation value with respect to global green technology stock in its own period, similar to $V_G^S(G, R)$ described in emissions stage.[12] The second order condition is $C''(G) + \delta\left(V_{RR}^S(G, R - V_{GR}^S(G, R))\right) \leq 0$. It holds due to $V_{RR}^S(G, R) = V_{GR}^S(G, R) = 0$ which will be shown at Lemma 1.

This FOC tells that I need the values of both V_R^S and V_G^S in order to calculate the complete results for both strategies. This necessity brings us to the following Lemma:

Lemma 1: Under the Success state, first derivatives of the continuation value V^S with respect to stocks are identical across countries. Moreover, the continuation values are linear in stocks (the first derivative of the continuation value with respect to both stocks is constant) and can be written as follows:

$$V_R^S = q_R \frac{k}{n},$$
$$V_G^S = -\alpha q_G \frac{k}{n}(1 - \delta q_R).$$

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[12] That is, $V_R^S(\underline{G}, \underline{R}) = \frac{\partial V^S(\underline{G}, \underline{R})}{\partial \underline{R}}$.

The proof of Lemma 1 is a simplified version of the proof of Lemma 2; the first derivatives of the continuation values in terms of its stocks under the Failure state. Therefore, the proof is omitted here.

Now that we have the first derivatives of the continuation value with respect to both stocks, the problems stated above can be solved explicitly. Let $(r^S_{i\ bau}, g^S_{i\ bau})$ be the symmetric Markov perfect equilibrium strategy profile of country i and (R^S_{bau}, G^S_{bau}) be the corresponding equilibrium stock variables in the Success state under business-as-usual scenario.

Proposition 1: The symmetric Markov perfect equilibrium strategy profile $(r^S_{i\ bau}, g^S_{i\ bau})$ and stocks (R^S_{bau}, G^S_{bau}) are

$$r^S_{i\ bau} = \frac{\alpha q_G \underline{G}}{n} - \frac{q_R \underline{R}}{n} + \bar{y} - \left[\frac{(b+cn)^2}{bcn(b+c)}\left(1 - \frac{\delta q_R}{n}\right)k - (1-\delta q_R)\frac{\alpha\delta q_G}{cn^2}k\right],$$

$$g^S_{i\ bau} = \overline{y_i} - \frac{R^S_{bau}}{n} - \left[\frac{cn(\alpha q_G \underline{G} - R^S_{bau}) + cn^2\bar{y} + \alpha\delta q_G(1-\delta q_R)k}{(b+cn)n}\right],$$

$$R^S_{bau} = \alpha q_G \underline{G} + \bar{y}n - \left[\frac{(b+cn)^2}{bc(b+c)}\left(1 - \frac{\delta q_R}{n}\right)k - (1-\delta q_R)\frac{\alpha\delta q_G}{cn}k\right],$$

$$G^S_{bau} = \frac{b(\alpha q_G \underline{G} - R^S_{bau}) + bn\bar{y} - \alpha\delta q_G k(1-\delta q_R)}{b+cn}.$$

Before moving to the proof, two things should be mentioned. First, these are the results of a representative period. Since the equilibrium strategies and the equilibrium stock variables are represented in terms of stocks from previous periods, it will be enough to update the values of previous stocks to get $\left(r^S_{i,\tau bau}, g^S_{i,\tau bau}, R^S_{\tau\ bau}, G^S_{\tau\ bau}\right)_{\tau=t}^{\infty}$.

Second, both G^S_{bau} and $g^S_{i\,bau}$ contain R^S_{bau}. When the optimal value of R^S_{bau} given in this proposition is plugged in, the explicit results of G^S_{bau} and $g^S_{i\,bau}$ are found.

Proof. Define $\widetilde{y_i} \equiv y_i + \overline{y} - \overline{y_i}$, where $\overline{y}$ represents the average $\overline{y_i}$ for all countries.[13] With this identity alongside with quadratic cost and benefit functions, the FOC from the emissions stage is rewritten as

$$b(\overline{y} - \widetilde{y_i}) - cG + \delta V^S_G(G, R) = 0,$$

where $\widetilde{y_i}$ is at optimal values in the above expression. Since rest of the expressions are aggregates (common for all countries), $\widetilde{y_i}$'s are identical across countries. Using V^S_G in Lemma 1, $\widetilde{y_i}$ and y_i are expressed as

$$\widetilde{y}^S_{ibau} = \overline{y} - \frac{cG + m}{b}, \tag{13}$$

$$y^S_{i\,bau} = \overline{y_i} - \frac{cG + m}{b} \tag{14}$$

where $m = -\delta V^S_G = \alpha\delta q_G(1 - \delta q_R)\frac{k}{n}$. Summing equation (13) across countries and using equation (12) yields

$$G^S_{bau} = \frac{b(\overline{\overline{G}} - R) + bn\overline{y} - mn}{b + cn} \tag{15}$$

where $\overline{\overline{G}} = \alpha q_G \underline{G}$. When m is plugged in, we get G^S_{bau}.

Plugging equation (15) into equation (14) gives us another expression of optimal consumption.

$$y^S_{i\,bau} = \overline{y_i} - \frac{c(\overline{\overline{G}} - R) + cn\overline{y} + m}{b + cn}. \tag{16}$$

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[13] Defined by Harstad (2016). When this equivalence is summed for n countries, $\overline{y}$ and $\overline{y_i}$'s cancel each other out.

Since $g_i = y_i - R_i$, substract R_i from equation (15) and plug in m to get $g_i^S{}_{bau}$ in Proposition 1.[14] Going back to the green technology investment maximization:

$$\max_{r_i} -\frac{b}{2}(\overline{y_i} - y_i)^2 - \frac{c}{2}G^2 - kr_i + \delta V_i^S(G, R)$$

Now that I have the values of y_i and G in terms of model parameters, I can restate the problem at the investment stage:

$$\max_{r_i} -\frac{b}{2}\left(\frac{cG + m}{b}\right)^2 - \frac{c}{2}G^2 - kr_i + \delta V_i^S(G, R).$$

The above expression can be expressed more compactly as

$$\max_{r_i} \left(-\frac{m^2}{2b} - \frac{cm}{b}G - \frac{c}{2}(1 + \frac{c}{b})G^2 - kr_i + \delta V_i^S(G, R)\right).$$

The FOC with respect to r_i gives

$$-\frac{cm}{b}\frac{\partial G}{\partial R}\frac{\partial R}{\partial r_i} - \frac{c}{2}\left(1 + \frac{c}{b}\right)2G\frac{\partial G}{\partial R}\frac{\partial R}{\partial r_i} - k + \delta\left[\frac{\partial V_i^S}{\partial G}\frac{\partial G}{\partial R}\frac{\partial R}{\partial r_i} + \frac{\partial V_i^S}{\partial R}\frac{\partial R}{\partial r_i}\right] = 0$$

Equations (12) and (15) respectively indicates $\frac{\partial R}{\partial r_i} = 1$ and $\frac{\partial G}{\partial R} = -\frac{b}{b+cn}$. Even more compact version of the above expression is

$$(-\frac{cm}{b})(-\frac{b}{b + cn}) - cG\left(1 + \frac{c}{b}\right)(-\frac{b}{b + cn}) - k + \delta\left[V_G^S(G, R)(-\frac{b}{b + cn}) + V_R^S(G, R)\right] = 0$$

Lemma 1 already provides V_R^S and V_G^S. When the expression of G from equation (15) is plugged in and R is isolated, we get R_{bau}^S. Equation (11) with identical investment of countries gives $r_i^S{}_{bau}$. □

3.4.2 Failure state

Equilibrium strategy of country i at the Failure state is $\left(r_i^F, g_i^F, x_i^F \right)$, where $\psi_t = 0$. Country i finds the optimal values of green technology investments, R&D

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[14] Symmetry of green technology investments allows us to say $R_i = R/n$.

investments and emissions in a given period. Then the problem of country i is

$$\max_{r_i, x_i, g_i} V_i^F(\underline{G}, \underline{R}, \underline{X}) = B_i(y_i) - C(G) - kr_i - ex_i + \delta\left[\left(1-p(X)\right)V_i^F(G, R, X) + p(X)V_i^S(G, R)\right].$$

Similar to the Success state, country i does not decide all of its strategies simultaneously and applies backward induction since each strategy has its own distinct stages within a period.

3.4.2.1 Emissions stage in the failure state

Country i maximizes the interim continuation value $M_i^F(q_G\underline{G}, R, X)$ with respect to y_i at the emissions stage:

$$\max_{y_i} B_i(y_i) - C(G) + \delta\left[\left(1-p(X)\right)V_i^F(G, R, X) + p(X)V_i^S(G, R)\right].$$

With equation (12), the above problem becomes:

$$\max_{y_i} B_i(y_i) - C(q_G\underline{G} + \sum_{i \in N} y_i - R) + \delta\left[\left(1-p(X)\right)V_i^F(q_G\underline{G} + \sum_{i \in N} y_i - R, R, X) + p(X)V_i^S(G, R)\right].$$

The FOC with respect to y_i gives:

$$B_i'(y_i) - C'(G)\frac{\partial G}{\partial y_i} + \delta\left(\left(1-p(X)\right)\frac{\partial V_i^F}{\partial G}\frac{\partial G}{\partial y_i} + p(X)\frac{\partial V_i^S}{\partial G}\frac{\partial G}{\partial y_i}\right) = 0.$$

As in the Success state by using $\frac{\partial G}{\partial y_i} = 1$, a more compact version of the above expression is:

$$B_i'(y_i) - C'(G) + \delta\left(\left(1-p(X)\right)V_G^F(G, R, X) + p(X)V_G^S(G, R)\right) = 0.$$

Now, the optimal y_i can be represented in terms of $\underline{G}$, R and X. Similarly, the value of V_G^F is required (which will be provided in Lemma 2). V_G^S is already found in the

Success state.[15] Second order condition is $B_i''(y_i) - C''(G) + \delta\Big(\big(1 - p(X)\big)V_{GG}^F(G, R, X) + p(X)V_{GG}^S(G, R)\Big) \leq 0$ and it holds when the second derivatives are equal to 0, which will be shown in Lemma 2.

