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MACROECONOMIC IMPACTS OF CLIMATE CHANGE UNDER NGFS SCENARIOS AND MONETARY POLICY

Abstract:

This paper examines the environmental and macroeconomic impacts of changes in global value chain (GVC) participation, cross-border externality of carbon emissions, environmental considerations in monetary policy, and international coordination in environmental policy across seven NGFS scenarios. An E-DSGE model analysis shows that i) increased GVC participation, with higher reliance on imported intermediate goods, slows economic growth more significantly in high-pollution regimes, ii) the emphasis on environmental issues in monetary policy has insignificant impact on carbon emissions while increasing macroeconomic volatility to more polluted regimes. These findings suggest that while less stringent environmental policies may offer short-term benefits, these are outweighed by higher long-term transition costs. Therefore, a proactive environmental policy, aimed at achieving a 'Net Zero 2050' scenario, could foster more stable economic conditions. Furthermore, the environmental concerns in monetary policy should be moderated to mitigate potential side effects of indirect interventions on carbon emissions.

Keywords:

Climate change, NGFS scenarios, Cross-border externalities, GVC participation, Monetary policy, Environmental policy coordination

JEL Classification: E52, E62, Q58

1. Introduction

Motivated by the sharply rising transitional and physical risks associated with climate change, this paper examines its potential macroeconomic impacts based on seven NGFS (Network for Greening the Financial System) scenarios released in November 2024. [1] These scenarios illustrate the global environmental and economic consequences of climate change, including potential damages under various conditions.

The NGFS scenarios provide detailed projections on the physical impacts of climate change and the resulting macroeconomic outcomes. Using these projections, we analyze the macroeconomic impacts of climate change through an Environmental Dynamic Stochastic General Equilibrium (EDSGE) model, primarily considering four factors: (i) changes in GVC participation, (ii) cross-border carbon emissions externalities, (iii) environmental considerations in monetary policy, and (iv) cross-border environmental policy complementarity across seven NGFS scenarios.

To examine the potential implications for South Korea, we consider the status of its environmental regime within the context of the NGFS scenarios. Under the environmental policy target announced by the South Korean government to achieve 'Net Zero 2050,' South Korea could be classified within this scenario. However, the country aligns more closely with the 'Delayed Transition' scenario group, given its lower carbon price level compared to the Euro area in 2024. [2] This study examines the macroeconomic impacts of shocks to GVC (Global Value Chain) participation, cross-border carbon emissions externalities, environmental considerations in

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[1] The NGFS (Network for Greening the Financial System) is a group of central banks and financial supervisors that was established in 2017 to address climate-related risks in the financial sector. The NGFS aims to enhance the role of the financial system in managing climate and environmental risks, and it also supports the transition to a sustainable economy. The network provides recommendations, research, and tools to help central banks and financial institutions incorporate climate-related risks into their operations and decision-making processes. The NGFS scenarios refer to a set of climate scenarios developed by the NGFS to help financial institutions, central banks, and policymakers assess and manage the financial risks associated with climate change. These scenarios are designed to explore the potential economic and financial impacts of different pathways of climate change and the global response to it. The NGFS scenarios was initially developed in 2020, and has been updated annually since then. For the details, please refer to https://www.ngfs.net/en/ngfs-climate-scenarios-phase-iv-november-2024.

[2] In 2024, South Korea's carbon price level is estimated at approximately US$7.25. (https://icapcarbonaction.com/en/ets-prices)

monetary policy, and international coordination in environmental policy, using the seven NGFS scenarios to derive policy implications for South Korea.

Reflecting growing concerns and the imminent physical and transitional threats posed by climate change, the literature on its macroeconomic impacts is extensive. The key studies include Annicchiarico and Dio (2015), Chan (2020), and Chan, Ji and Zhang (2024). Annicchiarico and Dio (2015) provide a foundational framework for exploring the dynamic paths of environmental policy regimes in a New Keynesian model, emphasizing how the price adjustment mechanism influences optimal policy responses to climate change. Chan (2020) compares the effectiveness of standard macroeconomic policy tools with carbon pricing policies, demonstrating that fiscal policy is a primary channel for controlling carbon emissions in the presence of TFP shocks and identifies conditions for complementarity between carbon taxation and monetary policy. Chan, Ji and Zhang (2024) investigate the formation of carbon and green bubbles, examining the macroeconomic impacts of carbon emissions and the optimal monetary responses.

While this paper shares the fundamental approach of identifying the social cost of carbon emissions and the responses of firms and policymakers with existing literature, it diverges by considering the impact of global value chain (GVC) participation on production processes and the resulting cross-border externalities of carbon emissions across seven NGFS scenarios. Additionally, we examine the potential environmental and macroeconomic impacts of incorporating environmental concerns into monetary policy and enhanced cross-border complementarity of environmental policies—challenging issues that, to our knowledge, have not been analytically explored.

Our study employs a general equilibrium model in which corporate sectors participate in GVCs through a simplified production technology reliant on imported intermediate goods. By analyzing varying levels of cross-border externalities from imported carbon emissions, we assess the macroeconomic implications of climate change via the channels of international linkages through GVCs and cross-border carbon emission externalities. Furthermore, using an extended Taylor rule that includes an environmental term, we explore the effects of environmental considerations in monetary policy. The impacts of different levels of cross-border environmental policy complementarity are also examined to identify macroeconomic implications, an approach that is rarely attempted in existing literature.

The paper is structured as follows: Section 2 introduces the model structure, detailing interactions among representative households, domestic corporate sectors (as downstream firms), foreign suppliers of intermediate goods, and policymakers responsible for carbon pricing and monetary policy within a dynamic general equilibrium framework. Additionally, it discusses the strategic aspects of environmental policy coordination. Section 3 examines how global value chain (GVC) participation, cross-border externalities, the emphasis on environmental concerns within monetary policy, and enhanced cross-border environmental policy complementarity influence the macroeconomic impacts of climate change based on NGFS scenarios, and Section 4 summarizes and suggests policy implications.

2. Model

To examine the impacts of climate change and environmental policies on the macroeconomic performance of an economy integrated into global value chains and subject to cross-border climate externalities, we develop an environmental dynamic stochastic general equilibrium (E-DSGE) model. To capture cross-border spillover effects, we incorporate global value chain structures in the production sector, where imported intermediate goods carry externalities from foreign carbon emissions.

Production sectors are vertically connected through supply chains linking foreign upstream firms with domestic downstream firms. This integration means that foreign carbon emissions affect domestic productivity, and vice versa, through cross-border externalities.

2.1. The Representative Consumer

The representative household maximizes the stream of expected utility,

$$\mathrm{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{C_t^{1-\sigma}}{1-\sigma} - \mu_L \frac{L_t^{1+\phi_0}}{1+\phi_0} \right) \tag{1}$$

where β is the discount factor, C_t is the amount of consumption at t, σ is the inverse of the elasticity of intertemporal substitution for consumption, which is equivalent to the relative risk aversion with the given constant relative risk aversion (CRRA) functional form. μ_L shows the disutility level of labor, *L* is the amount of labor, and ϕ_0 represents the Frisch labor supply elasticity.

The household is subject to the following budget constraints:

$$P_{d,t}C_t + P_{d,t}I_{d,t} = W_{d,t}L_{d,t} + R_{d,t}K_{d,t-1} + TR_{d,t} \tag{2}$$

where $TR_{d,t}$ is the government fiscal transfer equivalent to the carbon tax revenue, defined as $TR_{d,t} = \tau_{d,t} M_{d,t}$.

$M_{d,t}$ is the domestic carbon dioxide emitted, $\tau_{d,t}$ is the carbon tax rate.

The law of motion in capital is given as:

$$K_{d,t} = (1-\delta)K_{d,t-1} + I_{d,t} \quad (3)$$

where $I_{d,t}$ is the level of domestic investment at time *t*, $K_{d,t-1}$ is the capital stock inherited from the previous period, and δ is the depreciation rate of capital.

The optimality conditions are as follows. The first-order conditions for the representative consumer are:

$$\frac{\partial L}{\partial C_t} = \beta^t C_t^{-\sigma} - \lambda_t = 0$$

$$\frac{\partial L}{\partial L_t} = -\beta^t \mu L_t^{\phi} + w_t \lambda_t = 0$$

$$\frac{\partial L}{\partial K_t} = -\lambda_t + \beta \mathrm{E}_t \lambda_{t+1}(r_{t+1} + 1 - \delta) = 0$$

From the above first-order conditions, we obtain the following equilibrium conditions:

$$C_t^{-\sigma} = \mu L_t^{\phi_0} w_t^{-1} \quad (4)$$

$C_t^{-\sigma} = \beta \mathrm{E}_t C_{t+1}^{-\sigma}(r_{t+1} + 1 - \delta)$, which is the Euler equation. (5)

2.2. The Domestic Downstream Firm

The profit function of the domestic downstream firm is given as:

$$Max \prod_{d,t} = P_{d,t} y_{d,t} - w_t L_{d,t} - r_t K_{d,t} - P_{u,t} y_{u,t} - \tau_d M_{d,t} - C_{d,t} \tag{6}$$

subject to $y_{d,t} = A_{d,t}\left(1 - D_d(M_{d,t})\right) L_{d,t}{}^{\alpha} K_{d,t}{}^{\beta_1} y_{u,t}{}^{\gamma}$

where $y_{d,t}$ is the output level of the downstream firm, $C_{d,t}$ is the cost of the emission abatement, $M_{d,t}$ is the stock of domestic carbon dioxide emitted, $A_{d,t}$ is the domestic productivity shock, and *D(M)* denotes the negative shock to productivity due to carbon emission. α, β_1, and γ represent output elasticity of production factors: labor (*L*), capital (*K*) and imported intermediate goods ($y_{u,t}$), respectively. To examine the impacts of shocks in global value chains, including geopolitical shocks, we introduce: $\gamma_t = \rho\gamma_{t-1} + \varepsilon_{\gamma}$.

