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Green Energy Transition and the Importance Of Cross-Border Coordination

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Abstract

Economists and policymakers have deemed green energy transition as one of the most effective tools tackling climate change. Generally, strategic interactions are playing a huge role on the effectiveness of policies regarding green energy transition. In this paper we emphasize on the importance of cross-border coordination. Our analysis expands on a standard macroeconomic model of energy policy choices, in order to take into account the extremely important emission external effect of neighboring countries. Our findings suggest that countries are proceeding to a slow green transition because of the externalities produced by the emissions of neighboring countries. Thus countries are stuck in a prisoner's dilemma game, while international cooperation seems to be the only way for them to move to the socially optimal equilibrium.

Key words: Green Energy Transition, Coordination, Environmental Policy, Prisoner's Dilemma

JEL Classification: E6, Q28, Q43, Q58

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1 Introduction

Climate change is one of the most crucial issues of the 21st century, with unprecedented impact on the way our societies and economies are evolving. The World Economic Forum's (WEF) most recent Global Risks Report highlights extreme weather events, critical changes to Earth systems, and biodiversity loss as some of the top global risks (WEF, 2024). These interconnected risks emphasize the call for immediate action towards following a more comprehensive and coordinated approach to tackling climate change. We are already witnessing the effects, such as rising global temperatures, melting ice caps, and more frequent and severe natural disasters (NASA, 2024; Cantelmo et al. 2024). In case humanity fails to provide a coordinated and powerful response, these changes could cause irreversible damage, threatening the very foundations of life on Earth.

There is broad consensus that human activities, especially the burning of fossil fuels, are the main drivers of climate change (NASA, 2024). The Intergovernmental Panel on Climate Change (IPCC) indicated that global temperatures could potentially exceed the threshold of 1.5°C above pre-industrial levels within the next few decades (IPCC, 2023). This would lead to more extreme weather events, disruptions to food and water supplies, and the displacement of millions of people. In addition, because of climate change, natural disasters are projected to become more severe and frequent, and more countries are likely to be classified as "disaster-prone" in the immediate future (Cantelmo et al. 2024). Thus, immediate and implementable policies are crucial to mitigating these impacts and ensuring a more livable planet for the future generations.

One of the tools most frequently discussed among decision makers is the implementation of policies that incentivize the transition to green energy, while reducing dependence on fossil fuels. Green and renewable energy sources such as wind, solar, and hydroelectric energy, produce significantly lower greenhouse gas

emissions compared to fossil fuels. This reduction in emissions is vital for slowing global warming and mitigating its adverse effects. Additionally, renewable energy technologies are becoming more cost-effective, and their storage systems are becoming more efficient, making them a viable alternative to traditional energy sources, slowly tackling the key concerns regarding their broader use. Beyond environmental benefits, green energy offers significant indirect economic and health advantages, as renewable energy sources produce minimal harmful pollutants, which often contribute to respiratory and cardiovascular diseases, thereby improving public health (Clemmer, 2023). Lastly, the recent energy crisis has highlighted the importance of transitioning to green alternatives to the most commonly used fossil fuel (Hosseini, 2022).

As in most cases of market failure, economists have emphasized the importance of introducing strategic interactions into the analysis. Let us take the case of Windsor, Ontario as an example. Windsor is located in the Canadian province of Ontario, right on the shores of Lake Erie. What makes Windsor's case extremely interesting is that it is also 8 kilometers away from the highly industrialized American city of Detroit, Michigan. Although Canada's energy policies are more environmentally friendly than those of the United States, Windsor ranks not only as one of the most polluted cities in Canada but also among the cities with the highest fossil fuel usage. This raises concerns about the pollution spillover generated by the production activities in Detroit, and suggests that Windsor's energy policy mix are strategically influenced by its geographic proximity to Detroit.

Figure 1 illustrates the per capita CO_2 emissions in 2023 across the world. From this map a striking pattern arises. In terms of emissions, countries tend to cluster. In other words, the probability of observing a country featuring extremely high or high intensity of emissions next to a country of similar intensity