3.4.2.2 R&D investment stage in the failure state

At the R&D investment stage, county i maximizes the interim continuation value $W_i^F(q_G\underline{G}, R, q_X\underline{X})$ with respect to x_i:

$$\max_{x_i} B_i(y_i) - C(G) - ex_i + \delta\big[\big(1 - p(X)\big)V_i^F(G, R, X) + p(X)V_i^S(G, R)\big].$$

Note that x_i affects the utility through its investment cost and the continuation values of Success and Failure states through probabilities. Taking FOC with respect to x_i gives

$$-e + \delta\left[p'(X)V_i^S(G, R) + \big(1 - p(X)\big)V_X^F(G, R, X) - p'(X)V_i^F(G, R, X)\right] = 0$$

where V_X^F is the first derivative of the continuation value with respect to global R&D investment stock X.[16]

The above problem and its FOC reveal an issue. Since FOC with respect to y_i and r_i are linear in their respective choice variable, explicit results for them can be obtained. However, in R&D investments, both the probability of success function p(X) and the continuation value in the Failure state $V_i^F(G, R, X)$ depend on X, and the linearity of R&D investments in its FOC is violated due to Product Rule. Moreover, the value of $V_X^F(G, R, X)$ is needed in order to get explicit results. It requires a difference equation to be solved, which cannot be done. In order to overcome this issue, I am going to introduce two special cases of the R&D stock, which detaches the X from $V_i^F(G, R, X)$ as a choice variable, converting the continuation value into

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[15] Country subscript i is omitted from first derivatives of continuation values with the same reason indicated at footnote 11.

[16] Applying the Chain Rule, $\frac{\partial V^F(G,R,X)}{\partial X}\frac{\partial X}{\partial x_i} = V_X^F(G, R, X)$ where $\frac{\partial X}{\partial x_i} = 1$ from the accumulation equation of global R&D investment stock.

$V_i^F(G, R)$.

Case 1: Suppose $q_X = 0$, i.e. the stock of R&D is used up at the end of each period, thus it does not accumulate over time. Since there is no $\underline{X}$ coming from previous period, strategies and continuation values of countries are not going to be contingent on $\underline{X}$. At each period, countries decide whether to invest in R&D for that period alone, knowing zero survival for the next periods.

Case 2: Suppose an outside benefactor (Elon Musk for instance) decides to finance the R&D project. He/she announces to invest an amount of μ at $t = 1$. For the following periods, he/she invests the exact amount that depreciates from the previous period ($\mu - \mu q_X$), which makes the flow of X exogenously predetermined and equal to μ and the probability of success $p(\mu)$ to be equal to a constant p for all $t \in 1, \ldots \infty$.

He/she also assures the public that any additional cost that may arise during installation and maintenance will be covered by him. As before, the countries expect that the flow to R&D stops as soon as the project is successful and the stock of R&D is entirely used up for invention procedure. The R&D investment is now exogenous, thus X is not a choice variable anymore. Unlike Case 1, there is an amount of the stock survives to the next period. However, since x is not a choice variable anymore, we write the continuation value as a function of endogenous stock variables $\underline{G}$ and $\underline{R}$, while $\underline{X}$ serves as an exogenous stock variable in this case.

There is no need to solve for x_i in case 2 since it is exogenously determined. However, we still need to characterize the optimal amount of x_i in Case 1. Thus, the problem of country i can be rewritten as

$$\max_{x_i} B_i(y_i) - C(G) - ex_i + \delta\left[\left(1 - p(X)\right)V_i^F(G, R) + p(X)V_i^S(G, R)\right].$$

Taking FOC with respect to x_i characterizes the optimal investment to R&D as

$$-e + \delta\left[p'(X)V_i^S(G, R) - p'(X)V_i^F(G, R)\right] = 0.$$

Note that $V_X^F(G, R)$ is eliminated from the optimality condition, hence there is no need to find its value.

Rewrite the above condition as $\frac{e}{\delta} = p'(X)(V_i^S - V_i^F)$ where $X = \sum_{i \in N} x_i$. In the symmetric solution either all countries invest or no countries invest. If $x_i = 0$ for all i, $p'(X = 0) = \infty$. Moreover, if $x_i \to \infty$, $p'(X) = 0$ but this time $(V_i^S - V_i^F) = \infty$ (because of $-ex_i$ that comes from V_i^F), which rules out a corner solution and tells us $x_i > 0$ for all i.

Another way to look at it is to compare the continuation values when $x_i > 0$ and $x_i = 0$ for all i. Respectively, the continuation values in each scenario are

$$V_i^F(G, R|x_i > 0) = B_i(y_i) - C(G) - kr_i - ex_i + \delta\left[\left(1 - p(X)\right)V_i^F(G, R) + p(X)V_i^S(G, R)\right]$$

$$V_i^F(G, R|x_i = 0) = B_i(y_i) - C(G) - kr_i + \delta V_i^F(G, R)$$

where $p(X = 0) = 0$ when $x_i = 0$ for all i. Let ΔV^F denote the difference between the continuation values.

$$\Delta V_i^F = V_i^F(G, R|x_i > 0) - V_i^F(G, R|x_i = 0) = \delta p(X)(V_i^S - V_i^F) - ex_i.$$

When $\delta p(X)(V_i^S - V_i^F) > ex_i$, then the potential benefit of R&D investment exceeds its cost, thus countries invest. Plug the condition derived from FOC, $\frac{e}{\delta} = p'(X)(V_i^S - V_i^F)$ into above inequality to get $\frac{p(X)}{p'(X)} > x_i$ as the positive investment condition. Due to the symmetry of the problem, we expect every country to invest the same amount, which makes $x_i = X/n$. Positive investment condition holds for all n,[17] therefore countries invest in R&D even when $q_X = 0$. The optimal amount of x_i and X are characterized by the FOC equation.

Even though we cannot derive the explicit form of R&D investment in Case 1, I eliminated the corner solution and showed that the decision to invest or not invest does not depend on other stock variables, $\underline{G}$ and $\underline{R}$. This result is noteworthy and will be useful to characterize the optimal green technology investments and emissions.

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[17] Shown at Appendix A that it holds when $p(X) = 1 - e^{-X}$. Whether it holds for any generic p(X) needs to be checked!

3.4.2.3 Green technology investment stage in the failure state

Finally, at the beginning of the period, country i maximizes the continuation value $V_i^F(G,R)$ to choose its green technology investment level. The problem with country i is

$$\max_{r_i} B_i(y_i) - C(G) - kr_i - ex_i + \delta\left[\left(1 - p(X)\right)V_i^F(G,R) + p(X)V_i^S(G,R)\right].$$

Similar to the problem at the emission stage, when equations (11) and (12) are plugged in, the above expression becomes

$$\max_{r_i} B_i(y_i) - C(q_G\underline{G} + \sum_{i\in N} y_i - R) - kr_i - ex_i + \delta\Bigg[\left(1-p(X)\right)V_i^F(G, q_R\underline{R} + \sum_{i\in N} r_i) \\ +p(X)V_i^S(G, q_R\underline{R} + \sum_{i\in N} r_i)\Bigg].$$

Applying the Envelope Theorem, the FOC is

$$-C'(G)\frac{\partial G}{\partial R}\frac{\partial R}{\partial r_i} - k + \delta\Bigg((1 - p(X))\Bigg(\left[\frac{\partial V_i^F}{\partial G}\frac{\partial G}{\partial R}\frac{\partial R}{\partial r_i}\right] + \left[\frac{\partial V_i^F}{\partial R}\frac{\partial R}{\partial r_i}\right]\Bigg) + \\ p(X)\Bigg(\left[\frac{\partial V_i^S}{\partial G}\frac{\partial G}{\partial R}\frac{\partial R}{\partial r_i}\right] + \left[\frac{\partial V_i^S}{\partial R}\frac{\partial R}{\partial r_i}\right]\Bigg)\Bigg) = 0.$$

Again, equation (11) and equation (12) respectively imply $\frac{\partial R}{\partial r_i} = 1$ and $\frac{\partial G}{\partial R} = -1$. A more compact version of the above expression is

$$C'(G) - k + \delta\Bigg((1 - p(X))\Bigg(- V_G^F(G,R) + V_R^F(G,R)\Bigg) + \\ p(X)\Bigg(- V_G^S(G,R) + V_R^S(G,R)\Bigg)\Bigg) = 0,$$

where $V_R^F(G,R)$ indicates the derivative of continuation value with respect to global green technology stock in its own period. Again, second order condition holds from second derivatives being equal to 0 and $C''(G) \leq 0$. Similar to the problem in the Success state, the value of both V_G^F and V_R^F are needed to calculate the complete results for both strategies in the Failure state, which brings us to the following Lemma:

Lemma 2: Under the Failure state, the first derivatives of the continuation value V^F with respect to the endogenous stocks are identical across countries. Moreover, the continuation values are linear in stocks (the first derivative of the continuation value with respect to both stocks is constant) and can be written as follows:

$$V_R^F = q_R \frac{k}{n},$$
$$V_G^F = -q_G \frac{k}{n}\Big(1 - \delta q_R \big(1 - p(X)(1-\alpha)\big)\Big).$$

Proof. Each derivative of the continuation value will be calculated separately.

Step 1: At the green technology investment stage, the problem of country i can be represented in terms of the interim continuation value

$$\max_{r_i} W_i^F(q_G \underline{G}, R) - kr_i$$

Taking FOC gives $W_{(i)R}^F(q_G\underline{G}, R) = k$,[18] where each r_i is at its optimal value. Summing r_i's across countries gives the current global green technology stock R. The equality obtained from FOC should hold for any optimal R and the variation of R depends on the other stock in the equation; $\underline{G}$. In other words, the optimal value of R can be represented as a function in terms of $\underline{G}$.