The emission-induced damage function is given by

$D_d(M_{d,t}) = \gamma_0 + \gamma_1 M_{d,t} + \gamma_2 M_{d,t}^2$ where γ_1 is the parameter for a linear term of carbon emission stock reflecting short-term effects of carbon stock and γ_2 is the parameter for a quadratic term of carbon emission stock reflecting long-term effects of carbon stock.

The stock of carbon emission in period *t* is defined as follows:

$$M_{d,t} = (1 - \delta_M) M_{d,t-1} + Z_{d,t} + \gamma_{u,t} Z_{u,t}$$

where $M_{d,t}$ is the current stock of carbon emission, δ_M is the natural reduction rate of carbon emissions stock, $M_{d,t-1}$ is the stock of carbon emission in period *t*-1, $Z_{d,t}$ is the amount of carbon emission in period *t*, $Z_{u,t}$ is the amount of carbon emission in the foreign upstream country, and $\gamma_{u,t}$ is the coefficient of cross-border externality of carbon emissions. To examine the impacts of the uncertainty and shocks in the cross-border externality of carbon emissions, the following term is also considered: $\gamma_{u,t} = \rho\gamma_{u,t-1} + \varepsilon_{\gamma_u}$.

The amount of domestic carbon emission is determined as follows:

$$Z_{d,t} = \varphi(1 - e_{d,t}) y_{d,t} \tag{7}$$

where $\varphi > 0$ is the carbon intensity of the downstream production process and $e_{d,t}$ is the carbon emission abatement effort exerted by the domestic downstream firm, and $y_{d,t}$ is the output level.

In addition, the abatement cost is $C_{d,t} = \phi_1 e_{d,t}^{\phi_2} y_{d,t}$ with $\phi_1 > 0$ and $\phi_2 > 1$ implying that the abatement cost function is a convex function.

With the substitution of the abatement cost, the profit function of the domestic downstream firm is given as:

$$Max \prod_{d,t} = P_{d,t} y_{d,t} - w_{d,t} L_{d,t} - r_{d,t} K_{d,t} - P_{u,t} y_{u,t} - \tau_{d,t} \varphi (1 - e_{d,t}) y_{d,t} - \phi_1 e_{d,t}^{\phi_2} y_{d,t} \tag{8}$$

The strategic variables of the downstream firm include $L_{d,t}$, K_t, $y_{u,t}$, $e_{d,t}$. The first order conditions for the downstream firm are given as:

$$\frac{\partial L}{\partial L_{d,t}} = \frac{\partial \Pi_d}{\partial L_{d,t}} = P_{d,t}(1 - D(M_{d,t}, M_{u,t}))\alpha L_{d,t}^{\alpha-1} K_t^{\beta} y_{u,t}^{\gamma} - w_{d,t} = 0 \tag{9}$$

$$\frac{\partial L}{\partial K_{d,t}} = \frac{\partial \Pi_d}{\partial K_{d,t}} = P_{d,t}(1 - D(M_{d,t}, M_{u,t}))\beta L_t^{\alpha} K_t^{\beta-1} y_{u,t}^{\gamma} - r_{d,t} = 0 \tag{10}$$

$$\frac{\partial L}{\partial y_{u,t}} = \frac{\partial \Pi_d}{\partial y_{u,t}} = P_{d,t}(1 - D(M_{d,t}, M_{u,t}))\gamma L_t^{\alpha} K_t^{\beta} y_{u,t}^{\gamma-1} - P_{u,t} = 0 \tag{11}$$

$$\frac{\partial L}{\partial e_{d,t}} = \frac{\partial \Pi_d}{\partial e_{d,t}} = (P_{d,t}\gamma_1 + \tau_{d,t})\varphi - \phi_1 \phi_2 e_{d,t}^{\phi_2 - 1} = 0 \tag{12}$$

2.3 The Foreign Upstream Firm

The profit function of the representative upstream firms located in a foreign country is given as:

$$Max \prod_{u,t} = P_{u,t} y_{u,t} - w_{u,t} L_{u,t} - r_{u,t} K_{u,t} - \tau_{u,t} M_{u,t} - C_{u,t} \tag{13}$$

subject to $$y_{u,t} = A_{u,t}\left(1 - D_u(M_{d,t}, M_{u,t})\right) L_{u,t}^{\alpha} K_{u,t}^{\beta} \tag{14}$$

where *D(M)* denotes the shock to productivity due to carbon emission.

The emission-induced damage is given by

$$D_u(M_{u,t}) = \gamma_0 + \gamma_1 M_{u,t} + \gamma_2 M_{u,t}^2 \tag{15}$$

The stock of the foreign carbon emission in period *t* is defined as follows:

$$M_{u,t} = (1 - \delta_M) M_{u,t-1} + Z_{u,t} + \gamma_{d,t} Z_{d,t}$$

where $M_{u,t}$ is the current foreign stock of carbon emission, δ_M is the natural reduction rate of carbon emissions stock, $M_{u,t-1}$ is the stock of foreign carbon emission in period *t*-1, $Z_{u,t}$ is the amount of foreign carbon emission in period *t*, and $\gamma_{d,t}$ is the coefficient of cross-border externality of carbon emissions.

The amount of foreign carbon emission in period *t* is determined as follows:

$Z_{u,t} = \varphi_u (1 - e_{u,t}) y_{u,t}$ where $\varphi_u > 0$ is the carbon intensity of the upstream production process and $e_{u,t}$ is the carbon emission abatement effort exerted by the foreign upstream firm, and $y_{u,t}$ is the output level of the foreign upstream firm.

In addition, the abatement cost for the upstream firm is: $C_{u,t} = \phi_{1,u} e_{u,t}^{\phi_{2,u}} y_{u,t}$ with $\phi_{1,u} > 0$ and $\phi_{2,u} > 1$ implying a convex cost function.

When we substitute the abatement cost, the profit function is given as:

$$Max \prod\nolimits_{u,t} = P_{u,t} y_{u,t} - w_{u,t} L_{u,d} - r_{u,t} K_{u,t} - \tau_u \varphi_u (1 - e_{u,t}) y_{u,t} - \phi_{1,u} e_{u,t}^{\phi_{2,u}} y_{u,t} \tag{16}$$

The strategic variables of the downstream firm include $L_{u,t}$, $K_{u,t}$, $e_{u,t}$. The first order conditions for the downstream firm are given as:

$$\frac{\partial L}{\partial L_{u,t}} = \frac{\partial \Pi_u}{\partial L_{u,t}} = P_{u,t}(1 - D_u(M_{u,t}, M_{d,t}))\alpha L_{u,t}^{\alpha-1} K_{u,t}^{\beta} - w_{u,t} = 0 \tag{17}$$

$$\frac{\partial L}{\partial K_{u,t}} = \frac{\partial \Pi_u}{\partial K_{u,t}} = P_{u,t}(1 - D_u(M_{u,t}, M_{d,t}))\beta L_{u,t}^{\alpha} K_{u,t}^{\beta-1} - r_{u,t} = 0 \tag{18}$$

$$\frac{\partial L}{\partial e_{u,t}} = \frac{\partial \Pi_u}{\partial e_{u,t}} = (P_{u,t}\gamma_1 + \tau_{u,t})\varphi - \phi_{1,u}\phi_{2,u} e_{u,t}^{\phi_{2,u}-1} = 0 \tag{19}$$

2.4 The Central Bank for Monetary Policy

The central bank determines interest rates based on the following Taylor's rule:

$$R_{d,t}^{*} = R_d \left(\frac{\Pi_{d,t}}{\Pi_d}\right)^{\chi_{\Pi_d}} \left(\frac{Y_{d,t}}{Y_d}\right)^{\chi_{Y_d}} \left(\frac{D_{d,t}}{D_d}\right)^{\chi_{D_d}} \tag{20}$$

where $\chi_{\Pi_d} > 0$, $\chi_{Y_d} > 0$, and $\chi_{D_d} \geq 0$ represent the sensitivity of interest rate decision to the change in inflation rate, real output and damages due to carbon emissions. If the central bank's monetary policy is independent of the environmental concerns in terms of damages from climate changes due to carbon emissions, then $\chi_{D_d} = 0$.

Reflecting the weight and sensitivity of the inflation rate and real output on monetary policy, the interest rate is determined, followed by the determination of the corporate investment level for capital formation within the general equilibrium model. Given our focus on the role of χ_{D_d}, policy weight and sensitivity to environmental concerns in monetary policy - particularly their impact on carbon emissions, environmental damages, and macroeconomic effects -, we consider the following shocks to the policy weight assigned to environmental damages in monetary policy: $\chi_{D_d,t} = \rho\chi_{D_d,t-1} + \varepsilon_{\chi_{D_d}}$.