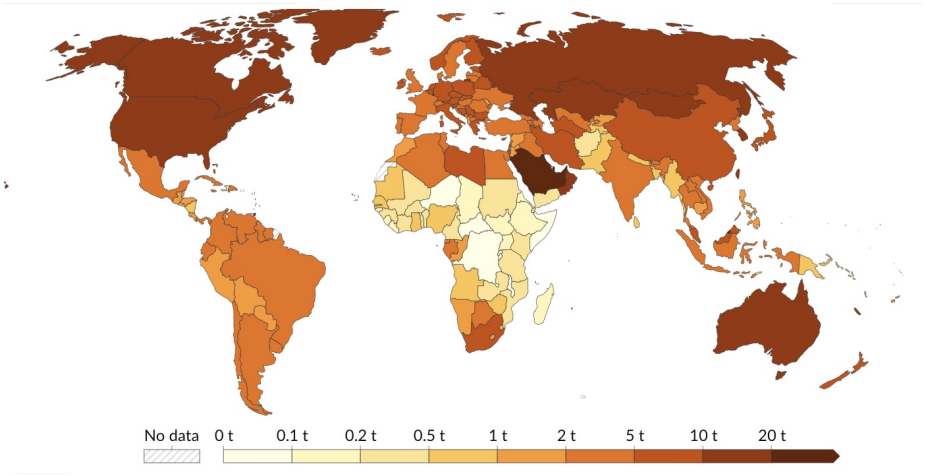

Figure 1: Per capita CO_2 emissions, 2023.
Carbon dioxide (CO_2) emissions from fossil fuels and industry.
Source:World Health Organization - Global Health Observatory (2024)

of emissions is higher, compared to a country generating low or extremely low emissions. The main determinants of emissions would be of course country specific, while their geography would most definitely play a crucial role, as it would affect their production. This pattern however could serve as statistical evidence supporting the cross-border interactions in regards to their energy policy mix hypothesis. Both the example of Windsor, Ontario and the global emission patterns, even if they can serve mostly as anecdotal evidence rather that statistical proof, highlight the need of examining the role of strategic interdependence in the emission generating process.

Game theory provides a powerful framework for analyzing and addressing global policy challenges, particularly the coordination required for an effective transition to green energy. By modeling strategic interactions between countries, game theory supports economists and policymakers to identify optimal strategies for cooperation. For instance, the Prisoner's Dilemma and other game-

We do not claim that the pattern in emissions serves as proof of cross-border interactions in the policy mix. It is merely a statistical pattern.

theoretic concepts can illustrate the challenges and benefits of international cooperation on climate policies (Ma et al., 2020; Marwala, 2023). Moreover, game theory can help policymakers design mechanisms that incentivize cooperation and discourage free-riding. By understanding the strategic behavior of different economic agents, a game-theoretic framework enables policy makers to develop policies, that align individual incentives with the ultimate goal of maximizing social welfare. This approach is essential for achieving the large-scale coordination necessary to address complex global challenges such as climate change.

In this paper, we aim to analyze the role of this strategic interaction between neighboring countries and highlight the importance of international cooperation for an efficient green transition that would allow humanity to collectively tackle the issue of climate change. To achieve this, we employ a standard macroeconomic model enhanced to account for the use of green energy in the policy mix and to account for the strategic interactions between neighboring countries as well, by introducing a game-theoretic framework into our analysis. The paper is structured as follows: Section 2 provides a literature review of the topic followed by Section 3 that illustrates our baseline and augmented model, its analytical solutions, calibration strategy and results, while Section 4 summarizes our conclusions and policy implications.

2 Literature Review

Our paper is situated among several strands of the economic literature on energy economics and optimal macroeconomic policies. These broader themes can be summarized into the subtopics of green and renewable energy (including nuclear energy) and economic growth, as well as studies analyzing the strategic interaction between neighboring countries, with the main strategies being their

decisions in regard to their energy policy mix.

Firstly, Acemoglu et al. (2016) thoroughly analyze the importance of green energy dominating dirty energy in the policy mix, as well as illustrate how can optimal policies can lead to technological advancements in the green sector, in order to achieve the desired outcome of sustainable growth. Other theoretical models emphasizing on the importance of green energy find similar results (Fatouros and Stengos, 2023). However the theoretical analysis of incorporating and enhancing the portion of green energy in the optimal policy mix in rather thin, since most studies on the topic have been mainly empirical.

Even if it is broadly accepted that green energy can help mitigate the adverse effects of climate change, the most commonly used argument against it, is the notion that it could potentially be harmful for economic growth. However, against popular belief, empirical evidence suggests that renewable and green energy are not always harmful for economic growth, and this effect broadly depends on the level of certain parameters such as the current level of renewable energy usage (Chen et al., 2020), foreign direct investment (Doytch and Narayan, 2021), and demographics (Kumar et al., 2024). For a more comprehensive review of the empirical literature on the growth effects of green energy please see Bhuiyan et al.(2022). Their meta-analysis approach suggests that renewable energy usage does not hinder economic growth for all countrywide levels of development.

This literature is complemented by the literature of the growth effect of nuclear energy usage, as typically nuclear energy is considered one of the cleanest energy sources in terms of emissions, with the downside being a small probability of a nuclear disaster (Fatouros and Stengos, 2023). Most of the empirical studies on the topic are finding evidence of a positive relationship between nuclear energy usage and economic growth (Wolde-Rufael and Menyah, 2010; Apergis

et al., 2010). However this relationship, may come to the form of an Environmental Kuznets Curve, where the effect would depend on a country's level of development (Iwata et al., 2010).