Since the the problem of other countries are symmetric, country i will expect the same amount of investment from the remaining j countries, i.e. $r_j = r$ for all $j \neq i$. Following from equation (11), the expected amount of investment from any country j is $\frac{R^{**}(\underline{G}) - q_R\underline{R}}{n}$, where $R^{**}(\underline{G})$ is the equilibrium $R(\underline{G})$. Then, r_i becomes

$$r_i = R(\underline{G}) - q_R\underline{R} - \sum_{j \neq i} \frac{R^{**}(\underline{G}) - q_R\underline{R}}{n}.$$

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[18] $W_R^F(q_G\underline{G}, R) = \frac{\partial W^F}{\partial R}$.

The continuation value at the beginning of the period can be represented as the interim continuation value minus the green technology investments,

$$V_i^F(\underline{G},\underline{R}) = W_i^F(q_G\underline{G},R) - k\left[R(\underline{G}) - q_R\underline{R} - (n-1)\frac{R^{**}(\underline{G}) - q_R\underline{R}}{n}\right].$$

Taking derivative of the above expression with respect to $\underline{R}$ proves V_R^F is invariant of i and gives the first result of Lemma 2.

Step 2: From the R&D investment stage at Case 1, the FOC for the optimal amount of R&D investment is given by $\frac{e}{\delta} = p'(X)(V_i^S(G,R) - V_i^F(G,R))$ where $X = \sum_{i\in N} x_i$. Using (12), the condition can be rewritten as:

$$\frac{e}{\delta} = p'(X)(V_i^S(\alpha q_G\underline{G} + \sum_{i\in N} y_i - R, R) - V_i^F(q_G\underline{G} + \sum_{i\in N} y_i - R, R)).$$

The above expression indicates that X can be represented as a function of $\underline{G}$ and R. This is chronologically sensible as well since at the R&D stage, green technology investments at a given period have been made by all countries. While the global green technology is updated to R, GHG stock is still $\underline{G}$. Therefore we would expect the R&D investments to be depended on $\underline{G}$ and R. Let the function $f^X(\underline{G},R)$ denote the optimal level of X.

At the emissions stage, choosing y_i is equivalent to choosing g_i. When G is represented as in equation (12), the problem becomes

$$\max_{y_i} B_i(y_i) - C(q_G\underline{G} + \sum_{i\in N} y_i - R) + \delta\Big[\big(1-p(X)\big)V_i^F(q_G\underline{G} + \sum_{i\in N} y_i - R, R) +$$
$$p(X)V_i^S(\alpha q_G\underline{G} + \sum_{i\in N} y_i - R, R)\Big].$$

Taking FOC with respect to y_i gives

$$B_i'(y_i) - C'(G) + \delta\Big[\big(1-p(X)\big)V_G^F(q_G\underline{G} + \sum_{i\in N} y_i - R, R) +$$
$$p(X)V_G^S(\alpha q_G\underline{G} + \sum_{i\in N} y_i - R, R)\Big] = 0.$$

The above equation holds for the optimal values of y_i and it tells that y_i can be represented as a function of $\underline{G}$, R and X. Let the function $f^{y_i}(\underline{G}, R, X)$ denote the optimal y_i.

Finally, using equation (12), G can be represented as a function of $\underline{G}$, R and X. Let the function $f^G(\underline{G}, R, X)$ denote the optimal G.

R is the to be determined by $R = q_G\underline{G} + \sum_{i \in N} f^{y_i}(\underline{G}, R, X) - f^G(\underline{G}, R, X)$ in the Failure state and $R = \alpha q_G\underline{G} + \sum_{i \in N} f^{y_i}(\underline{G}, R, X) - f^g(\underline{G}, R, X)$ in the Success state. Moreover, $r_i = (R - q_R\underline{R})/n$ and $(x_i = f^X(\underline{G}, R) - q_X\underline{X})/n$. Then the continuation value (at the beginning of the period) becomes:

$$V_i^F(\underline{G}, \underline{R}) = B_i(f^{y_i}) - C(f^G) - kr_i - ex_i + \delta\left[\left(1 - p(f^X)\right)V_i^F(f^G, R) + p(f^X)V_i^S(f^G, R)\right].$$

Applying the Envelope Theorem

$$V_G^F(\underline{G}, \underline{R}) = -\frac{k}{n}q_G + \delta\left[p(X)\alpha q_G V_R^S + \left(1 - p(X)\right)q_G V_R^F\right].$$

From Lemma 1 and the first part of Lemma 2, we know that $V_R^F = V_R^S = \frac{k}{n}q_R$. When these are plugged in:

$$V_G^F(\underline{G}, \underline{R}) = -\frac{k}{n}q_G + \delta\left[p(X)\alpha q_G\frac{k}{n}q_R + \left(1 - p(X)\right)q_G\frac{k}{n}q_R\right].$$

When this expression is written more compactly, we show that V_G^F is country invariant and its value is given at Lemma 2. □

Let $(r_{i\ bau}^F)$, $(g_{i\ bau}^F)$ be the symmetric Markov perfect equilibrium strategy profile of country i and $(R_{bau}^F$, $G_{bau}^F)$ be the corresponding equilibrium stock variables in the Failure state under business-as-usual scenario.

Proposition 2: The symmetric Markov perfect equilibrium strategy profile $(r_{i\ bau}^F$, $g_{i\ bau}^F)$ and stocks $(R_{bau}^F$, $G_{bau}^F)$ are

$$r^F_{i\ bau} = \frac{q_G\underline{G}}{n} - \frac{q_R\underline{R}}{n} + \bar{y} - \left[\frac{(b+cn)^2}{bcn(b+c)}\left(1 - \frac{\delta q_R}{n}\right)k - (1-\delta q_R)\frac{\delta q_G}{cn^2}k\vartheta\right],$$

$$g^F_{i\ bau} = \overline{y_i} - \frac{R^F_{bau}}{n} - \left[\frac{cn(q_G\underline{G} - R^F_{bau}) + cn^2\bar{y} + \delta q_G(1-\delta q_R)k\vartheta}{(b+cn)n}\right],$$

$$R^F_{bau} = q_G\underline{G} + \bar{y}n - \left[\frac{(b+cn)^2}{bc(b+c)}\left(1 - \frac{\delta q_R}{n}\right)k - (1-\delta q_R)\frac{\delta q_G}{cn}k\vartheta\right],$$

$$G^F_{bau} = \frac{b(q_G\underline{G} - R^F_{bau}) + bn\bar{y} - \delta q_G(1-\delta q_R)k\vartheta}{b+cn},$$

where $\vartheta = 1 - (1-\alpha)p(X)\frac{1-\delta q_R\left(2-p(X)\right)}{1-\delta q_R}$. Note that these results are characterized for case 1, where $q_X = 0$ and the optimal x_i obtained by $\frac{e}{\delta} = p'(X)(V^S - V^F)$. At Case 2, the accumulation of R&D stock is exogenous, $x_t = \mu$ for all $t \in 1, \ldots \infty$ and $p(X)$ in ϑ is replaced by p.

Proof. With the quadratic cost and benefit functions and $\widetilde{y_i} \equiv y_i + \bar{y} - \overline{y_i}$, the FOC from the problem at emissions stage can be rewritten as

$$b(\bar{y} - \widetilde{y_i}) - cG + \delta\left(p(X)V^S_G(G,R) + \left(1 - p(X)\right)V^F_G(G,R)\right) = 0.$$

From Lemma 1 and Lemma 2, I have the derivative of continuation value with respect to GHG stock both in Success and Failure. When they are plugged in:

$$\widetilde{y}^F_{i bau} = \bar{y} - \frac{cG+d}{b} \tag{17}$$

$$y^F_{i\ bau} = \overline{y_i} - \frac{cG+d}{b} \tag{18}$$

where $d = -\delta\left[p(X)V^S_G(G,R) + \left(1 - p(X)\right)V^F_G(G,R)\right]$. When both first derivatives are plugged in; $d = \delta[q_G(1 - \delta q_R)\frac{k}{n}\vartheta]$ with ϑ defined above. Summing equation (17) across countries and using equation (12) yields

$$G^F_{bau} = \frac{b(\widetilde{G} - R) + bn\bar{y} - dn}{b + cn}, \tag{19}$$

where $\widetilde{G} = q_G\underline{G}$. Plugging this expression into equation (18), we get another expression of optimal consumption under Failure.

$$y^F_{i\;bau} = \overline{y_i} - \frac{c(\widetilde{G} - R) + cn\bar{y} + d}{b + cn} \tag{20}$$

Since $g_i = y_i - R_i$, substract R_i from equation (20) and plug in d to get $g^F_{i\;bau}$ in Proposition 2.

Finally, at the green technology investment stage, country i maximizes

$$\max_{r_i} -\frac{b}{2}(\overline{y_i} - y_i)^2 - \frac{c}{2}G^2 - kr_i - ex_i + \delta\left(p(X)V^S_i(G, R) + \big(1 - p(X)\big)V^F_i(G, R)\right).$$

Now that I have the values of y_i and G in terms of model parameters, I can restate the problem at the investment stage:

$$\max_{r_i} -\frac{b}{2}\left(\frac{cG + d}{b}\right)^2 - \frac{c}{2}G^2 - kr_i - ex_i + \delta\left(p(X)V^S_i(G, R) + \big(1 - p(X)\big)V^F_i(G, R)\right).$$

Similar to the problem in Success, $\frac{\partial G}{\partial R}$ and $\frac{\partial R}{\partial r_i}$ will appear when equation (12) is plugged in the above expression and the Chain Rule is applied. Equations (12) and (19) respectively indicate $\frac{\partial R}{\partial r_i} = 1$ and $\frac{\partial G}{\partial R} = -\frac{b}{b+cn}$. Lemma 1 provides V^S_R, V^S_G and Lemma 2 provides V^F_R, V^F_G. After some lengthy algebra, we get R^F_{bau} and $r^F_{i\;bau}$. □

Propositions 1 and 2 tell us a few things. An increase in the overall energy demand of the world (can be predicted by ($\bar{y}$), the average bliss point of energy consumption) increases the investment in green technology and global green technology stock, yet increases the GHG stock as well. Its effect on individual emissions seems inversely proportioned at first glance, however, the increasing effect of the individual bliss point $\overline{y_i}$ should offset the decreasing effect of $\bar{y}$. We can say that if the average bliss point of energy consumption increases while the individual bliss point remains the same, the emissions of a country decrease. In other words, if a country expects increasing energy demand for other countries while its demand stays the same, that country decreases emissions to partially offset the increasing environmental cost in the future.