As a precondition for making the role of monetary policies non-trivial, the Calvo price-rigidity term is introduced as:

$$P_{d,t} = \left(\theta P_{d,t-1}^{1-\varepsilon} + (1-\theta)(P_{d,t}^{*})^{1-\varepsilon}\right)^{\frac{1}{1-\varepsilon}} \tag{21}$$

where $\theta \in [0,1]$ represents the fraction of domestic downstream firms that do not adjust their prices. Therefore, a firm can adjust its price with a probability $1-\theta$. ε represents the elasticity of substitution between different goods, which determines the degree of price dispersion.

The domestic downstream firms that adjust their prices in period *t* choose the price $P_{d,t}^{*}$ to maximize the present discounted value of their expected profits, taking into account $\theta \in [0,1]$, the probability of not being able to adjust the price in future periods. The first-order condition for this optimization problem is written as:

$$P_{d,t}^{*} = \frac{\varepsilon}{\varepsilon - 1} \frac{\sum_{k=0}^{\infty} (\beta\theta)^k E_t[Y_{d,t+k} MC_{d,t+k} P_{d,t+k}^{\varepsilon}]}{\sum_{k=0}^{\infty} (\beta\theta)^k E_t[Y_{d,t+k} P_{d,t+k}^{\varepsilon-1}]} \tag{22}$$

where β is the discount factor, $Y_{d,t+k}$ is the demand for the domestic downstream firm's product in period *t+k*, MC_{t+k} is the marginal cost of production in period *t+k*, and $P_{d,t+k}$ is the aggregate price level in period *t+k*.

The log-linearization of the above first-order condition around a steady state provides the following New Keynesian Phillips Curve (NKPC), which describes the relationship between inflation and the real marginal cost:

$$\Pi_{d,t} = \beta E_t[\Pi_{d,t+1}] + \eta(mc_{d,t}) \tag{23}$$

where $\Pi_{d,t}$ is the rate of inflation at time *t*, $mc_{d,t}$ is the real marginal cost of the domestic downstream firm related to the output gap, and $\eta = \frac{(1-\theta)(1-\beta\theta)}{\theta}$ is a parameter that depends on the degree of price stickiness θ and the discount factor *β*.

In addition, the capital adjustment cost function is introduced as:

$$\Psi(I_{d,k}, K_{d,t-1}) = \frac{\psi}{2}\left(\frac{I_{d,k}}{K_{d,t-1}} - \delta\right)^2 K_{d,t-1} \tag{24}$$

Where ψ is a parameter that controls the magnitude of the adjustment costs.

In the foreign country where the upstream firm operates, the foreign central bank operates in a symmetric fashion as follows:

$$R^*_{u,t} = R_u \left(\frac{\Pi_{u,t}}{\Pi_u}\right)^{\chi_{\Pi_u}} \left(\frac{Y_{u,t}}{Y_u}\right)^{\chi_{Y_u}} \left(\frac{D_{u,t}}{D_u}\right)^{\chi_{D_u}} \tag{25}$$

where $\chi_{\Pi_u} > 0$, $\chi_{Y_u} > 0$, and $\chi_{D_u} \geq 0$ represent the sensitivity of interest rate decision to the inflation rate, real output and carbon emissions of the foreign country, where the upstream firm is located. If the foreign central bank's monetary policy is independent of the environmental concerns in terms of damages from climate changes due to carbon emissions, then $\chi_{D_u} = 0$.

The Calvo price-rigidity term is incorporated into the foreign monetary policy in a symmetric fashion, similar to the domestic monetary policy-making process, as follows:

$$P_{u,t} = \left(\theta P^{1-\varepsilon}_{u,t-1} + (1-\theta)(P^*_{u,t})^{1-\varepsilon}\right)^{\frac{1}{1-\varepsilon}} \tag{26}$$

The first-order condition for this optimization problem is:

$$P^*_{u,t} = \frac{\varepsilon}{\varepsilon - 1} \frac{\sum_{k=0}^{\infty} (\beta\theta)^k E_t[Y_{u,t+k} MC_{u,t+k} P^{\varepsilon}_{u,t+k}]}{\sum_{k=0}^{\infty} (\beta\theta)^k E_t[Y_{u,t+k} P^{\varepsilon-1}_{u,t+k}]} \tag{27}$$

This leads to the foreign New Keynesian Phillips Curve (NKPC), which describes the relationship between inflation and the real marginal cost:

$$\Pi_{u,t} = \beta E_t[\Pi_{u,t+1}] + \eta(mc_{u,t}) \tag{28}$$

where $\eta = \frac{(1-\theta)(1-\beta\theta)}{\theta}$.

In the same way, the foreign capital adjustment cost function is introduced as:

$$\Psi(I_{u,k}, K_{u,t-1}) = \frac{\psi}{2}\left(\frac{I_{u,k}}{K_{u,t-1}} - \delta\right)^2 K_{u,t-1} \tag{29}$$

where ψ is a parameter that controls the magnitude of the adjustment costs, $I_{u,k}$ is the level of foreign investment at time *t*, $K_{u,t-1}$ is the foreign capital stock inherited from the previous period.

If the foreign country with the upstream firm is perfectly coordinated with the home country with the downstream firm, the subscripts denoting the two different countries will collapse, resulting in a single monetary policy governing both firms. Otherwise, the two firms are managed by independent central banks, and the degree of policy coordination becomes crucial for both firms and countries, especially when dealing with significant cross-border externalities from carbon emissions.

2.5 Governments for Environmental Regulatory Policies and Strategic Interactions

The home government determines the carbon tax by solving the following domestic social welfare maximization problem, where social welfare consists of consumer surplus (CS), producer surplus (PS), and government surplus (GS):

$$\underset{\tau_d}{Max}\, SW_{d,t}(\tau_u) = CS_{d,t} + PS_{d,t}(\tau_u) + GS_{d,t}(\tau_u) = \mathrm{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{C_t^{1-\sigma}}{1-\sigma} - \mu_L \frac{L_t^{1+\phi}}{1+\phi}\right)$$

$$+ P_{d,t} y_{d,t} - w_t L_{d,t} - r_t K_{d,t} - P_{u,t} y_{u,t} - \tau_{d,t} \varphi(1-e_{d,t}) y_{d,t} - \phi_1 e_{d,t}^{\phi_2} y_{d,t}. \tag{30}$$

The optimal carbon tax is determined as the social welfare maximizing tax as a function of the foreign carbon tax rate reflecting the environmental externalities of foreign upstream firm's carbon emissions: $\tau_d^*(\tau_u)$. The structure of the strategic interactions between the home and foreign government is that the foreign government's decision on the carbon tax will influence the amount of the foreign upstream firm's carbon emission, which eventually influences home country's welfare through the deteriorated productivity via environmental shocks.

In the same way, the foreign government determines her optimal carbon tax, $\tau_u^*(\tau_d)$, from the following foreign social welfare maximization problem:

$$\underset{\tau_u}{Max}\, SW_{u,t}(\tau_d) = CS_{u,t} + PS_{u,t}(\tau_d) + GS_{u,t}(\tau_d) = \mathrm{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{C_t^{1-\sigma}}{1-\sigma} - \mu_L \frac{L_t^{1+\phi}}{1+\phi} \right)$$

$$+ P_{u,t} y_{u,t} - w_t L_{u,t} - r_t K_{u,t} - \tau_{u,t} \varphi_u (1-e_{u,t}) y_{u,t} - \phi_{1,u} e_{u,t}^{\phi_{2,u}} y_{u,t} \,. \quad (31)$$

Then, the first order conditions for the equilibrium for the home country and the foreign country are given as:

$$\frac{\partial SW_{d,t}(\tau_u)}{\partial \tau_d} = \frac{\partial CS_{d,t}}{\partial \tau_d} + \frac{\partial PS_{d,t}(\tau_u)}{\partial \tau_d} + \frac{\partial GS_{d,t}(\tau_u)}{\partial \tau_d} = 0 \quad (32)$$

$$\frac{\partial SW_{u,t}(\tau_u)}{\partial \tau_u} = \frac{\partial CS_{u,t}}{\partial \tau_u} + \frac{\partial PS_{u,t}(\tau_d)}{\partial \tau_u} + \frac{\partial GS_{u,t}(\tau_d)}{\partial \tau_u} = 0 \quad (33)$$

Since the explicit functional form for the optimal carbon tax cannot be derived from the current model structure, we introduce an analytical shortcut by assuming that foreign emissions are influenced by domestic carbon policy, and vice versa, as follows:

$$M_{u,t}(\tau_{d,t}) = \bar{M}_{u,t} - c_{d,u,t}\tau_{d,t}$$

$$M_{d,t}(\tau_{u,t}) = \bar{M}_{d,t} - c_{u,d,t}\tau_{u,t} \quad (34)$$

where $M_{u,t}$ is the carbon emissions of the foreign (i.e., upstream) country, $\bar{M}_{u,t}$ is the status quo carbon emission in the absence of domestic carbon policy, $c_{d,u,t}$ is the coefficient for the cross-border carbon policy complementarity, and $\tau_{d,t}$ is the domestic (i.e., downstream) carbon tax. To examine the macroeconomic impacts of changes in the cross-border carbon policy complementarity, we consider the following shocks to the carbon policy complementarity: $c_{d,u,t} = \rho c_{d,u,t-1} + \varepsilon_{c_{d,u,t}}$.

Based on this setup, we examine the macroeconomic impact of the stochastic shock in the cross-border carbon policy complementarity on the economy. Analytic procedures of tracking the strategic interactions in environmental policies between the upstream and downstream economies are as follows.