As mentioned before, our research is also related to the literature of the importance of international coordination on Climate Change issues. When dealing with cross-border coordination, there is strong evidence that the energy policy decisions of neighboring countries are strategically intertwined, with the differences in income, specilization and trade linkages being the most important driving factors. (Copeland and Taylor, 2017). Particularly in the case of cross-border pollution, the strategic interaction of two countries with the key strategic variable being home pollution as a result of foreign (neighboring countries') emissions seems to be one of the key determinants of policy makers' decisions (Copeland, 1996).

3 The Model

3.1 Baseline Model

Consider a centralized closed economy with zero population growth and zero capital accumulation, where consumers receive utility from consumption (c_t) and disutility from pollution (P_t). Without loss of generality, we assume that the number of consumers is equal to one. We also assume a social welfare function with concave preferences described by:

$$U = \int_0^\infty e^{-\rho t} u(c_t, P_t) dt \tag{1}$$

where $u(c_t, P_t)$ is the instantaneous utility function and ρ is rate of time preference. For the first and second order partial derivatives of the utility function above u, and for consistency of consumer preferences, we assume that $u_c > 0$,

$u_P < 0$, $u_{PP} > 0$, $u_{cc} < 0$, and $u_{cP} = 0$ to avoid cross effects.

The social planner wants to maximize the discounted present value of the future utility stream $u(c_t, P_t)$. To make our analysis tractable, we assume a utility function of the following form: $u(c, P) = wlnc - (1 - w)lnP$, where w is the weight that the representative household assigns to consumption. A linear utility function would make the consumption path disappear, so we have opted to use a logarithmic function that satisfies our assumptions about the consumer preferences and the utility derivatives. Finally, we assume that the intertemporal elasticity of substitution is constant at each point and, due to the specific utility form, it is also equal to one: $\frac{-u_c}{u_{cc}c} = 1$.

The production of the representative final good (q) uses two sources of energy: green energy (x_t) and fossil fuel (z_t), which feature a certain level of substitutability in the production process. Under current production patterns, green energy is not able to completely substitute the use of fossil fuels, so we exclude the case of perfect substitutability between them. The usage of the two types of energy are also assumed to grow over time, as the economy grows. Production is characterized by a concave function (ϕ), which for simplicity, is given by a Cobb-Douglas function:

$$q = \phi(x_t, z_t) = A x_t^{(\gamma)} z_t^{1-\gamma} \tag{2}$$

where A is the total factor productivity (we assume no technilogical growth) and $0 < \gamma < 1$ is the output elasticity of green energy.

The use of fossil fuels in the production process is accompanied by emissions. It is widely accepted that when fossil fuels are burned, they release compounds that are dangerous to the environment, such as nitrogen oxides and smog. It is also well known that green energy leads to significantly lower levels of air

pollution. For simplicity, we assume that the use of green energy does not lead to emissions. Hence, in our model, the total amount of emissions at each time (S_t) stems from the use of fossil fuels:

$$S_t = \alpha z_t \tag{3}$$

where α is the rate at which fossil fuels lead to emissions and is a constant. We can rewrite equation 3 to express fossil fuels as a function of emissions as follows: $z_t = S_t/\alpha$. Substituting this equation for fossil fuels into the production function (equation 2), we get: $\phi(x_t, S_t/\alpha) = Ax_t^{(1-\gamma)}(S_t/\alpha)^{\gamma}$. The way in which emissions change over time depends on the amount of fossil fuels used compared to the total amount of energy used in production. Thus, the law of motion of emissions, depends on the policy mix and is given by:

$$\dot{S} = \frac{z_t}{x_t + z_t} \text{ or } \dot{S} = \frac{S_t}{\alpha x_t + S_t} \tag{4}$$

Ultimately, this economy faces challenges due to pollution, and a trade off between consumption and pollution. The use of fossil fuels in production leads to emissions that increase the level of pollution in a one-to-one rate. However, this is generally not the only way that production leads to pollution. In many cases, production is accompanied by more than one of the following types of pollution: water, soil, waste, noise, microplastic, light, thermal, or chemical pollution. In our analysis, we assume that any source of pollution coming from production is captured by the pollution rate of production θ. Moreover, we assume that the consumption of the final good, leads to pollution of the environment by a rate equal to ξ (pollution rate of consumption), a reasonable assumption as most consumable goods increase pollution through waste (packages, plastic waste, and more), chemical release (batteries, cleaning supplies, and more),

microplastic pollution (cosmetics, washing synthetic fabrics, and more), and indirect ways (online shopping increases transportation emissions, food waste increases methane emissions, and more). Finally, the environment is assumed to be self-renewed, reducing the accumulated emissions at each period by a rate equal to δ. Hence, the law of motion of pollution is described by:

$$\dot{P} = S_t + \xi c_t + \theta\phi(x_t, S_t/\alpha) - \delta P_t \tag{5}$$

The solution of this problem as well as the graphical representation of the results is described in the following Section.