Another noteworthy feature of the results is the relation between emissions and green technology investments. Notice that both current green technology investment and global stock of green technology are independent of current emissions (they obviously depend on $\underline{G}$), while emissions and GHG stock depend on the green technology stock. The main reasons for this feature are the timing within the period and the restriction to symmetric MPE. At the beginning of the period, countries invest in green technology without any information regarding the emissions of countries in that period. Symmetric MPE ensures identical investment across countries and the prior position of the green technology investment stage lets the investments be independent of current emissions. Whereas in emissions, both the independence (from investments) and homogeneity no longer persist. It is reasonable for countries to formulate emission strategies contingent on current green technology stock since current investments already updated the stock and that information is available. The heterogeneous emissions do not violate the symmetric MPE since, in terms of the functional form of the strategy, g_i's are identical across countries. The difference is caused by the heterogeneous component of their utility function, individual bliss points.

Corollary 1: When $\alpha = 1$, the stocks and strategies in Propositions 1 and 2 converge to the business-as-usual results Harstad (2016) where there is no R&D project.[19]

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[19] Harstad (2016) also has investment externalities. The results in my model converge to a version where there are no externalities.

Denote the business-as-usual results from Harstad (2016) as $\left(R^*_{bau}, G^*_{bau}, r^*_{i\,bau}, g^*_{i\,bau}\right)$.

$$r^*_{i\,bau} = \frac{q_G\underline{G}}{n} - \frac{q_R\underline{R}}{n} + \overline{y} - \left[\frac{(b+cn)^2}{bcn(b+c)}\left(1 - \frac{\delta q_R}{n}\right)k - (1-\delta q_R)\frac{\delta q_G}{cn^2}k\right],$$

$$g^*_{i\,bau} = \overline{y_i} - R_i - \left[\frac{cn(q_G\underline{G} - R) + cn^2\overline{y} + \delta q_G(1-\delta q_R)k}{(b+cn)n}\right],$$

$$R^*_{bau} = q_G\underline{G} + \overline{y}n - \left[\frac{(b+cn)^2}{bc(b+c)}\left(1 - \frac{\delta q_R}{n}\right)k - (1-\delta q_R)\frac{\delta q_G}{cn}k\right],$$

$$G^*_{bau} = \frac{b(q_G\underline{G} - R) + bn\overline{y} - (\delta q_G(1-\delta q_R)k)}{b+cn}.$$

Proof. With $\alpha = 1$, the R&D project is ineffective and we expect countries not to invest in it. Also, G is equal for both Success and Failure.

With $\alpha = 1$, one period utility of each state for country i is

$$u_i^F = B_i(y_i) - C(G) - kr_i - ex_i$$
$$u_i^S = B_i(y_i) - C(G) - kr_i.$$

If $x_i > 0$, $u_i^F < u_i^S$ and if $x_i = 0$, $u_i^F = u_i^S$. In terms of continuation values:

$$V_i^F = B_i(y_i) - C(G) - kr_i - ex_i + \delta\left(p(X)V_i^S(G,R) + \left(1 - p(X)\right)V_i^F(G,R)\right)$$
$$V_i^S = B_i(y_i) - C(G) - kr_i + \delta V_i^S(G,R).$$

Note that if X = 0 (implies $x_i = 0$), $V^F = V^S$ due to p(0) = 0.

When $\alpha = 1$, the highest possible value for V^F happens when $x_i = 0$. Even if the R&D project becomes successful ($\psi = 1$), nothing changes in the one period utility except ($-ex_i$) term disappears. The exact same thing can be sustained with $x_i =$

0 for current and future periods under the Failure state. Thus $x_i > 0$ is a never best response for country i. □

The above result applies in Case 1, when x_i is endogenous. When $x_i > 0$ exogenously as in Case 2 (Elon Musk case), the rest of the utility function is identical in both states (Success and Failure) and the problem is identical Harstad (2016) without the R&D investment stage and $\alpha = 1$.

Proposition 3: When the R&D project is available for countries to invest in, they invest less in green technology and make more emissions, both before and after the R&D project is successful. Consequently, global green technology stock is lower and GHG stock (pollution) is higher.

$$r_{i\ bau}^{S} < r_{i\ bau}^{*} \Rightarrow R_{bau}^{S} < R_{bau}^{*}$$
$$r_{i\ bau}^{F} < r_{i\ bau}^{*} \Rightarrow R_{bau}^{F} < R_{bau}^{*}$$
$$g_{i\ bau}^{S} > g_{i\ bau}^{*} \Rightarrow G_{bau}^{S} > G_{bau}^{*}$$
$$g_{i\ bau}^{F} > g_{i\ bau}^{*} \Rightarrow G_{bau}^{F} > G_{bau}^{*}$$

The proof follows from $0 < \alpha < 1$, provided that $0 < \vartheta < 1$.[20]

It is important to highlight that both the equilibrium strategies and stocks depend on previous stocks ($\underline{G}$ and $\underline{R}$). When there is no R&D project to invest in (or $\alpha = 1$), my model becomes identical to Harstad (2016) what the previous corollary indicates. To compare my results with the results of Harstad, benchmarks for $\underline{G}$ and $\underline{R}$ are useful.

The comparison between my model and Harstad (2016) in terms of the results in the same period holds little value since the stocks will follow different paths and most likely to have different values in both models at the same period. Comparing

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[20] For $\delta q_R \leq 1/2$, $0 < \vartheta < 1$ for all possible values of p(X). As the upper bound of δq_R increases, p(X) needs to be sufficiently higher than 0 in order to sustain $0 < \vartheta < 1$.

the results of both models when they have the same state variables ($\underline{G}$ and $\underline{R}$) allows me to capture the differences in behaviour caused by the existence of an R&D project when all decision related variables are the same.

Next subsection will characterize the first-best strategies and consequent equilibrium results. The results of both business-as-usual and first-best will be discussed in chapter 4.

3.5 First-best

Now consider the scenario where countries are willing to reach a global agreement and negotiate both their investments in green technology and R&D, as well as their emissions. Since the model takes participation in the agreement as given, the results of complete contracts will be found by solving the social planner's problem. While the maximization at the Success state takes place with respect to green technology investment (r_i) and emissions (g_i), R&D investment (x_i) is added to the choice variables under Failure state.

The continuation values (V, W and M) are identical to the ones in business-as-usual. Using these, the optimal strategies come from applying backward induction within a period. Similar to the problem at business-as-usual, the solution begins with the specification of the optimal amount of consumption (will be used interchangeably with emissions) by maximizing the interim continuation value (M^S) or (M^F) depending on the state that the planner finds herself in. This will give the optimal consumption and optimal emission as a function of GHG stock where G can be represented in terms of $\underline{G}$ and R.

Then, the optimal amount of R&D investment will be determined by the planner by maximizing the second interim continuation value, W. Naturally, this step is only taken if the R&D project is yet to be successful and the planner still invests in R&D, i.e. if the game is in Failure state. Under the Success state, this step does not exist.

In the final step, the planner decides on the amount of green technology investment at the beginning of the period by maximizing the complete continuation value, (V^S) or (V^F). At this point, the results derived from the first step also come into play because optimal consumption is already formulated in terms of G, and consequently in terms of R_i and r_i. In the end, the results from each three (or two) steps are combined and the strategies and stocks are written in terms of stocks from the previous period.

3.5.1 Success state

The equilibrium strategy of a representative country i chosen by the social planner at the Success State is (r_i^S, g_i^S). Since $\psi_t = 1$ and the entire R&D investment stock is used up, $\underline{X}$ becomes irrelevant for the future utilities as well.

At the Success state, social planner decides only on its green technology investment, r_i and emissions, g_i in a given period. The problem of country i is:

$$\max_{y_i, g_i} \sum_{i \in N} V^S(\underline{G}, \underline{R}) = \sum_{i \in N} \left[B_i(y_i) - C(G) - kr_i + \delta V^S(G, R) \right]$$

However, the strategies are chosen at separate points within the period, which allows us to solve the problem by applying backward induction.

While obtaining the equilibrium strategies, it would be convenient to use the consumption identity given by $\widetilde{y_i} \equiv y_i + \overline{y} - \overline{y_i}$ in order to avoid heterogeneity between countries. Therefore, we use $\widetilde{y_i}$ as the choice variable instead of y_i. For the optimal $\widetilde{y_i}$ alongside with the quadratic benefit function given by equation (4), this adjustment makes the benefit function and the continuation variables country invariant.

3.5.1.1 Emissions stage in the success state

At the emissions stage, the social planner would decide on the amount of consumption that maximizes the interim continuation value $M^S(\alpha q_G \underline{G}, R)$. The green technology investments are already made at the beginning of the period. Emissions and green technology investments are perfect substitutes for consumption. Thus the problem planner solves for any country i is:

$$\max_{\tilde{y}_i} \sum_{i\in N} \left[B(\tilde{y}_i) - C(G) + \delta V^S(G, R)\right]$$

Since the environmental cost and the continuation value do not depend on i, the above problem becomes:

$$\max_{\tilde{y}_i} \sum_{i\in N} \left[B(\tilde{y}_i)\right] - nC(G) + n\delta V^S(G, R)$$

Using equations (9) and (12), taking FOC with respect to $\tilde{y}_i$ gives:

$$B'(\tilde{y}_i) - nC'(G) + n\delta V^S_G(G, R) = 0,$$

where $V^S_G(G, R)$ indicates the derivative of the continuation value (under first-best scenario) with respect to the GHG stock in its own period. Recall that Lemma 1 indicates derivative of the continuation value (under business-as-usual scenario) with respect to the GHG stock and global green technology stock.