The equilibrium conditions for the optimal carbon tax is defined as follows.

From $\frac{\partial L}{\partial e_{d,t}} = \frac{\partial \Pi_d}{\partial e_{d,t}} = (P_{d,t}\gamma_1 + \tau_{d,t})\varphi - \phi_1\phi_2 e_{d,t}^{\phi_2 - 1} = 0$, the optimal abatement efforts for the downstream firm is given as: $e_{d,t}^* = \left(\frac{(P_{d,t}\gamma_1 + \tau_{d,t})\varphi}{\phi_1\phi_2}\right)^{\frac{1}{\phi_2 - 1}}$.

(35)

Then, the amount of the domestic carbon emissions is $M_{d,t} = \varphi\left(1 - \left(\frac{(P_{d,t}\gamma_1 + \tau_{d,t})\varphi}{\phi_1\phi_2}\right)^{\frac{1}{\phi_2 - 1}}\right) y_{d,t}$, and the total environmental damage is given as:

$$D_{d,t} = \gamma_1\varphi\left(1 - \left(\frac{(P_{d,t}\gamma_1 + \tau_{d,t})\varphi}{\phi_1\phi_2}\right)^{\frac{1}{\phi_2 - 1}}\right) y_{d,t} + \gamma_2\varphi\left(1 - \left(\frac{(P_{u,t}\gamma_1 + \tau_{u,t})\varphi}{\phi_1\phi_2}\right)^{\frac{1}{\phi_2 - 1}}\right) y_{u,t} \tag{36}$$

The best response function of the domestic carbon tax policy is defined as:

$$\frac{\partial D_{d,t}}{\partial \tau_{d,t}} = \left(1 - \frac{\varphi}{(\phi_2 - 1)\phi_1\phi_2}\left(\frac{(P_{d,t}\gamma_1 + \tau_{d,t})\varphi}{\phi_1\phi_2}\right)^{\frac{2-\phi_2}{\phi_2 - 1}}\right)\left(1 - \gamma_1\varphi\left(1 - \left(\frac{(P_{d,t}\gamma_1 + \tau_{d,t})\varphi}{\phi_1\phi_2}\right)^{\frac{1}{\phi_2 - 1}}\right) y_{d,t} - \gamma_2\varphi\left(1 - \left(\frac{(P_{u,t}\gamma_1 + \tau_{u,t})\varphi}{\phi_1\phi_2}\right)^{\frac{1}{\phi_2 - 1}}\right) y_{u,t}\right) = 0$$

In the symmetric way, the best response function for the foreign carbon tax policy is given as:

$$\frac{\partial D_{u,t}}{\partial \tau_{u,t}} = \left(1 - \frac{\varphi}{(\phi_2 - 1)\phi_1\phi_2}\left(\frac{(P_{u,t}\gamma_1 + \tau_{u,t})\varphi}{\phi_1\phi_2}\right)^{\frac{2-\phi_2}{\phi_2 - 1}}\right)\left(1 - \gamma_1\varphi\left(1 - \left(\frac{(P_{u,t}\gamma_1 + \tau_{u,t})\varphi}{\phi_1\phi_2}\right)^{\frac{1}{\phi_2 - 1}}\right) y_{u,t} - \gamma_2\varphi\left(1 - \left(\frac{(P_{d,t}\gamma_1 + \tau_{d,t})\varphi}{\phi_1\phi_2}\right)^{\frac{1}{\phi_2 - 1}}\right) y_{d,t}\right) = 0$$

Based on the equilibrium best response conditions for domestic and foreign carbon tax policies, we can determine the conditions for strategic complementarity and substitutability of the two countries' carbon tax policies, focusing on the cross-border externality of carbon emissions, γ_2, and the convexity of emission abatement costs, ϕ_2.

3. Macroeconomic Impacts of Climate Changes Based on NGFS Scenarios

The initial estimation of the macroeconomic impacts of climate change is based on the NGFS scenarios.[3] The NGFS scenarios provide predictions for both climate-related and general macroeconomic variables at regional and sectoral levels. Using

[3] For the detailed discussions on the political and economic backgrounds of the formation of NGFS and the features of operation in connection to central banks of each sovereignty, refer to Appendix A.

these scenarios, which include assessments of environmental damage such as productivity losses across seven different scenarios, we estimate the macroeconomic impacts of changes in GVC participation and cross-border externalities of carbon emissions. We also examine the effects of incorporating environmental damages into monetary policy decisions, focusing on the policy weights assigned to these damages. Finally, we analyze the conditions for cooperative environmental policy coordination, with particular attention to when carbon taxation policies might serve as strategic complements rather than substitutes among countries facing cross-border externalities.

3.1 NGFS Scenarios

The latest NGFS scenarios (2024) are organized into four categories, encompassing seven specific tracks: i) Orderly Transition, which includes 1) Net Zero 2050, 2) Below 2°C, and 3) Low Demand; ii) Disorderly Transition, which includes 4) Delayed Transition; iii) Hot House World, which includes 5) NDCs (Nationally Determined Contributions) and 6) Current Policies; and iv) Too Little, Too Late, which includes 7) Fragmented World. [4]

Details of the seven NGFS scenarios are provided in Appendix B, with their assumptions characterized as follows: 1) The 'Net Zero 2050' scenario assumes that net-zero emissions are achieved by 2050 through an orderly transition by all major economies. 2) The 'Below 2°C' scenario assumes that global warming is limited to below 2°C above pre-industrial levels with moderate transition efforts. 3) The 'Low Demand' scenario assumes that lower energy demand, driven by technological and demand-side innovation, facilitates a smooth transition to low emissions. 4) The 'Delayed Transition' scenario assumes that the transition starts late, necessitating more drastic measures later. 5) The 'NDCs (Nationally Determined Contributions)' scenario assumes that countries adhere to current NDC commitments, leading to moderate warming. 6) The 'Current Policies' scenario assumes that existing environmental policies are continued, resulting in higher emissions and climate warming. Finally, 7) The 'Fragmented World' scenario assumes that a lack of global coordination leads to uneven and insufficient climate action.

Based on these assumptions, the NGFS provides predictions on climate and macroeconomic variables for each of the seven scenarios at global and regional levels. The predictions for the global economy under these scenarios are presented in Table 1. The environmental variables predicted in Table 1 are used as parameters in

[4] Appendix B shows the details of seven NGFS scenarios including the assumptions of the policy regimes and the predicted environmental and macroeconomic features.

estimating the impacts of shocks in GVC participation, cross-border externalities of carbon emissions, the policy weight of environmental damages in monetary policy, and the effects of cross-border externalities and emission abatement costs on environmental policy coordination in the following sections.

Table 1. The Seven NGFS Scenarios at the Global Level

Scenario	GDP Growth (2050, %)	Productivity Loss Due to Climate Change (2050, %)	Carbon Emissions (2050, $MtCO_2$)	Temperature Increase (2100, °C)	Physical Risk (Extreme Events)
Net Zero 2050	+2.3%	0.4%	1,800	1.4°C	Low
Below 2°C	+1.9%	0.8%	2,400	1.7°C	Low-Moderate
Low Demand	+2.1%	0.6%	1,700	1.3°C	Low
Delayed Transition	+1.4%	1.8%	2,900	2.0°C	Moderate
NDCs	+0.9%	2.3%	3,400	2.5°C	Moderate-High
Current Policies	+0.4%	3.2%	3,900	2.8°C	High
Fragmented World	-0.1%	3.8%	4,800	3.1°C	High

Source: NGFS Climate Scenarios Technical Documentation V. 4.2, NGFS Scenarios for central banks and supervisors (2024)

3.2 Macroeconomic Impacts of GVC Participation Shocks on Economic Performances

This section examines the macroeconomic impacts of shocks in GVC participation, specifically focusing on a 1 percent increase in the share of imported intermediate goods used in production technologies.

3.2.1 Macroeconomic Impacts of GVC Participation Shocks Based on NGFS Productivity Scenarios

In the NGFS scenarios, environmental regimes with higher policy coordination and lower pollution—such as 'Net Zero 2050' and 'Low Demand'—experience minimal productivity losses due to climate change, estimated at 0.4% and 0.6%, respectively. Conversely, regimes with higher pollution and looser environmental policies, such as the 'Fragmented World' scenario, show significantly greater productivity loss, reaching up to 3.8%, as detailed in Table 1.

Based on the NGFS scenarios, a 1% increase in dependence on imported intermediate goods—indicating deeper backward GVC participation—results in GDP shocks, as shown in Figures 1 and 2. In the 'Net Zero 2050' scenario, all major parties are expected to implement stringent environmental policies, leading to an estimated productivity loss of -0.004%, resulting in a productivity parameter of 0.996. Similar productivity values are calculated for the six other scenarios.

The impulse response function (IRF) analysis over 100 periods shows that the initial impacts of the GVC shock on the economic growth rate range from -0.084% to -0.088%, eventually converging to the original equilibrium over time, with minimal differences across the seven scenarios. However, the differences between the scenarios become more evident in the IRF analysis over 20 periods. The 'Fragmented World' scenario exhibits the most significant negative impact on GDP and output, while the 'Net Zero 2050' scenario shows the least impact. As the analysis extends to 100 periods, the negative shocks gradually dissipate across all scenarios, with GDP in each ultimately converging to its original state, as illustrated in Figures 1 and 2.