3.1.1 Solution and The Optimal Growth Path

The social planner wants to maximize the social welfare function (equation 1), subject to the laws of motion of emissions and pollution (equation 4 and 5 respectively). This problem is solved using the following Hamiltonian function, considering that pollution (P_t) and emissions (S_t) are the state variables, while consumption (c_t) and green energy (x_t) are the control variables.

$$H_t = e^{-\rho t}u(c_t, P_t) + \lambda_t \left[\frac{S_t}{\alpha x_t + S_t}\right] + \mu_t[S_t + \xi c_t + \theta\phi(x_t, S_t/\alpha) - \delta P_t] \tag{6}$$

where λ_t and μ_t represent the shadow values of the hamiltonian with respect to our constraints. Specifically, λ_t is the shadow price of the evolution of emissions and μ_t is the shadow price of the accumulation path of pollution. The first-order conditions of the above problem with respect to the control variables are given by the equations below:

$$H_c = e^{-\rho t} u_c + \mu \xi = 0 \tag{7}$$

$$H_x = -\lambda a S (ax + S)^{-2} + \mu \theta \phi_x = 0 \tag{8}$$

which can also be expressed as:

$$\mu = -\frac{e^{-\rho t} u_c}{\xi} \tag{9}$$

$$\lambda = -\frac{e^{-\rho t} \theta u_c \phi_x (\alpha x + S)^2}{\alpha \xi S} \tag{10}$$

Additionally, the first-order conditions of the Hamiltonian with respect to the state variables, after substituting the expressions for λ and μ, factoring common terms, and simplifying the resulting equations, are as follows:

$$H_S = -\left[\frac{e^{-\rho t} u_c}{\alpha \xi}\right]\left[\frac{\theta \phi_x (\alpha x + S)}{S} + \theta(\phi_z - \phi_x) + \alpha\right] = -\dot{\lambda} \tag{11}$$

$$H_P = e^{-\rho t}\left[u_P + u_c \frac{\delta}{\xi}\right] = -\dot{\mu} \tag{12}$$

By totally differentiating equation 7 with respect to time, and substituting equation 5 for $\dot{P}$ and equation 12 for $\dot{\mu}$, we derive the following Eurel equation for consumption:

$$\frac{\dot{c}}{c} = \frac{1}{u_{cc} c}\left[u_c(\rho + \delta) + \xi u_P - u_{cP}\dot{P}\right] \tag{13}$$

Similarly, by totally differentiating equation 8 with respect to time, and substituting $\dot{S}$, $\dot{\mu}$, λ, and μ from equations 4, 12, 9, and 10 respectively, we

construct the optimal growth path for the green energy described by:

$$\dot{x} = -\frac{S}{2\alpha\phi_x + \phi_{xx}(\alpha x + S)} \left[\frac{(\phi_x + \phi_z)\theta + \alpha}{\theta(\alpha x + S)} + \frac{\phi_{xz}}{\alpha} \right] - \frac{\phi_x(\alpha x + S)}{2\alpha\phi_x + \phi_{xx}(\alpha x + S)} \left[\xi \frac{u_P}{u_c} + \delta \right] \quad (14)$$

The solution to the system of the four differential equations described by equations 4, 5, 13, and 14, enables the calculation of emissions (S), pollution (P), consumption (c), and the amount of green energy used in the production (x) over time. These, in turn, allow us to calculate the fossil fuels usage in production (z), the quantity of final good produced at each point in time (q), and the utility of the representative consumer (c).

3.1.2 Calibration and Results

Table 1: Calibration Parameters

Parameter	**Value**
Technology Level (A)	1
Discount Factor (ρ)	0.025
Weight of Consumption (w)	0.6
Output Elasticity of Green Energy (γ)	0.3
Emission Intensity of Dirty Energy (α)	1
Pollution rate of Production (θ)	0.4
Pollution rate of Consumption (ξ)	0.6
Environmental Regeneration Rate (δ)	0.03

Table 1 summarizes the values of our model's parameters. Since our model does not feature technological growth, we normalize the technology parameter (A) to equate 1. This choice is further supported by Allen (2009) who showed that the minimum level of technological progress in a Cobb Douglas production function must be set to 1. Furthermore, the discount rate is set at 0.025, a result obtained by Jones and Tonetti (2020). Following Skare et al. (2024), output elasticity

of green energy (γ) is set to 0.3, in order to match their estimation. We also set the environmental regeneration rate (δ) equal to 0.03, following Acemoglu et al., 2016), while the weight of consumption (w) is set to 0.6, in order to match the 0.4 weight of environmental quality reported by Delis and Iosifidi (2020). In addition, the pollution rates of production (θ) and consumption (ξ), are set to 0.4 and 0.6 respectively in order to match the estimation of Ivanova et al. (2016).