Lemma 3: The first derivatives of the continuation value are identical in first-best and business-as-usual cases under the Success state.

$$V^{S(bau)}_R(G, R) = V^{S(fb)}_R(G, R)$$
$$V^{S(bau)}_G(G, R) = V^{S(fb)}_G(G, R)$$

The proof can be found in Appendix B.

Then, using quadratic cost and benefit functions, the optimal consumption becomes

$$\tilde{y}^S_{ifb} = \bar{y} - \frac{n(cG + m)}{b} \tag{21}$$

$$y^S_{i\,fb} = \bar{y}_i - \frac{n(cG + m)}{b} \tag{22}$$

where $m = -\delta V^S_G = \alpha\delta q_G(1 - \delta q_R)\frac{k}{n}$. Summing equation (21) across countries and using the general representation of GHG stock equation (12) yields

$$G^S_{fb} = \frac{b(\overline{\overline{G}} - R) + bn\bar{y} - mn^2}{b + cn^2} \tag{23}$$

where $\overline{\overline{G}} = \alpha q_G \underline{G}$. Plugging this expression into equation (22), we get another expression of optimal consumption.

$$y^S_{i\ fb} = \overline{y_i} - \frac{cn(\overline{\overline{G}} - R) + cn^2\bar{y} + mn}{b + cn^2}. \tag{24}$$

Since $g_i = y_i - R_i$, we substract R_i from equation (24) and plug in m to get the optimal first-best amount of emissions under the Success state.

3.5.1.2 Green technology investment stage in the success state

At the beginning of the period, the social planner maximizes the sum of continuation values $V^S(\underline{G}, \underline{R})$ across all countries.

$$\max_{r_i} \sum_{i \in N} \Big[B_i(y_i) - C(G) - kr_i + \delta V^S(G, R) \Big]$$

Similar to the previous stage, the problem becomes

$$\max_{r_i} \sum_{i \in N} \Big[B_i(y_i) - kr_i \Big] - nC(G) + n\delta V^S(G, R).$$

Plugging the quadratic functions alongside with equation (22) gives:

$$\max_{r_i} \sum_{i \in N} \left[-\frac{b}{2}\left(\frac{ncG + mn}{b}\right)^2 - kr_i \right] - \frac{cn}{2}G^2 + n\delta V^S(G, R).$$

The above problem can be expressed more compactly as

$$\max_{r_i} \left(-\frac{m^2n^3}{2b} - \frac{cmn^3}{b}G - \frac{cn}{2}(1 + \frac{cn^2}{b})G^2 - kr_i + n\delta V^S(G, R) \right).$$

The FOC with respect to r_i gives

$$-\frac{cmn^3}{b}\frac{\partial G}{\partial R}\frac{\partial R}{\partial r_i} - \frac{cn}{2}\left(1 + \frac{cn^2}{b}\right)2G\frac{\partial G}{\partial R}\frac{\partial R}{\partial r_i} - k + n\delta\left[V_G^S(G, R)\frac{\partial G}{\partial R} + V_R^S(G, R)\right] = 0.$$

$V_G^S(G, R)$ is already found in the previous stage. $V_R^S(G, R)$ indicates the derivative of continuation value (under first-best scenario) with respect to global green technology stock in its own period. Lemma 3 indicates derivative of the continuation value (under business-as-usual scenario) with respect to the global green technology stock is equal to its first-best counterpart.

Equations (11) and (23) respectively indicate $\frac{\partial R}{\partial r_i} = 1$ and $\frac{\partial G}{\partial R} = -\frac{b}{b+cn^2}$. After some lengthy algebra, the first-best values of $r_{i\ fb}^S$ and R_{fb}^S are derived.

Together, the problems in both stages give the explicit results. Let $(r_{i\ fb}^S, g_{i\ fb}^S)$ be the symmetric Markov perfect equilibrium strategy profile of country i and (R_{fb}^S, G_{fb}^S) be the corresponding equilibrium stock variables in the Success state under first-best scenario.

Proposition 4: The symmetric Markov perfect equilibrium strategy profile $(r_{i\ fb}^S, g_{i\ fb}^S)$ and stocks (R_{fb}^S, G_{fb}^S) are

$$r_{i\ fb}^S = \frac{\alpha q_G \underline{G}}{n} - \frac{q_R \underline{R}}{n} + \bar{y} - (1 - \delta q_R)\left[\frac{1 - \alpha\delta q_G}{cn^2} + \frac{1}{b}\right]k$$

$$g_{i\ fb}^S = \overline{y_i} - \frac{R_{fb}^S}{n} - \left[\frac{cn\left(\alpha q_G \underline{G} - R_{fb}^S\right) + cn^2\bar{y} + \alpha\delta q_G(1 - \delta q_R)k}{b + n^2 c}\right]$$

$$R_{fb}^S = \alpha q_G \underline{G} + \bar{y}n - (1 - \delta q_R)\left[\frac{1 - \alpha\delta q_G}{cn} + \frac{n}{b}\right]k$$

$$G_{fb}^S = \frac{(1 - \delta q_R)(1 - \alpha\delta q_G)}{cn}k$$

Additional proof is not necessary since the solutions in the green technology investment stage and emission stage already provide the equilibrium strategies and stocks. Note that these are the results of a representative period. Since the equilibrium strategies and the equilibrium stock variables are represented in terms of stocks from previous periods, it will be enough to update the values of previous stock to get $\left(r^S_{i,\tau\,fb}, g^S_{i,\tau\,fb}, R^S_{\tau\,fb}, G^S_{\tau\,fb}\right)^{\infty}_{\tau=t}$.

Moreover, $g^S_{i\,bau}$ contains R^S_{fb}. When the optimal value of R^S_{fb} given in this proposition are plugged in, the explicit result of $g^S_{i\,fb}$ is found.[21]

3.5.2 Failure state

Equilibrium strategy of a representative country i chosen by the social planner at the Failure state is $\left(r^F_i, g^F_i, x^F_i\right)$, where $\psi_t = 0$. Country i finds the optimal values of green technology investments, R&D investments, and emissions in a given period. Then the problem of country i is

$$\max_{r_i,x_i,g_i} \sum_{i\in N} V^F(\underline{G},\underline{R},\underline{X}) = \sum_{i\in N}\Big[B_i(y_i) - C(G) - kr_i - ex_i + \delta\big[\big(1-p(X)\big)V^F(G,R,X) + p(X)V^S(G,R)\big]\Big].$$

Similar to the Success state, the social planner does not optimize all of its strategies simultaneously and applies backward induction since each strategy has its own distinct stages within a period. Also, the planner again substitutes $\tilde{y}_i$ as the choice variable instead of y_i to avoid the country variant benefit function and the continuation variables.

3.5.2.1 Emissions stage in failure state

At the emissions stage, the social planner would decide on the amount of consumption that maximizes the sum of interim continuation value $M^F(\alpha q_G \underline{G}, R, X)$.

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[21] Symmetry of green technology investments allows us to say $R^S_{i\,fb} = R^S_{fb}/n$, which is used to represent $g^S_{i\,fb}$ following equation (5).

Since the green technology investments are already made at the beginning of the period, it is acceptable to use y_i and g_i interchangeably at this stage, due to perfect substitutability of g_i and R_i on the consumption equation. Thus the problem the planner solves for any country i is:

$$\max_{\tilde{y}_i} \sum_{i \in N} \left[B(\tilde{y}_i) - C(G) + \delta\left[\left(1 - p(X)\right)V^F(G, R, X) + p(X)V^S(G, R)\right]\right].$$

Since the environmental cost and the continuation value does not depend on i, the above problem becomes:

$$\max_{\tilde{y}_i} \sum_{i \in N} \left[B(\tilde{y}_i)\right] - nC(G) + n\delta\left[\left(1 - p(X)\right)V^F(G, R, X) + p(X)V^S(G, R)\right]$$

Using equation (12) and taking FOC with respect to y_i gives:

$$B'(\tilde{y}_i) - nC'(G) + n\delta\left(\left(1 - p(X)\right)V_G^F(G, R, X) + p(X)V_G^S(G, R)\right) = 0.$$

$V_G^S(G, R)$ is already defined in the Success state. $V_G^F(G, R)$ indicates the (first-best) derivative of the continuation value with respect to the GHG stock in its own period. Recall that Lemma 2 indicates (business-as-usual) derivative of the continuation value with respect to the GHG stock $V_G^{F(bau)}(G, R) = -q_G\frac{k}{n}\left(1 - \delta q_R\left(1 - p(X)(1 - \alpha)\right)\right).$

Lemma 4: The first derivatives of the continuation value are identical in first-best and business-as-usual cases.

$$V_R^{F(bau)}(G, R) = V_R^{F(fb)}(G, R)$$
$$V_G^{F(bau)}(G, R) = V_G^{F(fb)}(G, R)$$

The proof can be found in Appendix C.