Figure 1. Impacts of GVC Participation Shock (ε_γ) on GDP ($y_{d,t}$) across NGFS Scenarios over 100 Periods

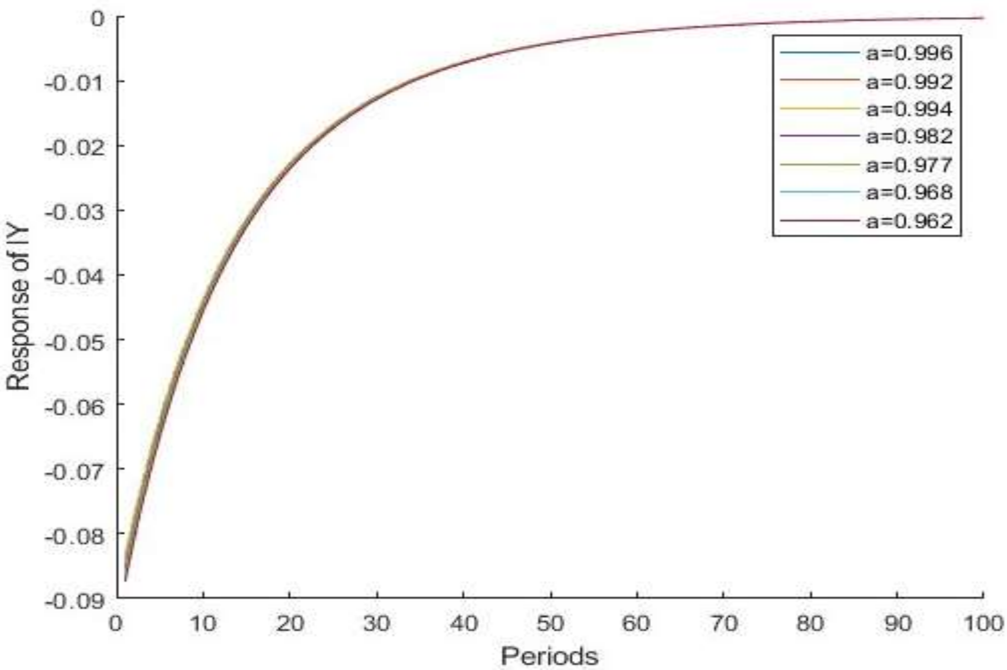
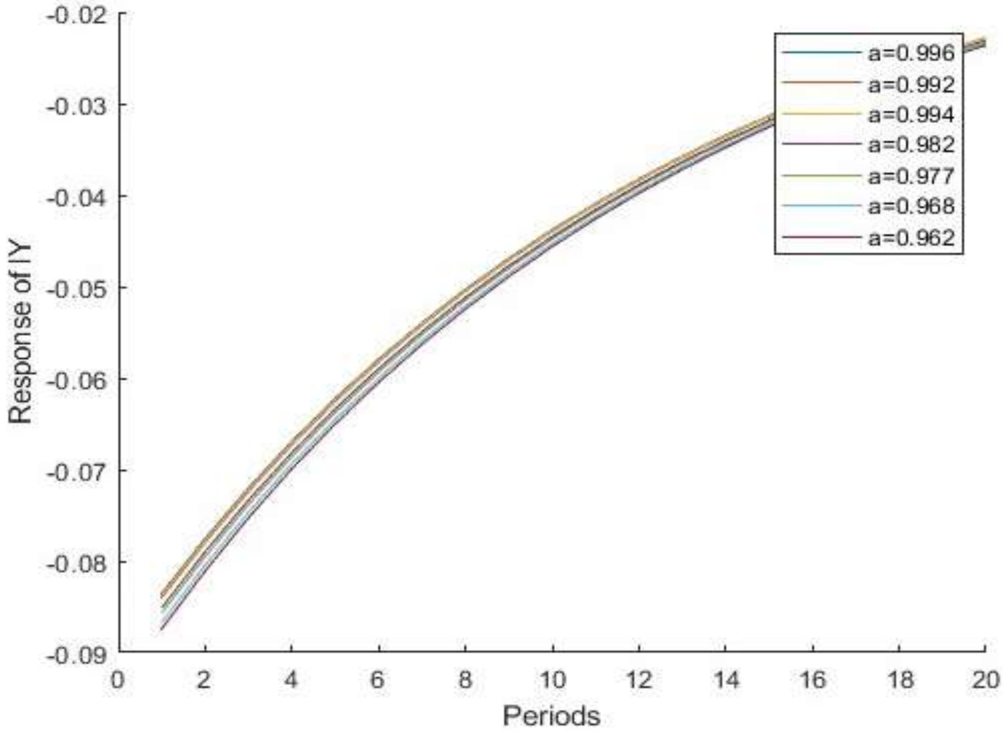


Figure 2: Impacts of GVC Participation Shock (ε_γ) on GDP ($y_{d,t}$) across NGFS Scenarios over 20 Periods



While the scale of GVC shock impacts on economic growth generally aligns with the level of environmental coordination—evidenced by more pronounced growth reductions in less coordinated, more polluted scenarios like 'Fragmented World' compared to more coordinated, less polluted ones like 'Net Zero 2050'—the overall magnitude of difference remains limited. This indicates that dependency on imported intermediate goods has a contained effect on economic growth, as long as GVC dependency remains within manageable levels, as assumed in the model. However, if dependency were to exceed a certain threshold, the negative impact on economic growth could be substantially greater than current estimates suggest.

3.2.2 Impacts of GVC Participation Shocks on Capital Formation Based on NGFS Scenarios of Carbon Emissions

The NGFS scenarios also provide carbon emission levels for seven scenarios, measured in metric tons of CO_2 per million US dollars of GDP. Carbon intensities as a percentage of value are then calculated using the projected average carbon price of US$200 per ton in 2050, as shown in Table 2. [5]

[5] Carbon intensity in this paper is defined as the value of carbon dioxide (CO_2) emissions per GDP, which means the carbon cost for producing unit of output or economic activity. It is commonly used as a measure of the environmental impact of economic activity including industrial processes. The

Table 2. NGFS Scenarios on Expected Carbon Emissions per Million US Dollars >

NGFS Scenarios	Expected Carbon Emissions per Million US Dollars of GDP (2050)	Expected Carbon Intensity (% of value, 2050)
Net Zero 2050	55tCO_2	0.011
Below 2°C	85tCO_2	0.017
Low Demand	70tCO_2	0.014
Delayed Transition	100tCO_2	0.020
NDCs (Nationally Determined Contributions)	175tCO_2	0.035
Current Policies	200tCO_2	0.040
Fragmented World	190tCO_2	0.038

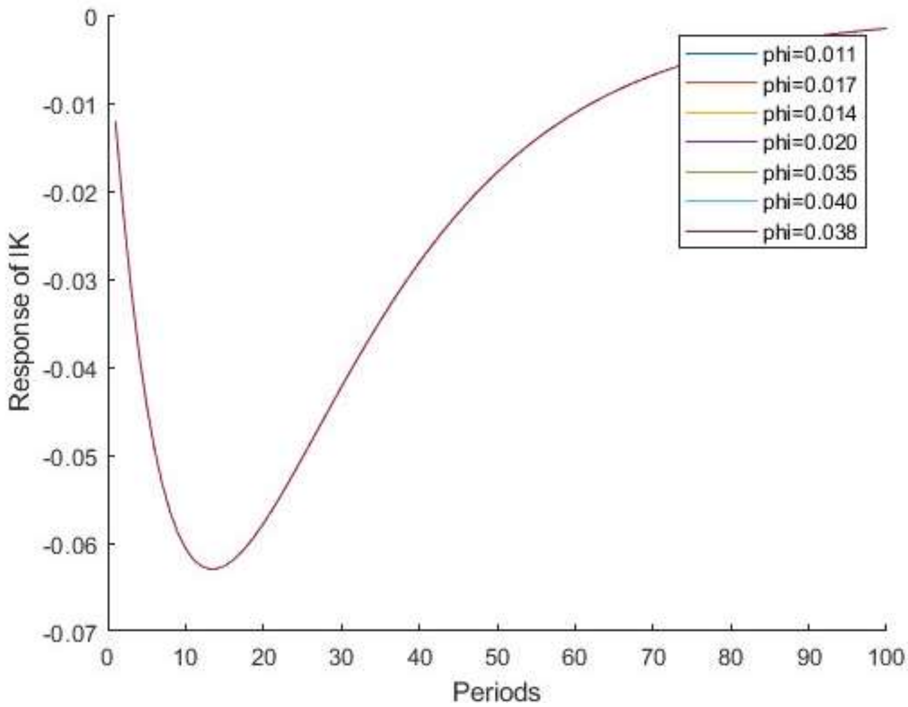
Source: NGFS Climate Scenarios Technical Documentation V. 4.2, NGFS Scenarios for central banks and supervisors (2024)

Based on the NGFS scenarios on carbon intensity, the impulse response analysis of capital formation, K, in response to GVC shocks shows that a 1% increase in dependence on imported intermediate goods—indicating deeper backward GVC participation—leads to a gradual decrease in domestic capital formation of -0.063% until the 13th period after the GVC shock, followed by a gradual recovery, as shown in Figure 2. The increased dependence on imported intermediate goods substitutes for domestic capital formation, resulting in a negative impact on the domestic growth rate, as illustrated in Figure 1.