Our baseline results are illustrated in Figure 2. Our main result regarding green energy usage is that is would be optimal for a country to increase its usage whenever possible. This is because of the utility trade off between consumption and environmental quality. However, as the economy develops it would seem impossible to sustain an increasing consumption path. When the economy's consumption path starts declining, we would expect green energy usage to follow a similar path, however with a much less dramatic decrease.

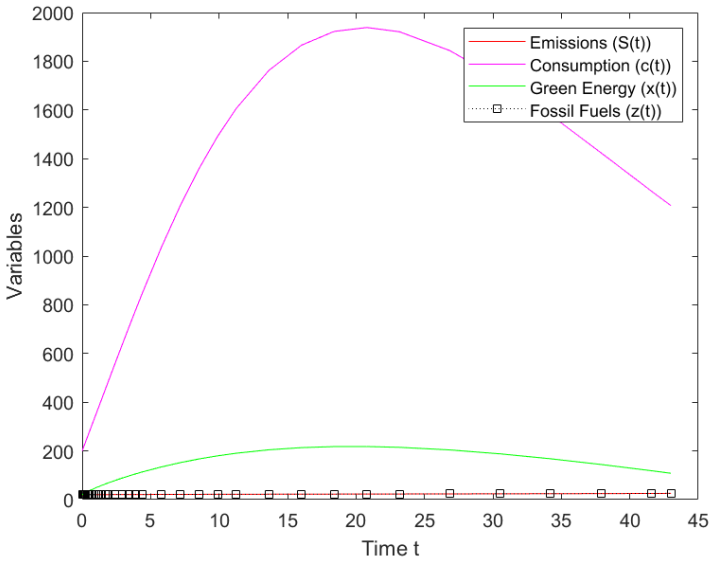

Figure 2: Solution of Baseline Model

Something extremely sensible as in our model we do not account for technological growth.

3.2 A Model of Cross-Border Interactions

3.2.1 Solution and The Optimal Growth Path

As we have already mentioned, the analysis above will simply serve as a baseline model since it fails to take into account strategic interactions between neighboring countries. Let us assume that there are two neighboring countries (i, j), each facing the dynamic optimization problem as outlined above. In addition, assume that the emissions produced in countries (i, j) are denoted with $\{S_i, S_j\}$. The two countries are facing two separate but identical dynamic optimization problems, without updating their beliefs and while they have perfect access to information . A country's emissions do not affect its own pollution level, but also the pollution level of the neighboring country. Specifically, we assume that the path of pollution of country i is now not only affected by its own decisions (similar to Equation 5), but is is also additionally affected by emissions produced in its neighboring country. It is also assumed that the neighboring emissions marginal effect in country's i pollution is equal to the externality rate β. Hence, the law of motion of pollution in country i is now described by:

$$\dot{P}_i = S_{it} + \beta S_{jt} + \xi c_{it} + \theta \phi_i(x_{it}, S_{it}/\alpha) - \delta P_{it} \tag{15}$$

Although our model focuses on the analysis of emission externalities between two neighboring countries, our results can be applicable to every pair of countries within a reasonable distance. Nevertheless, our results provide significant information to understand how a country's choices regarding their energy consumption and pollution, affect the decisions of their neighboring countries as

These two assumptions allow us to solve the model as a simultaneous game on which the best response functions are dynamic. Essentially this allows us to focus on computing the Nash Equilibrium (NE), as opposed to a Subgame Perfect Nash Equilibrium (SPNE) or a Bayesian Nash Equilibrium (BNE) solution concept.

well, and at this stage we elect not to complicate the model by accounting for additional countries. Each country is facing a dynamic optimization problem that is closely related to the one illustrated in Section 3.1. Thus, the dynamic optimization problem faced by country i can now be expressed by the following Hamiltonian function:

$$H_{it} = e^{-\rho t}u(c_{it}, P_{it}) + \lambda_t \left[\frac{S_{it}}{\alpha x_{it} + S_{it}}\right] + \mu_t[S_{it} + \beta S_{jt} - \delta P_{it} + \xi c_{it} + \theta\phi(x_{it}, S_{it}/\alpha)] \tag{16}$$

The solution of the above problem for country i provides the following Euler equation and optimal growth path for the green energy. A detailed illustration of the solution can be found in Appendix B

$$\frac{\dot{c_i}}{c_i} = \frac{1}{u_{cc,i}c_{it}}\left[u_{c,i}(\rho + \delta) + \xi u_{P,i} - u_{cP,i}\dot{P_i}\right] \tag{17}$$

$$\dot{x_i} = -\frac{S_{it}}{2\alpha\phi_{x,i} + \phi_{xx,i}(\alpha x_{it} + S_{it})}\left[\frac{(\phi_{x,i} + \phi_{z,i})\theta + \alpha}{\theta(\alpha x_{it} + S_{it})} + \frac{\phi_{xz,i}}{\alpha}\right] - \frac{\phi_{x,i}(\alpha x_{it} + S_{it})}{2\alpha\phi_{x,i} + \phi_{xx,i}(\alpha x_{it} + S_{it})}\left[\xi\frac{u_{P,i}}{u_{c,i}} + \delta\right] \tag{18}$$