Then, under quadratic cost and benefit functions, the optimal consumption becomes

$$\tilde{y}^F_{ifb} = \bar{y} - \frac{n(cG + d)}{b} \tag{25}$$

$$y^F_{i\,fb} = \overline{y_i} - \frac{n(cG + d)}{b} \tag{26}$$

where $d = -\delta\left[p(X)V^S_G(G, R) + \big(1 - p(X)\big)V^F_G(G, R)\right]$. When both first derivatives are plugged in; $d = \delta[q_G(1 - \delta q_R)\frac{k}{n}\vartheta]$ where $\vartheta = 1 - (1 - \alpha)p(X)\frac{1-\delta q_R\left(2-p(X)\right)}{1-\delta q_R}$. Summing equation (25) across countries and using equation (12) yields

$$G^F_{fb} = \frac{b(\tilde{G} - R) + bn\bar{y} - dn^2}{b + cn^2} \tag{27}$$

where $\tilde{G} = q_G\underline{G}$. Plugging this expression into equation (26), we get another expression of optimal consumption.

$$y^F_{i\,fb} = \overline{y_i} - \frac{cn(\tilde{G} - R) + cn^2\bar{y} + dn}{b + cn^2}. \tag{28}$$

Since $g_i = y_i - R_i$, we substract R_i from equation (28) and plug in d to get the optimal first-best amount of emissions under Failure state.

3.5.2.2 R&D investment stage in failure state

At the R&D investment stage, the social planner maximizes the sum of interim continuation value $W^F(q_G\underline{G}, R, q_X\underline{X})$ across countries, with respect to x_i to find the R&D investment of a representative country i

$$\max_{x_i} \sum_{i \in N} \left(B(\tilde{y}_i) - C(G) - ex_i + \delta\left[\big(1 - p(X)\big)V^F(G, R, X) + p(X)V^S(G, R)\right] \right).$$

Notice that x_i affects the utility through its investment cost and the continuation values. Taking FOC with respect to x_i gives

$$-e + n\delta\left[p'(X)V^S(G,R) + \left(1 - p(X)\right)V^F_X(G,R,X) - p'(X)V^F(G,R)\right] = 0.$$

where V^F_X is the first derivative of the continuation value with respect to global R&D investment stock X. Only the part of continuation values is multiplied by n, due to continuation values being country invariant.

The issues that arose at the business-as-usual R&D investment stage persist here. Therefore, Case 1 and Case 2 characterized before will be used here as well and X will not be a choice variable for the continuation value V^F.

Due to its exogenous nature, Case 2 is identical to its business-as-usual counterpart. For Case 1, we showed that countries invest positive amounts of R&D investments. This result needs to be checked for first-best as well. The problem of the planner is

$$\max_{x_i} \sum_{i\in N} \left(B(\tilde{y}_i) - C(G) - ex_i + \delta\left[\left(1 - p(X)\right)V^F(G,R) + p(X)V^S(G,R)\right]\right).$$

Taking FOC with respect to x_i characterizes the optimal investment in R&D by the social planner as

$$-e + n\delta\left[p'(X)\left(V^S(G,R) - V^F(G,R)\right)\right] = 0.$$

Rewrite the above condition as $\frac{e}{n\delta} = p'(X)(V^S - V^F)$ where $X = \sum_{i\in N} x_i$. Social planner either invests through all countries or there will not be any investment. If X = 0, then $p'(X = 0) = \infty$ which rules out a corner solution and tells us $x_i > 0$ for all i.

If we look at the difference of the sum of continuation values and derive the positive investment condition (as we did in business-as-usual R&D investment stage), we get the inequality $\frac{p(X)}{p'(X)} > X$, which has been shown to hold at Appendix A. The planner invests in R&D at Case 1. Moreover, the decision to invest entirely depends on the probability of success function. Hence optimal x_i is independent of other strategies and stocks.

3.5.2.3 Green technology investment stage in failure state

At the beginning of the period, the social planner maximizes the sum of continuation values $V^F(\underline{G}, \underline{R})$ across all countries.

$$\max_{r_i} \sum_{i \in N} \left[B(\tilde{y}_i) - C(G) - kr_i - ex_i + \delta \Big(\big(1 - p(X)\big) V^F(G, R) + p(X) V^S(G, R) \Big) \right]$$

Similar to the previous stage, the problem becomes

$$\max_{r_i} \sum_{i \in N} \left[B(\tilde{y}_i) - kr_i - ex_i \right] - nC(G) + n\delta \Big(\big(1 - p(X)\big) V^F(G, R) + p(X) V^S(G, R) \Big).$$

Plugging the quadratic functions alongside with equation (22) gives:

$$\max_{r_i} \sum_{i \in N} \left[-\frac{b}{2} \left(\frac{ncG + mn}{b} \right)^2 - kr_i - ex_i \right] - \frac{cn}{2} G^2 + n\delta \Big(\big(1 - p(X)\big) V^F(G, R) + p(X) V^S(G, R) \Big).$$

The above problem can be expressed more compactly as

$$\max_{r_i} \left(-\frac{d^2 n^3}{2b} - \frac{cdn^3}{b} G - \frac{cn}{2} \left(1 + \frac{cn^2}{b}\right) G^2 - kr_i - ex_i + n\delta \Big(\big(1 - p(X)\big) V^F(G, R) + p(X) V^S(G, R) \Big) \right).$$

The FOC with respect to r_i gives

$$-\frac{cdn^3}{b} \frac{\partial G}{\partial R} - \frac{cn}{2} \left(1 + \frac{cn^2}{b}\right) 2G \frac{\partial G}{\partial R} - k + n\delta \Bigg((1 - p(X)) \left[V^F_G(G, R) \frac{\partial G}{\partial R} + V^F_R(G, R) \right] + p(X) \left[V^S_G(G, R) \frac{\partial G}{\partial R} + V^S_R(G, R) \right] \Bigg) = 0.$$

$V^S_G(G, R)$, $V^F_G(G, R)$, $V^S_R(G, R)$ and $V^F_R(G, R)$ are already found in Lemma 1 and 2. In addition, Lemma 3 and 4 indicates that the derivatives of continuation value (under first-best scenario) are equal to their business-as-usual counterpart.

Equation (23) indicates $\frac{\partial G}{\partial R} = -\frac{b}{b+cn^2}$. After some lengthy algebra, the first-best values of $r_{i\ fb}^{F}$ and R_{fb}^{F} are derived.

Together, the problems in both stages give the explicit results. Let $(r_{i\ fb}^{F}, g_{i\ fb}^{F})$ be the symmetric Markov perfect equilibrium strategy profile of country i and (R_{fb}^{S}, G_{fb}^{S}) be the corresponding equilibrium stock variables in the Success state under first-best scenario.

Proposition 5: The symmetric Markov perfect equilibrium strategy profile $(r_{i\ fb}^{F}, g_{i\ fb}^{F})$ and stocks (R_{fb}^{F}, G_{fb}^{F}) are

$$r_{i\ fb}^{F} = \frac{q_G\underline{G}}{n} - \frac{q_R\underline{R}}{n} + \bar{y} - (1-\delta q_R)\left[\frac{1-\vartheta\delta q_G}{cn^2} + \frac{1}{b}\right]k$$

$$g_{i\ fb}^{F} = \overline{y_i} - \frac{R^{fb}}{n} - \left[\frac{cn(q_G\underline{G} - R^{fb}) + cn^2\bar{y} + \vartheta\delta q_G(1-\delta q_R)k}{b+n^2c}\right]$$

$$R_{fb}^{F} = q_G\underline{G} + \bar{y}n - (1-\delta q_R)\left[\frac{1-\vartheta\delta q_G}{cn} + \frac{n}{b}\right]k$$

$$G_{fb}^{F} = \frac{(1-\delta q_R)(1-\vartheta\delta q_G)}{cn}k$$

where $\vartheta = 1-(1-\alpha)p(X)\frac{1-\delta q_R\left(2-p(X)\right)}{1-\delta q_R}$. Note that these results are characterized for case 1, where $q_X = 0$ and the optimal x_i obtained by $\frac{e}{\delta} = p'(X)(V^S - V^F)$. At Case 2, the accumulation of R&D stock is exogenous, $x_t = \mu$ for all $t \in 1, \ldots \infty$ and p(X) in ϑ is replaced by p.

Corollary 2: Similar to the previous corollary, when $\alpha = 1$, the stocks, and strategies in Propositions 4 and 5 converge to the first-best results in Harstad (2016) where there is no R&D project.

Denote the non-cooperative results from Harstad (2016) as $\left(R^*_{fb}, G^*_{fb}, r^*_{i\,fb}, g^*_{i\,fb}\right)$.

$$r^*_{i\,fb} = \frac{q_G\underline{G}}{n} - \frac{q_R\underline{R}}{n} + \bar{y} - (1-\delta q_R)\left[\frac{1-\delta q_G}{cn^2} + \frac{1}{b}\right]k$$

$$g^*_{i\,fb} = \overline{y_i} - \frac{R^{fb}}{n} - \left[\frac{cn(q_G\underline{G} - R^{fb}) + cn^2\bar{y} + \delta q_G(1-\delta q_R)k}{b+n^2c}\right]$$

$$R^*_{fb} = q_G\underline{G} + \bar{y}n - (1-\delta q_R)\left[\frac{1-\delta q_G}{cn} + \frac{n}{b}\right]k$$

$$G^*_{fb} = \frac{(1-\delta q_R)(1-\delta q_G)}{cn}k$$

The proof of the corollary 2 follows from the proof of corollary 1 in section 3.4.2.3.

Proposition 6: When the R&D project is available for the social planner to invest in, she invests less in green technology and emits more, both before and after the R&D project is successful. Consequently, global green technology stock is lower and GHG stock (pollution) is higher.

$$r^S_{i\,fb} < r^*_{i\,fb} \Rightarrow R^S_{fb} < R^*_{fb}$$

$$r^F_{i\,fb} < r^*_{i\,fb} \Rightarrow R^F_{fb} < R^*_{fb}$$

$$g^S_{i\,fb} > g^*_{i\,fb} \Rightarrow G^S_{fb} > G^*_{fb}$$

$$g^F_{i\,fb} > g^*_{i\,fb} \Rightarrow G^F_{fb} > G^*_{fb}$$

The proof follows from $0 < \alpha < 1$, provided that $0 < \vartheta < 1$.[22]

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[22] For $\delta q_R \leq 1/2$, $0 < \vartheta < 1$ for all possible values of $p(X)$. As the upper bound of δq_R increases,

As in business-as-usual, both the equilibrium strategies and stocks depend on previous stocks ($\underline{G}$ and $\underline{R}$). When there is no R&D project to invest in (or $\alpha = 1$), the results converge to the first-best results in Harstad (2016) as corollary 1 indicates. Again, comparisons are made when state variables ($\underline{G}$ and $\underline{R}$) are identical.