The variation in impacts of GVC shocks on capital formation across seven NGFS scenarios remains fairly limited, as shown in Figure 2, primarily because the rate at which domestic capital is substituted by imported intermediate goods is not significantly influenced by differences in carbon intensity among the various scenario regimes. However, regimes characterized by lower pollution and higher coordination exhibit slightly milder negative impacts.

formula is given as: $\text{Carbon Intensity} = \frac{CO_2 \text{ emissions (tons)} \times \text{Carbon price per ton}}{\text{GDP (in million US Dollars)}}$.

Figure 2. Impacts of GVC Shock (ε_γ) on Domestic Capital Formation ($K_{d,t}$) across NGFS Scenarios



3.3 Impacts of Cross-Border Externalities of Climate Change on Macroeconomic Performances

The impacts of climate change on macroeconomic performance are significantly influenced by the pattern and strength of cross-border externalities. In this model, cross-border externalities are measured by the spillover effects of foreign carbon emissions on domestic productivity, which declines due to imported carbon emissions. Figure 3 shows that a 1% increase in the cross-border externality of foreign carbon emissions reduces GDP by 1.22E-6% in the 'Current Policies' scenario and by 0.33E-6% in the 'Net Zero 2050' scenario by the 12th period after the initial shock. Subsequently, the GDP growth rate gradually recovers to its initial state. The NGFS scenarios assuming more active policy responses to climate change (Net Zero 2050, Below 2°C, Low Demand, Delayed Transition) show a relatively limited negative impact on economic growth due to externality shocks, compared to the less coordinated scenarios (Current Policies, NDCs, and Fragmented World).

Figure 3. Impacts of Foreign Emission Externality Shock (ε_{γ_u}) on GDP ($y_{d,t}$) across NGFS Scenarios

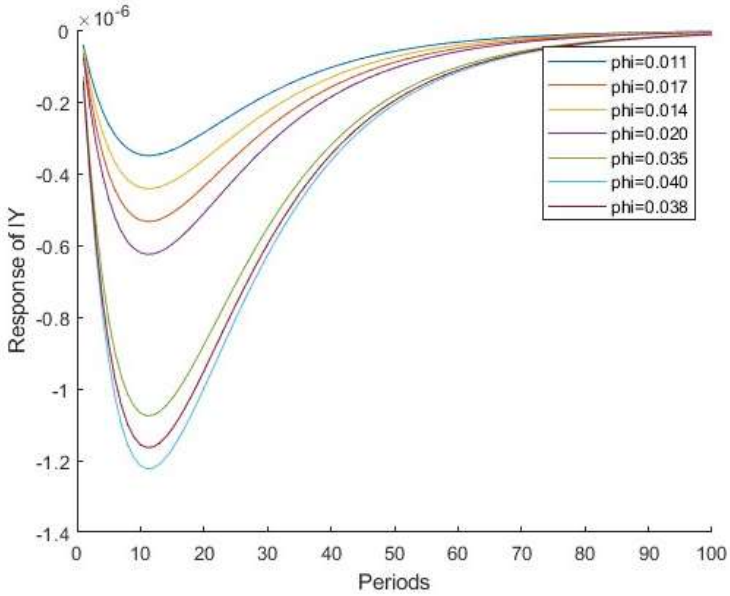


Figure 4 illustrates the impact of a 1% increase in the externality of foreign emissions on domestic consumption. In the NGFS 'Current Policies' scenario, which assumes minimal environmental policy efforts, consumption is most affected, decreasing by 3.92E-7% at the 20th period (approximately 5 years) after the initial externality shock from foreign emissions. This significant decline is primarily driven by the greater negative productivity shock associated with emissions in more polluted regimes. Over time, the negative impact on consumption diminishes, eventually converging to the baseline level. In contrast, under the 'Net Zero 2050' scenario, domestic consumption decreases by 1.09E-7% by the 20th period before gradually recovering to its original level.

Following the initial externality shock from foreign emissions, consumption declines over the first 20 periods due to multiplier effects from the negative productivity shock.

Similar to the impacts on the GDP growth rate, the effects on consumption reveal two distinct patterns: scenarios with relatively active environmental efforts (Net Zero 2050, Below 2°C, Low Demand, Delayed Transition) experience limited negative impacts on consumption, while the less coordinated scenarios (Current Policies, NDCs, and Fragmented World) undergo more pronounced negative impacts on domestic consumption.

Figure 4. Impacts of Foreign Emission Externality Shock (ε_{γ_u}) on Consumption (C_t) across NGFS Scenarios

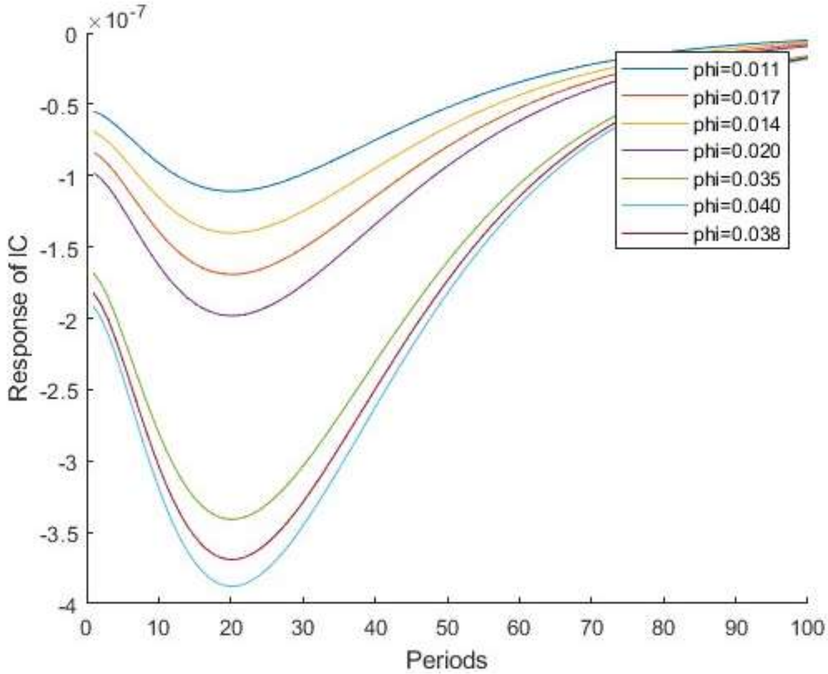
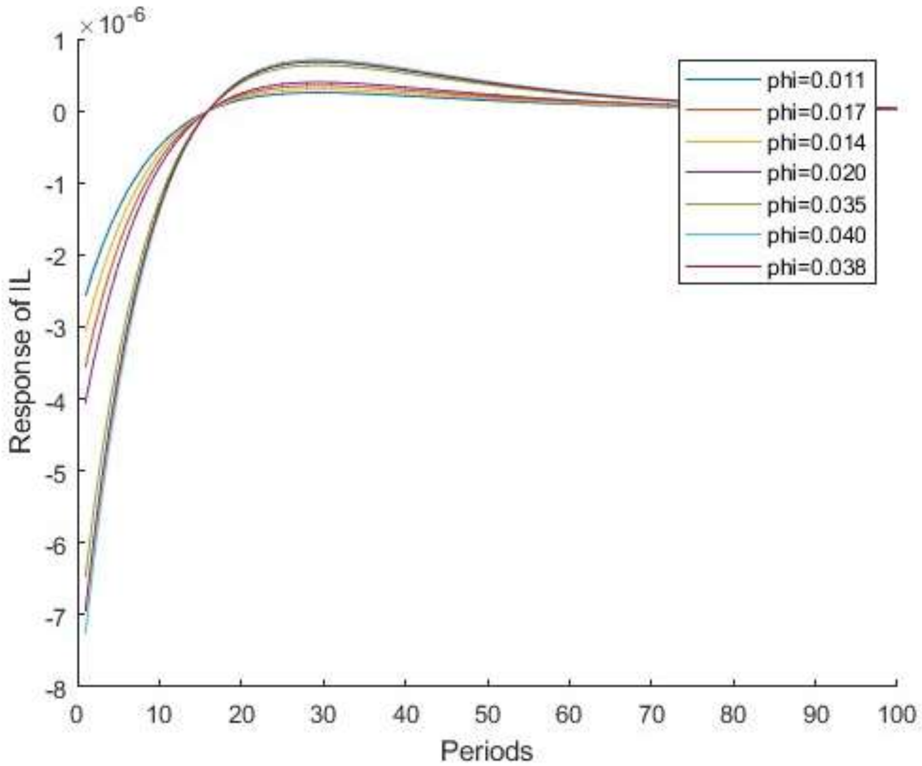


Figure 5 shows that a foreign carbon externality shock causes an initial drop in labor employment across all seven NGFS scenarios. In the most polluted scenario, i.e., 'Current Policies,' labor employment experiences the largest decline, dropping by 0.006% immediately after the shock, while in the least polluted scenario, 'Net Zero 2050,' it declines by 0.0019%. However, because more polluted regimes in the NGFS scenarios enforce less stringent environmental regulations and have looser emission abatement efforts, the recovery in labor employment is faster than in less polluted regimes, where more stringent and costly environmental regulations are in place.

Consequently, after a critical period, the growth rate of labor employment in more polluted regimes surpasses its original level before the shock. Additionally, around the 15th period after the shock, the growth rate of employment in more polluted regimes surpasses that of less polluted regimes, mainly due to lower transition costs—specifically, less stringent environmental regulations and the reduced costs associated with emission abatement efforts.