Hence, country i faces the problem described by the four differential equations given by the law of motion of emissions (given in Appendix B by 23), 15, 17, and 18. The primary interest of our paper is to examine the effect on cross-border interactions on optimal policies. In the interest of reducing the computational burden, we assume that countries i and j are identical and thus

Once again, pollution P_{it} and emissions S_{it} are assumed to be the state variables, while consumption c_{it} and green energy x_{it} are the control variables. Additionally, λ_{it} represents the shadow price of the evolution of emissions and μ_{it} represents the shadow price of the pollution accumulation path.

they face the same identical problem, so country j's problem can also be expressed by the same differential equations. Since countries i and j are identical, it is evident that in equilibrium:

$$S_{it} = S_{jt} = S_t \tag{19}$$

The system of equations described above is simply the Best Response function of country i (and thus for country j). The Nash Equilibrium can be found by solving the system of the two Best Response functions, while while imposing the natural result obtained by symmetry as illustrated in 19.

3.2.2 Calibration and Results

In our model with cross-border interactions we elect to use the same set of parameters, which are presented in Table 1. This is done in order to ensure consistency on the comparison between the two models. The externality rate (β) is set to 1. Setting $\beta = 1$ implies that emissions in country A generate pollution in country B in an one-to-one ratio. This would of course apply only to provinces located exactly on the border (similar to the case of Windsor, Ontario and Detroit, Michigan mentioned in Section 1, but is not a realistic value for provinces located farther away from the border. More precisely, as the geographical distance of a province from the border increases, the value of β should decline, while the same would apply for countries that are located farther away from each other. Later, we analyze the comparative statics of our model with respect to this parameter, in order to examine the role of geographical distance on the strategic policy decisions of provinces and countries. Our results for our augmented model are illustrated in Figure 3, and at first glance are strikingly

The only reasonable values of β would correspond to $0 < \beta < 1$. That is, a country's emissions would have an one-to-one effect in to the pollution of countries in extremely close vicinity, but as distance increases β would decrease. When a country's emissions does not have any impact on another country's pollution β should be equal to zero.

similar to the ones of the Baseline model. However, further examination of their comparison, would assist us identify the key differences between the baseline and a more realistic scenario, one at which countries do take into account their neighboring countries' energy policy choices.

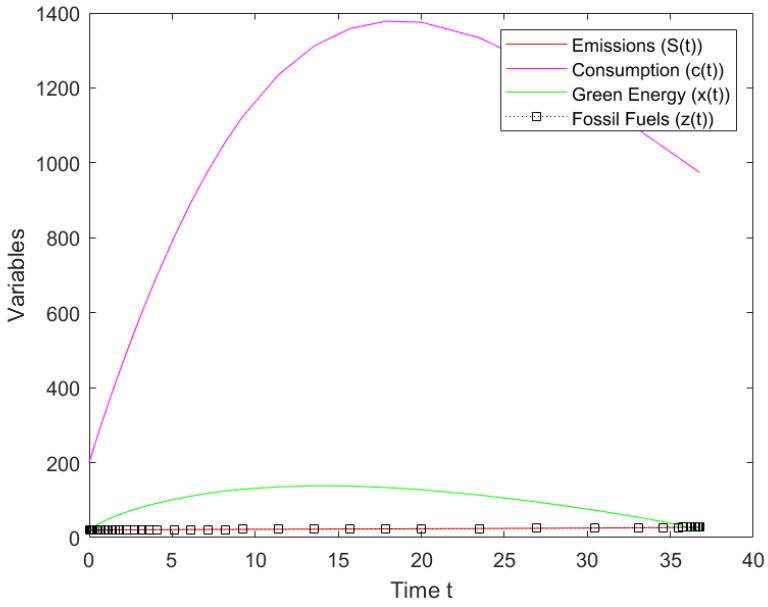

Figure 3: Solution of Cross-Border Model

3.3 Comparison

As mentioned above, the key research question our study aims to address, is the extent at which countries' green transition decisions are influenced by the interactive emission effect produced by neighboring countries. Our best estimate for this exact effect would be a direct comparison of the optimal green energy path between the two models . Hence, we create a direct measure of the differences between the optimal green energy path with $Dx(t) =$

Of course we are proceeding on using the exact same parameter values, as otherwise any direct comparison between the two models would be impossible.

$x_{baseline}(t) - x_{strategic}(t)$. Positive values of $Dx(t)$ would indicate a higher level of optimal green energy usage when countries do not take strategic interactions into account, while negative values would indicate the opposite. Our results on the path of $Dx(t)$ are illustrated in Figure 4.