The next chapter discusses the results obtained so far with a particular concentration on Propositions 3 and 6.

$p(X)$ needs to be sufficiently higher than 0 in order to sustain $0 < \vartheta < 1$.

CHAPTER 4

DISCUSSION

Our model successfully captures the effect of technological optimism. We observe that the existence of an R&D project alters the behavior of countries. Proposition 3 indicates that after the project is successful, knowing that the accumulation of GHG is now slowed down, countries emit more and invest less in green technology. Even though the environmental cost is ceteris paribus lower, the accumulation will keep on going unless carbon capture is almost complete.[23] Then, we may face the possibility that a project intended to fix the climate change problem may only postpone the issue. In this case, the depreciation rate of the GHG stock after the R&D project is successful $(1 - \alpha qG)$, and consequently the value of α becomes extremely important to predict the future path of GHG stock. Whether the decreasing effect of α on GHG stock outweighs its indirect increasing effect on current emissions should be answered. This remark is in parallel with the argument against technological fixes at chapter 2.3, where a breakthrough does not completely solve the problem or arises unintended consequences.

Perhaps the more alarming of our results (Proposition 3) stands out in the case of the Failure state, where under certain conditions,[24] we can observe the technological optimist behavior even more clearly. The results of the Failure state contains a coefficient ϑ where $\vartheta = 1 - (1 - \alpha)p(X)\frac{1-\delta q_R\left(2-p(X)\right)}{1-\delta q_R}$. As Corollary 1 suggests, when the R&D project is ineffective or does not exist $(\alpha = 1)$, equilibrium strategies converge to the results of Harstad (2016) since $\vartheta = 1$. Thus, ϑ can be interpreted as the coefficient of technological optimism. Emission levels and the stock of the GHG increase even though the carbon capture technology is not invented yet. Moreover, the deviation increases when the project is more ambitious (α is lower). Following Proposition 2, when α decreases, ϑ also decreases which leads to higher emissions (and GHG stock), and lower green technology investments (and

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[23] Carbon capture is almost complete when the fraction of GHG stock that survives to the next period (denoted by αq_G) becomes dramatically close to 0.

[24] Footnote 20 indicates these conditions.

global green technology stock), even though the probability of success has not changed. It is safe to say, when the the prize gets bigger with higher depreciation of the GHG stock due to lower alpha, heavier the potential downfall becomes with increasing emissions and decreasing green technology investments.

A similar relation exists for the probability of success function, p(X). When p(X) increases, decreasing ϑ leads to higher g_i's. As long as the additional investments contribute more to the R&D stock than its depreciation, g_i's further increase since the probability of success increases with higher R&D investment. The more confident countries get in terms of the invention of new technology, the more emissions they will release.

The above remark is also quite susceptible to public manipulation. New developments or exterior conditions concerning the technology may have an impact on how countries characterize the probability of success function p. If somehow they start to believe the success probability is now characterized by the function $\overline{p}$, where $\overline{p}$ has first order stochastic dominance over p, they emit more.

All in all, under business-as-usual scenario, even though there is no global consensus on how to deal with climate change, countries are less willing to combat climate change due to potential future cost reductions. The technology I propose is not invented yet, might be invented when the effects of climate change are irreversible, or might not be invented at all. Yet, the potential of the invention is enough to deviate from low emission paths that are available when an R&D project does not exist.[25] Countries rely on future technologies to solve current problems, which is the definition of technological optimism.

One might argue that the deviation observed in the business-as-usual results are caused by the lack of cooperation between countries. However, the first best results beg to differ. Proposition 6 indicates that even when global cooperation is sustained, countries emit more and invest less in green technology compared to the inexistence of the R&D project. The most efficient outcome possible suffers from

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[25] Corollary 1 explicitly gives the emission and green technology investment levels when R&D project does not exist.

technological optimism, which tells us that technological optimism is not an efficiency issue. Every remark made in this chapter regarding the business-as-usual persists in the first-best as well.

CHAPTER 5

CONCLUSION

This research aims to capture the role of technological optimism in the fight against climate change. Technological optimism is argued to be detrimental by delaying immediate climate action or creating ambiguity regarding which policy portfolio should be implemented. While technological optimism is held accountable for the lack of global cooperation on a normative basis, theoretical and empirical studies to support this view are minimal, and game-theoretical studies are non-existent. To this end, I reviewed the literature for games of climate change (with a specific focus on technology) and technological optimism with the intent of designing an appropriate game. I believe that my model succeeds in this effort and contributes to the literature on climate agreements, and introduces technological optimism within a game-theoretical context.

Since the main characteristic of climate change is the accumulating nature of GHG in the atmosphere, I opted to frame my model as a dynamic game. The game builds upon Harstad (2012, 2016). Countries contribute to the GHG stock by emitting and investing in two channels, green technology, and an R&D project, where both of them accumulate as stocks. In a given period, a country's utility consists of the benefit of energy consumption, the global environmental cost, and individual investment costs. The objective of a country is to formulate strategies that maximize the present discounted value of future utilities. In this research, I characterized the non-cooperative (business-as-usual) and cooperative (first best) equilibrium.

It is common in the literature to use the Markov Perfect Equilibrium for dynamic games where strategies are only contingent on the payoff relevant elements of the history. Hence in my model, the strategies of countries are only contingent on the stock variables from previous periods.

The R&D project decreases the amount of the GHG stock that survives to the next period if successfully yields an invention. Its realization is ex-ante linked to a probability of success function, where more investment increases the invention probability. The project's success is characterized as a random variable to be revealed at the beginning of a period. Thus, there are two potential futures where the R&D project turns out to succeed or fail. We hypothesized that if technological optimism endangers climate action, then the introduction of the R&D project should increase the emission levels compared to the baseline model of Harstad (2016).

The results of the model validate my hypothesis. Under certain conditions,[26] the emission levels increase both before and after the invention of the new technology. Moreover, the investment in green technology decreases in both scenarios, which further argues for technological optimism. As a matter of fact, the higher the potential effect of the technology gets (given that the proportion of the GHG stock survives to the next period diminishes), the higher the emissions of countries get. This remark allows the effect of technological optimism to be conceptualized in a calculable manner.

This research is believed to pave the way for several new research areas. The most prominent one would be an endogenously-determined R&D investment, as I introduced in section 3.2. In my model the stock of the R&D investment is studied in two special cases where the stock depreciates entirely in Case 1 and the investment to the stock is exogenously predetermined in Case 2. Endogenously decided R&D investment would enrich the model by comprehensively analyzing the interactions between strategies.

Another path to explore could be more restricted modeling environments where decisions of the countries have additional constraints. For instance, my model does not contain a budget constraint. If introduced, the trade-off of strategies within and between periods could be better captured.

Moreover, my model characterizes non-cooperative outcomes as a lack of climate agreements and cooperative outcomes as global agreements with complete contracts. Other contracting environments could be investigated, such as incomplete

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[26] Footnote 20 explains these conditions.

contracts where only a subset of strategies is contractible. I would expect common effects of technological optimism for incomplete contracts as well as complete and no contracts since the latter serves as extreme benchmarks.

Another direction is to relax the homogeneity of certain model features. In my model, each country incurs the same environmental cost and starts with identical initial technological positions. However, we know that climate change will affect countries with different magnitudes. Allowing severeness of climate change parameters to vary could be helpful to reflect the different positions of countries regarding climate negotiations. Likewise, the inequality of countries in terms of technological capital is beyond question. Allowing heterogeneity in their initial stock of technologies or their capacity to preserve their stocks to the next period might have more real-life applicability.

Finally, heterogeneity could be used to capture technological optimism itself. If countries have different beliefs concerning the probability of success function, it would be possible to capture the deviation of the strategies of more 'optimist' and 'pessimist' countries. As such, another layer of technological optimism could be explored. The results of the model persist in both non-cooperative (business-as-usual) and cooperative (first-best) outcomes. The result in the first best tells that the deviation towards higher emissions and lower investments is not an efficiency issue caused by the lack of cooperation between countries. The variation is caused by countries maximizing their present discounted expected utilities as rational agents. Perhaps the solution may emerge from questioning the responsibility of economic rationality in tackling climate change or how to reinforce our rational framework with additional tools to avoid this outcome. What other tools and how they can be implemented are beyond the scope of this research, yet it could be an interesting future research direction.

All in all, I believe that the role of technological optimism in climate change and climate agreements deserves further attention. The main aim of this research was to contribute to the literature and introduce game-theoretical foundations to the discussion. My model accomplishes this and opens the avenue for several future research directions.

APPENDIX A

VERIFICATION OF POSITIVE INVESTMENT CONDITION

Proof. Need to show $\frac{p(X)}{p'(X)} > x_i$ where $x_i = \frac{X}{n}$ and $p(X) = 1 - e^{-X}$. Reorganise the inequality as $p(X) > p'(X)\frac{X}{n}$. If $p(X) > p'(X)X$, then $p(X) > p'(X)\frac{X}{n}$ as $p'(X)X > 0$.

With $p(X) = 1 - e^{-X}$, we have $p'(X) = e^{-X}$. Put it in the inequality $p(X) > p'(X)X$ and organise to get $1 > e^{-X}(X+1)$. Further reorganising gives $(X+1)^{-1} > e^{-x}$. Taking the natural logarithm and multiply the inequality with –1 gives $\ln(X + 1) < X$.