Figure 5. Impacts of Foreign Emission Externality Shock (ε_{γ_u})
on Labor Employment ($L_{d,t}$) across NGFS scenarios



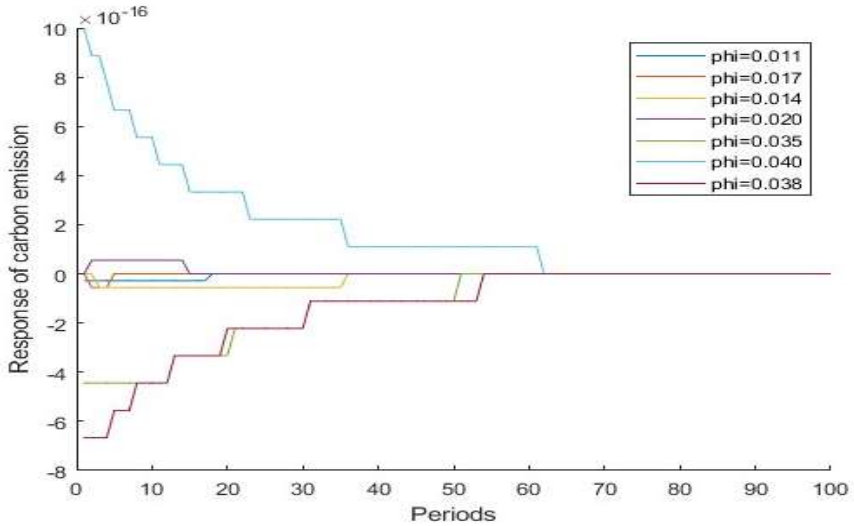
3.4 Impacts of Environmental Considerations in Monetary Policy

To examine the effects of monetary policymakers' emphasis on environmental damage on macroeconomic performances and carbon emissions, we analyze the impact of a shock to the policy weight assigned to carbon emissions within monetary policy, using stochastic shocks in χ_{D_d}, i.e., $\varepsilon_{\chi_{D_d}}$. Price rigidity is introduced through Calvo pricing to assess the effects of monetary policies, alongside an extended Taylor rule that incorporates policymakers' concerns about carbon emissions.

Figure 6 illustrates that a 1% increase in the policy weight on carbon emissions within monetary policy has a limited impact on changes in carbon emissions, with values ranging from -6.72E-16% to 9.98E-16%. Notably, NGFS scenarios representing more coordinated and less polluted regimes—such as 'Net Zero 2050,' 'Below 2°C,' 'Low Demand,' and 'Delayed Transition'—show minimal impact on carbon emissions. In contrast, scenarios characterized by less coordination and higher pollution, including 'Current Policies,' 'Fragmented World,' and 'NDCs (Nationally Determined Contributions),' exhibit more pronounced and distinct impacts on carbon emissions.

A notable aspect is observed in the 'Current Policies' scenario, where limited flexibility in environmental policy adjustments results in a continuation of existing policies with minimal coordination. In this context, an increased policy weight on carbon emissions in monetary policy initially leads to higher emissions, as polluting firms respond to interest rate pressures without complementary environmental policies to curb emissions. Conversely, the 'Fragmented World' and 'NDCs' scenarios exhibit an opposite pattern: relatively lower transition costs enable these regimes to adapt more flexibly. In the Fragmented World scenario, this flexibility results in an initial carbon emissions reduction of -6.72E-16%, a sharper drop than in other NGFS scenarios, although the overall magnitude remains limited. Overall, while the seven NGFS scenarios reveal variations in carbon emissions in response to an increased policy weight on emissions in monetary policy, the impact scale remains relatively small.

Figure 6: Impacts of Environmental Policy Weight Shock in Monetary Policy ($\varepsilon_{\chi_{D_d}}$) on Carbon Emissions ($M_{d,t}$) across NGFS Scenarios



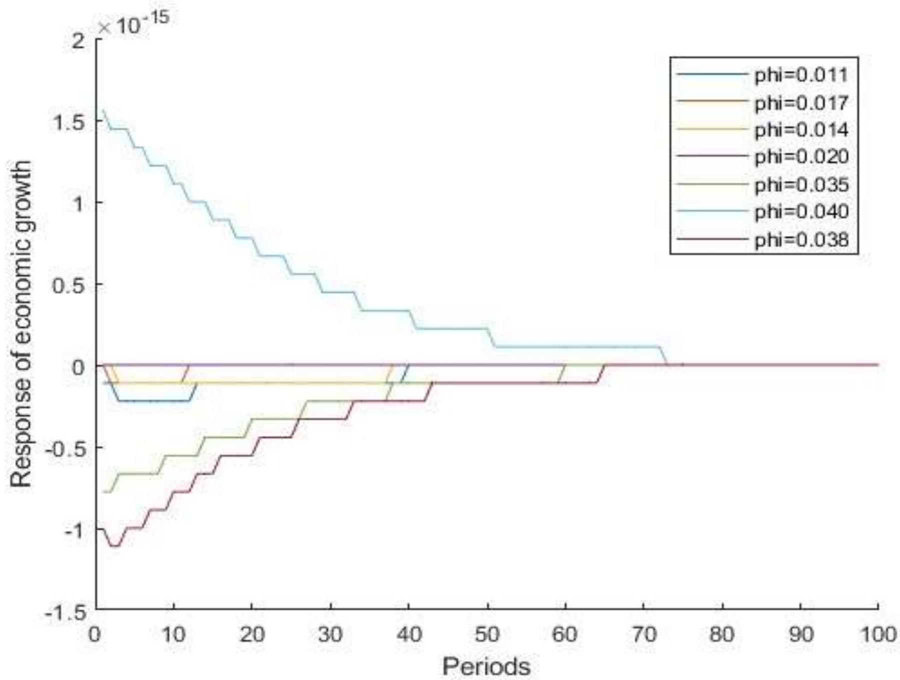
Although the overall scale of impact remains fairly limited, the results reveal important policy implications: monetary policy alone may trigger unintended side effects in reducing carbon emissions, particularly in less coordinated, more polluted NGFS scenarios. This finding aligns with a fundamental policy principle that the most effective approach is direct intervention with minimal indirect effects. In this context, it's notable that monetary policy represents an indirect approach to managing carbon emissions, carrying a high potential for unintended side effects. Therefore, when central banks address environmental concerns, policy actions should be closely coordinated with direct measures such as carbon pricing.

Figure 7 shows that when the policy weight on carbon emissions in monetary policy (χ_{D_u}) is increased by 1%, the impact on economic growth also remains limited, ranging from -1.16E-15% to 1.58E-15%. This reflects the constrained effect on carbon emissions observed earlier. Similar to the patterns in carbon emissions, NGFS scenarios with more coordinated, less polluted regimes (Net Zero 2050,' 'Below 2°C,' 'Low Demand,' and 'Delayed Transition') show minimal impact on economic growth. In contrast, the less coordinated and more polluted regimes (Current Policies,' 'Fragmented World,' and 'NDCs') exhibit relatively amplified and more variable impacts on economic growth.

In the case of the 'Current Policies' scenario, increasing the policy weight on carbon emissions in monetary policy initially leads to a limited increase in economic growth (1.58E-15%), as firms respond to interest rate changes with minimal efforts to reduce emissions, resulting in increased output without significant pollution abatement. On the other hand, the 'Fragmented World' and 'NDCs' scenarios display an opposite pattern, with lower transition costs allowing for greater flexibility. Thus, the 'NDCs' scenario shows an initial GDP drop of -3.89E-15%, though the overall effect remains minor.

In summary, while the scale of impact remains limited, the findings underscore key policy implications: relying solely on monetary policy could inadvertently result in economic downturns in less coordinated, more polluted regimes. This suggests that, even as central banks become more aware of climate change impacts, monetary policy alone is not an ideal tool for managing carbon emissions due to its indirect side effects. Carbon pricing policies should be prioritized as direct interventions, while monetary policy should be seen as a secondary measure implemented in close coordination with direct environmental policies.

Figure 7: Impacts of Environmental Policy Weight Shock in Monetary Policy ($\varepsilon_{\chi_{D_d}}$) on GDP ($y_{d,t}$) across NGFS Scenarios