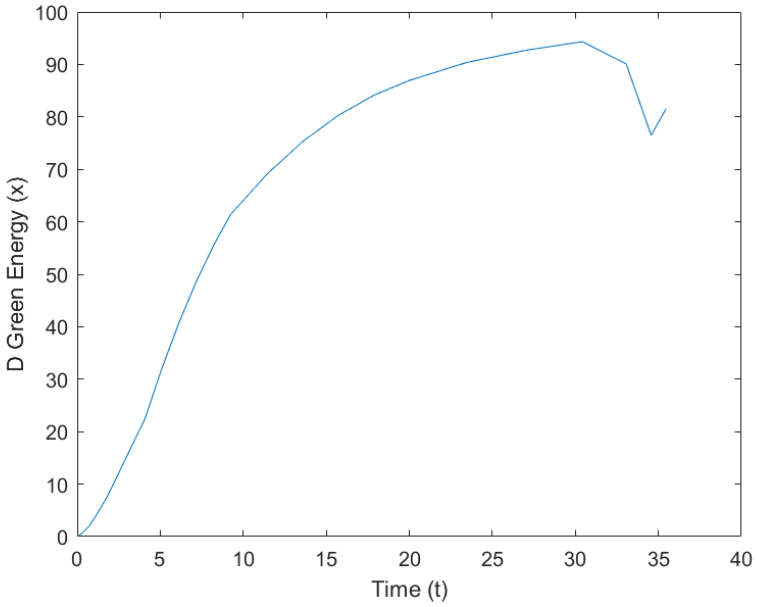

Figure 4: Difference of Green Energy Use Between the Models in Time

Our results show that, for the choice of parameters illustrated above, the optimal green energy path is always lower when countries take into account their neighboring country's energy choices. This serves as clear evidence that a country's green transition efforts produce a negative external effect on neighboring countries' green transition, supporting the prisoner's dilemma hypothesis outlined in Section 1.

This result holds true not only for our baseline parameters, but for all reasonable ranges of them. Figures A.5 and A.6 of the Appendix illustrate the comparative statics of our main result on the path of $Dx(t)$, for different val-

ues of all our parameters. Regardless of the choice of parameters, $Dx(t) > 0$, $\forall t$, which provides further support not only on our findings, but also on their non-sensitivity on the parameter values choice.

4 Conclusion and Policy Implications

The climate change issue has been central on attracting the attention of both policy makers and researchers. General consensus points to the conclusion that green transition is one of the most effective tools humanity could utilize in order to tackle the issue in an adaptive manner. Even if the importance of facilitating a faster and more efficient green transition is undeniable, the dynamics of green energy decisions and more precisely the effect of strategic interactions between neighboring countries, has not been studied sufficiently.

Building on a standard macroeconomic model, which allows for both green and brown energy usage as inputs of the production function, we model the strategic interaction of neighboring countries, utilizing the reasonable assumption that a country's pollution levels are affected by both their own and their neighboring countries' emissions. We are then able to generate directly comparable results in terms of the differences in the optimal green energy path, which is our proxy for green transition. Thus, our main result is the difference in green transition when countries take into account their strategic interaction (realistic scenario), and when countries act myopically (not realistic scenario).

Our results suggest that in the Nash Equilibrium, neighboring countries' emissions negatively impact a country's green transition. Since this effect is calculated relative to the case when countries do not take into account the strategic impact of neighboring countries' decision, we can also conclude that the dynamics of green transition can be modeled as a prisoner's dilemma game.

Our results are robust to a vast array of parameter choices.

In this game, a country's best response function in terms of the path of green energy usage is decreasing on the emission efforts made by neighboring countries.

Thus, in this prisoner's dilemma game, countries could form mutually beneficial agreements that would guarantee sustained increases in their green energy usage, which translates to a facilitated and swifter green transition. Absence of international cooperation would lead countries to a path of a significantly slower green transition which would harm their welfare outcomes in the long-run. As in every similar game, cooperation has to be established in the basis of binding agreements, as the green transition best response functions are always decreasing in the neighboring countries' abatement efforts, which highlights the ever present incentive to unilaterally deviate from such agreements.

Our theoretical framework provides a basis to policy makers' efforts to tackle one of the biggest challenges of our century. However the fact that our analysis is purely theoretical, even if it is robust to the choice of certain parameters, is pointing out the importance of further empirical investigation. Our effort to shed light in the mechanisms that determine our green transition policy choices would have to be based on both theoretical and empirical studies that embody these crucial strategic interactions. Thus, our recommendation on future research is to put a significant emphasis on the empirical analysis of the topic, using models that do take into account such interactions, with the highest recommendation given to spatial empirical analysis.