Love (1980) gives a lengthy proof of $\ln(X + 1) < X$ for all $X > -1$. Since we restrict the R&D investments to be positive, the positive investment condition for $p(X) = 1 - e^{-X}$ is verified. □

APPENDIX B

PROOF OF LEMMA 3

Lemma 1 states that under Success state, the first derivatives of the continuation value with respect to stocks are as follows:

$$V_R^{S(bau)} = q_R\frac{k}{n},$$
$$V_G^{S(bau)} = -\alpha q_G\frac{k}{n}(1-\delta q_R).$$

I need to show that $V_R^{S(bau)} = V_R^{S(fb)}$ and $V_G^{S(bau)} = V_G^{S(fb)}$.

Proof. Each derivative of the continuation value will be proved separately.

Step 1: At the green technology investment stage, the problem of social planner can be represented in terms of the interim continuation value

$$\max_{r_i}\sum_{i\in N} W^F(q_G\underline{G}, R) - kr_i.$$

Taking FOC gives $W_R^F(q_G\underline{G}, R,) = \frac{k}{n}$, where each r_i is at its optimal value.[27] Summing r_i's across countries gives the updated global green technology stock R. The equality obtained from FOC should hold for any optimal R and the variation of R depends on the other stock in the equation; $\underline{G}$. In other words, the optimal value of R can be represented as a function in terms of $\underline{G}$.

At the symmetric equilibrium, $r_i = r$ for all i. From equation 11:

$$r_i = r = \frac{R(\underline{G}) - q_R\underline{R}}{n}$$

The complete continuation value can be represented as the interim continuation value minus the green technology investments

$$V^F(\underline{G}, \underline{R}) = W^F(q_G\underline{G}, R) - \frac{k}{n}[R(\underline{G}) - q_R\underline{R}].$$

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[27] Recall that the continuation values are country-invariant.

Taking derivative of the above expression with respect to $\underline{R}$ gives the result that $V_R^{F\,fb} = q_R \frac{k}{n}$.

Step 2: At the emissions stage, choosing $\tilde{y}_i$ is equivalent to choosing g_i. When G is represented as in equation (9), the problem becomes

$$\max_{\tilde{y}_i} \sum_{i\in N} \left(B(\tilde{y}_i) - C(q_G\underline{G} + \sum_{i\in N} \tilde{y}_i - R) + \delta \left[V^S(q_G\underline{G} + \sum_{i\in N} \tilde{y}_i - R, R) \right] \right).$$

Taking FOC with respect to $\tilde{y}_i$ gives

$$B'(\tilde{y}_i) - nC'(G) + n\delta \left[V_G^S(q_G\underline{G} + \sum_{i\in N} \tilde{y}_i - R, R) \right] = 0.$$

The above equation holds for the optimal values of $\tilde{y}_i$. Now we define $\varphi = q_G\underline{G} - R$. We observe that the optimal values of $\tilde{y}_i$ can be represented as a function of φ and. Using equation (12), $G = \varphi + \sum_{i\in N} \tilde{y}_i$, which means G is also a function of φ and. Consequently, $B(\tilde{y}_i) - C(G)$ becomes a function of φ and as well.

Now let's go back to the green technology investment stage. From the equation(11), the newly defined φ and the symmetric investment solution at the first part of the proof, green technology investments can be represented as

$$r_i = r = \frac{q_G\underline{G} - q_r\underline{R} - \varphi}{n}$$

. Then the complete continuation value becomes:

$$V^S(\underline{G}, \underline{R}) = B_i(y_i) - C(G) - \frac{k}{n}[q_G\underline{G} - q_r\underline{R} - \varphi] + n\delta\left[V^S(G, R)\right]$$

When we take the derivative of the above expression with respect to $\underline{G}$, the Envelope Theorem allows me to disregard the indirect effects. The derivative gives

$$V_G^S(\underline{G}, \underline{R}) = -\frac{k}{n} q_G + \delta V_R^S.$$

From step 1, I know that $V_R^{S\,fb} = \frac{k}{n} q_R$. Then, $V_G^{S\,fb} = -\alpha q_G \frac{k}{n}(1 - \delta q_R)$. $\square$

APPENDIX C

PROOF OF LEMMA 4

Lemma 2 states that under Failure state, the first derivatives of the continuation value with respect to stocks are as follows:

$$\begin{aligned} V_R^{F(bau)} &= q_R \frac{k}{n}, \\ V_G^{F(bau)} &= -q_G \frac{k}{n}\Big(1 - \delta q_R\big(1 - p(X)(1-\alpha)\big)\Big). \end{aligned}$$

I need to show that $V_R^{F(bau)} = V_R^{F(fb)}$ and $V_G^{F(bau)} = V_G^{F(fb)}$.

Proof. Each derivative of the continuation value will be proved separately.

Step 1: At the green technology investment stage, the problem of social planner can be represented in terms of the interim continuation value

$$\max_{r_i} \sum_{i \in N} W^F(q_G \underline{G}, R) - k r_i$$

Taking FOC gives $W_R^F(q_G \underline{G}, R) = \frac{k}{n}$, where each r_i is at its optimal value.[28] Summing r_i's across countries gives the updated global green technology stock R. The equality obtained from FOC should hold for any optimal R and the variation of R depends on the other stock in the equation; $\underline{G}$. In other words, the optimal value of R can be represented as a function of $\underline{G}$.

At the symmetric equilibrium, $r_i = r$ for all i. From equation (11):

$$r_i = r = \frac{R(\underline{G}) - q_R \underline{R}}{n}$$

The complete continuation value can be represented as the interim continuation value minus the green technology investments

$$V^F(\underline{G}, \underline{R}) = W^F(q_G \underline{G}, R) - \frac{k}{n}[R(\underline{G}) - q_R \underline{R}].$$

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[28] Recall that the continuation values are country invariant.

Taking derivative of the above expression with respect to $\underline{R}$ gives the result that $V_R^{F\,fb} = q_R \frac{k}{n}$.

Step 2: From the R&D investment stage at Case 1, the FOC for the optimal amount of R&D investment is given by $\frac{e}{n\delta} = p'(X)(V_i^S(G,R) - V_i^F(G,R))$ where $X = \sum_{i \in N} x_i$. Using (12), the condition can be rewritten as:

$$\frac{e}{n\delta} = p'(X)(V_i^S(\alpha q_G \underline{G} + \sum_{i \in N} y_i - R, R) - V_i^F(q_G \underline{G} + \sum_{i \in N} y_i - R, R)).$$

The above expression indicates that X can be represented as a function of $\underline{G}$ and R. This is chronologically sensible as well since at the R&D stage, green technology investments at a given period have been made by all countries. While the global green technology is updated to R, GHG stock is still $\underline{G}$. Therefore we would expect the R&D investments to be depended on $\underline{G}$ and R. Let the function $f^X(\underline{G}, R)$ denote the optimal level of X.

At the emissions stage, choosing $\tilde{y}_i$ is equivalent to choosing g_i. When G is represented as in equation (12), the problem becomes

$$\max_{\tilde{y}_i} \sum_{i \in N} \left(B(\tilde{y}_i) - C(q_G \underline{G} + \sum_{i \in N} \tilde{y}_i - R) + \delta \left[\left(1 - p(X)\right) V^F(q_G \underline{G} + \sum_{i \in N} \tilde{y}_i - R, R) + \right.\right.$$
$$\left.\left. p(X) V^S(q_G \underline{G} + \sum_{i \in N} \tilde{y}_i - R, R) \right] \right).$$

Taking FOC with respect to $\tilde{y}_i$ gives

$$B'(\tilde{y}_i) - nC'(G) + n\delta \left[\left(1 - p(X)\right) V_G^F(q_G \underline{G} + \sum_{i \in N} \tilde{y}_i - R, R) + p(X) V_G^S(q_G \underline{G} + \sum_{i \in N} \tilde{y}_i - R, R) \right] = 0.$$

The above equation holds for the optimal values of y_i and it tells that y_i can be represented as a function of $\underline{G}$, R and X. Let the function $f^{y_i}(\underline{G}, R, X)$ denote the optimal y_i.

Finally, using equation (12), G can be represented as a function of $\underline{G}$, R and X. Let the function $f^G(\underline{G}, R, X)$ denote the optimal G.

R is the to be determined by $R = q_G\underline{G} + \sum_{i\in N} f^{y_i}(\underline{G}, R, X) - f^G(\underline{G}, R, X)$ in Failure state and $R = \alpha q_G\underline{G} + \sum_{i\in N} f^{y_i}(\underline{G}, R, X) - f^g(\underline{G}, R, X)$ in Success state. Moreover, $r_i = (R - q_R\underline{R})/n$ and $(x_i = f^X(\underline{G}, R) - q_X\underline{X})/n$. Then the continuation value (at the beginning of the period) becomes:

$$V_i^F(\underline{G},\underline{R}) = B_i(f^{y_i}) - C(f^G) - kr_i - ex_i + \delta\left[\left(1 - p(f^X)\right)V_i^F(f^G, R) + p(f^X)V_i^S(f^G, R)\right].$$

Applying the Envelope Theorem

$$V_G^F(\underline{G},\underline{R}) = -\frac{k}{n}q_G + \delta\left[p(X)\alpha q_G V_R^S + \left(1 - p(X)\right)q_G V_R^F\right].$$

From Lemma 3 and the first part of Lemma 4, we know that $V_R^{F\,fb} = V_R^{S\,fb} = \frac{k}{n}q_R$. When these are plugged in:

$$V_G^F(\underline{G},\underline{R}) = -\frac{k}{n}q_G + \delta\left[p(X)\alpha q_G\frac{k}{n}q_R + \left(1 - p(X)\right)q_G\frac{k}{n}q_R\right].$$

When this expression is written more compactly, we show that $V_G^{F\,fb}$ is country invariant and equal to $-q_G\frac{k}{n}\left(1 - \delta q_R\left(1 - p(X)(1-\alpha)\right)\right)$. □

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