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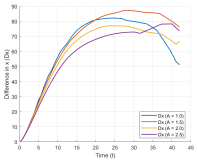
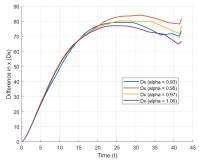
Appendices

A Figures



(a) Difference of Green Energy Use Between the Models When A Changes



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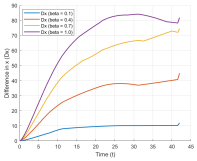
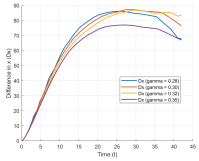
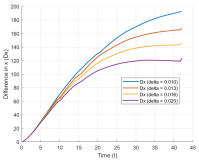


(c) Difference of Green Energy Use Between the Models When β Changes

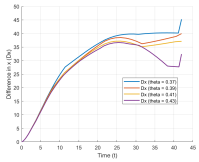


(d) Difference of Green Energy Use Between the Models When γ Changes

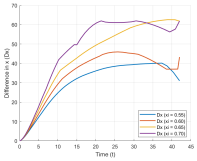
Figure 5: Comparative Statics of Green Energy Usage wrt A, α, β and γ



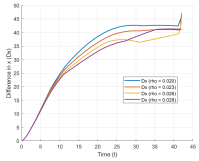
(a) Difference of Green Energy Use Between the Models When δ Changes



(b) Difference of Green Energy Use Between the Models When θ Changes



(c) Difference of Green Energy Use Between the Models When ξ Changes



(d) Difference of Green Energy Use Between the Models When ρ Changes

Figure 6: Comparative Statics of Green Energy Usage wrt δ, θ, ξ and ρ

B Solution of the Cross-Border Interactions Model

This section outlines the cross-border interactions model presented in Section 3.2.1, and specifically the formation and solution of the Hamiltonian equation given by 16. The analysis is based on a world consisting of two countries; nevertheless, our analysis and results can be extended to more than two countries.

Each country has a benevolent social planner who wants to maximize the social welfare of the economy described by 20, considering at the same time that the consumers' instantaneous utility function is given by $u_t(c_{it}, P_{it}) = wlnc_{it} - (1-w)lnP_{it}$:

$$U_{it} = \int_0^\infty e^{-\rho t} u_t(c_{it}, P_{it}) dt \tag{20}$$

Furthermore, each country produces an identical final good using green energy and fossil fuels with the following production function:

$$q = \phi(x_{it}, z_{it}) = A x_{it}^{\gamma} z_{it}^{1-\gamma} \tag{21}$$

The use of fossil fuels is negatively affecting the environmental quality of each country by releasing emissions. Specifically, our framework assumes that the emissions released in each country are exclusively arising from the use of fossil fuels in the production process. Hence, the relationship between emissions and fossil fuels can be expressed as:

$$S_{it} = \alpha z_{it} \tag{22}$$

Finally, the way emissions change in time within each country, is not affected by the production of the second economy, as it is exclusively influenced by

their optimal energy policy mix. Hence, the law of motion of emissions of each economy is described by:

$$\dot{S}_i = \frac{z_{it}}{x_{it} + z_{it}} \text{ or } \dot{S}_i = \frac{S_{it}}{\alpha x_{it} + S_{it}} \tag{23}$$

Finally, the law of motion of each country's pollution is affected by the emissions of the neighboring country as illustrated by 15. The solution of 16 considers consumption (c_{it}) and green energy (x_{it}) as the control variables, while emissions (S_{it}) and pollution (P_{it}) are the state variables. The first-order conditions with respect to the control and state variables are given below:

$$H_{i,c} = e^{-\rho t} u_{i,c} + \mu_{it}\xi = 0 \tag{24}$$

$$H_{i,x} = -\lambda a S_{it}(a x_{it} + S_{it})^{-2} + \mu_{it}\theta\phi_{i,x} = 0 \tag{25}$$

$$H_{i,S} = -\left[\frac{e^{-\rho t}u_{i,c}}{\alpha\xi}\right]\left[\frac{\theta\phi_{i,x}(\alpha x_{it} + S_{it})}{S_{it}} + \theta(\phi_{i,z} - \phi_{i,x}) + \alpha\right] = -\dot{\lambda}_i \tag{26}$$

$$H_{i,P} = e^{-\rho t}\left[u_{i,P} + u_{i,c}\frac{\delta}{\xi}\right] = -\dot{\mu}_i \tag{27}$$

The Euler equation for consumption (17) is derived from the substitution of 15 for $\dot{P}_i$ and 27 for $\dot{\mu}$ to the total differentiation of equation 24 with respect to time (t). Similarly, the optimal growth path for green energy use (18) is obtained by the substitution of $\dot{S}_i$, $\dot{\mu}_i$, λ_{it}, and μ_{it} from equations 23, 27, 25, and 24 respectively, to the total differentiation of equation 25 with respect to time t.

The results presented in both Section 3.2.2 and 3.3 are based on the solution of the system of four differential equations given by 15, 23, 17, and 18, taking into account that the countries are identical (Equation 19).