3.5 Macroeconomic Impacts of Cross-Border Environmental Policy Complementarity

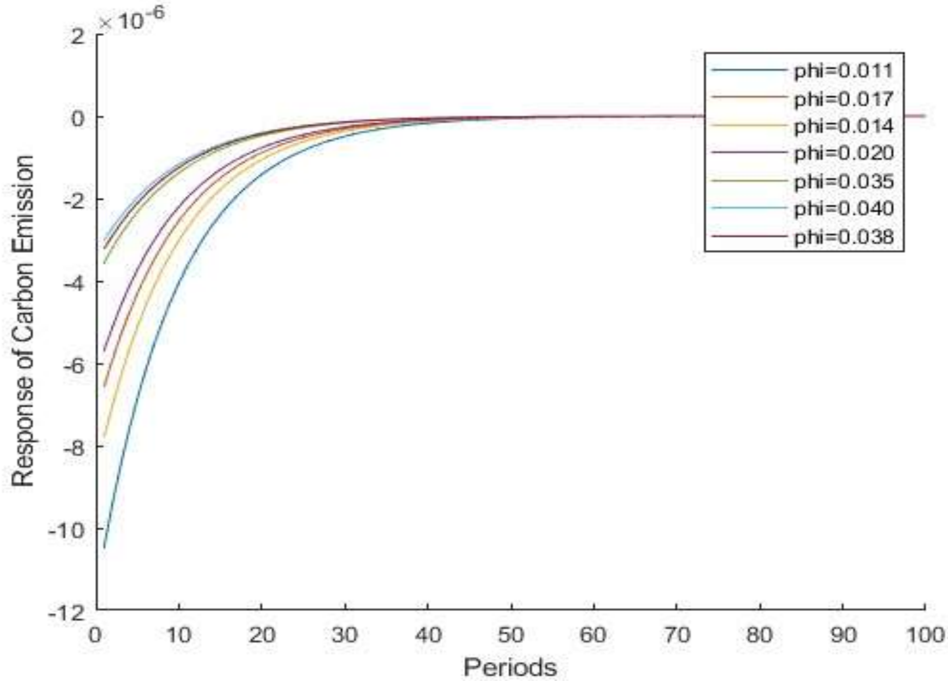
The degree of international coordination in environmental policy is the primary factor distinguishing the seven NGFS environmental scenarios. This section examines the macroeconomic impacts of increased complementarity in cross-border carbon tax policies. In the model, a domestic carbon tax policy can reduce foreign carbon emissions when it complements foreign carbon tax policies, represented by the variable ‘ $c_{d,u,t}$ ’. We analyze the macroeconomic impact of a 1 percent increase in cross-border policy complementarity using a conservative empirical estimate of this complementarity from Fournier et al. (2024).[6]

Figure 8 shows that a 1 percent increase in cross-border carbon tax policy complementarity initially reduces carbon emissions by 10.38E-6% in the ‘Net Zero 2050’ scenario, while the reduction is limited to 2.98E-6% in the ‘Current Policies’ scenario. In the NGFS scenarios with higher coordination and lower pollution, such as ‘Net Zero 2020,’ ‘Below 2°C,’ ‘Low Demand,’ and ‘Delayed Transition,’ increased complementarity in carbon policies amplifies existing commitments to emissions reduction. These economies already have policies aligned toward achieving lower emissions, so enhanced cross-border coordination further reinforces their efforts. Consequently, more coordinated regimes experience a more pronounced reduction in carbon emissions.

On the other hand, in the NGFS scenarios involving less coordinated and more polluting regimes, a positive cross-border policy complementarity shock does not directly increase transition costs. These regimes are less prepared for the rapid adoption of environmental regulations, leading to lower transition costs and greater flexibility for adjustments. As a result, they can more easily continue along traditional, high-carbon production and consumption paths.

[6] The coefficient for the carbon policy cross-border complementary externality is based on Fournier et. al. (2024).

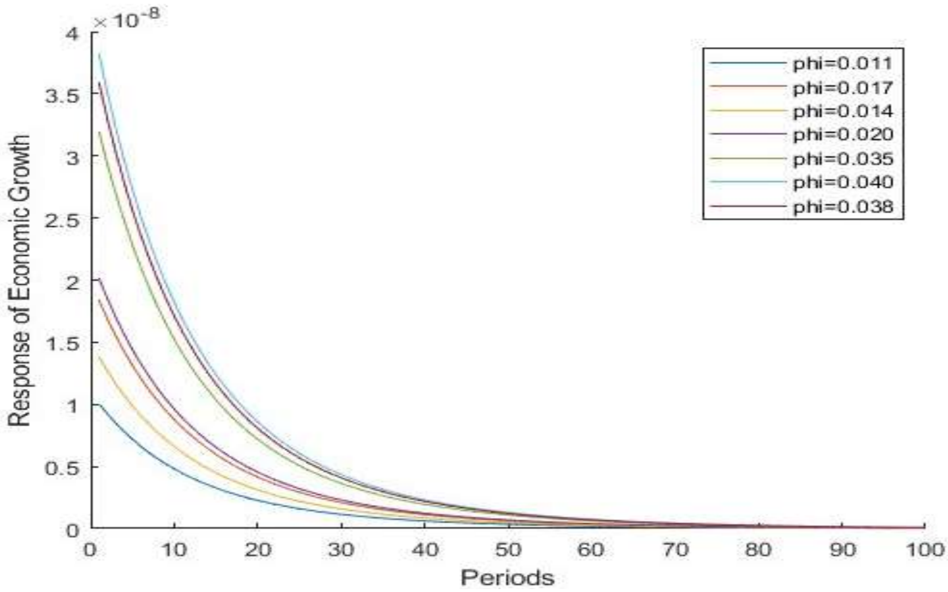
Figure 8. Impact of Cross-Border Carbon Policy Complementarity ($\varepsilon_{c_{d,u,t}}$) on Carbon Emissions ($M_{d,t}$) across NGFS Scenarios



As shown in Figure 8, economies with high pollution levels and low coordination show less immediate emissions reduction, while already-regulated, coordinated regimes are better positioned to absorb these changes and achieve substantial emissions cuts. Economies that are already coordinated and less polluted benefit more from increased policy complementarity, as they can leverage existing infrastructure, technology, and policy frameworks to accelerate emissions reductions. In contrast, high-pollution, low-coordination economies face structural and economic barriers that limit the immediate effectiveness of such policy changes in reducing emissions.

Figure 9 illustrates the impulse response of economic growth to a shock in cross-border carbon policy complementarity across NGFS scenarios. The results show that more polluted, less coordinated NGFS regimes exhibit a higher initial economic growth response to increases in cross-border complementarity of carbon policies. This is because carbon tax policies in these economies tend to be less stringent or misaligned with neighboring economies.

Figure 9. Impacts of Carbon Policy Complementarity Shock ($\varepsilon_{c_{d,u,t}}$)
on GDP ($y_{d,t}$) across NGFS Scenarios



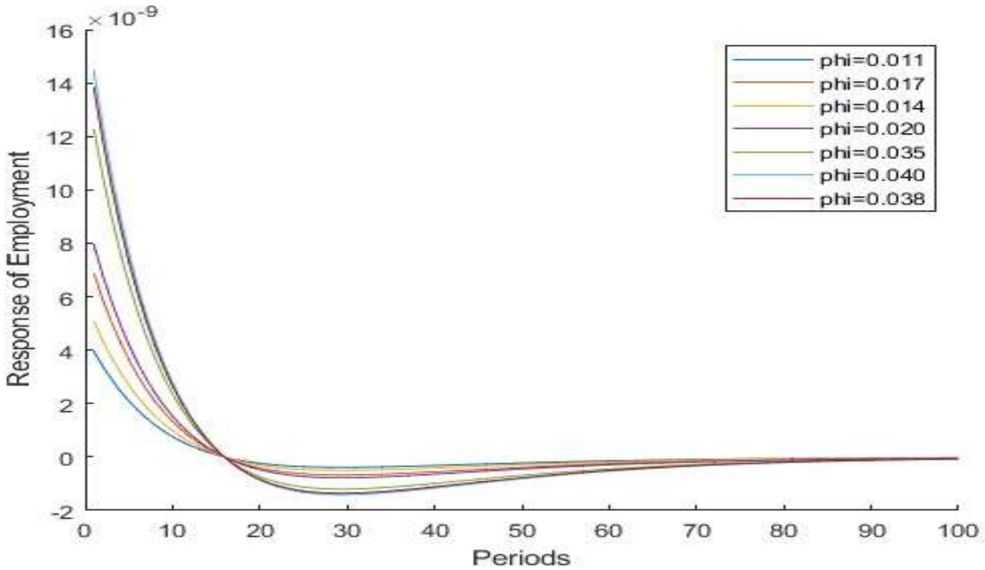
When cross-border policy alignment in carbon taxes improves, these economies experience a stronger initial boost in economic activity, driven by 'catch-up' effects and the greater marginal impact of policy alignment, which reduces trade and investment frictions associated with inconsistent carbon policies. This initial growth boost reflects a more level playing field that lowers trade costs and improves market efficiency—especially beneficial for economies that are less regulated and thus more responsive to international policy shifts. However, this boost may diminish as these economies converge with global standards, leading to a more balanced, long-term growth path across scenarios.

In contrast, economies with high carbon standards and well-coordinated policies may experience smaller growth impacts from increased complementarity, as they are already adapted to stringent environmental policies. These economies have lower potential gains from marginal improvements in cross-border coordination, benefiting from relatively stable policy alignment and facing higher adjustment costs without significant short-term economic gains.

Figure 10 shows the impulse response of labor employment to a shock in cross-border complementarity of carbon tax policies across various NGFS scenarios. Scenarios with less coordinated and more polluted regimes, such as 'Current Policies,' initially experience a spike in employment growth, followed by a subsequent decline after a critical adjustment period. In less coordinated, high-pollution economies, industries tend to be more carbon-intensive. Increased cross-border complementarity in carbon taxes can initially stimulate these economies by attracting investment or trade flows geared toward policy adaptation. This adjustment period may create jobs as firms engage in restructuring, compliance adjustments, or adopt transitional practices to better align with new policies, temporarily boosting employment. Furthermore, less coordinated, high-pollution regimes often delay the full implementation of complementary policies, giving local businesses time to adjust without incurring high compliance costs initially. This approach allows them to capture short-term job gains as they transition without immediately shifting to fully green practices.

After the initial adjustment phase, firms in high-pollution, less coordinated regimes face increasing pressure to fully comply with complementary carbon policies. As compliance costs rise and enforcement strengthens, the transition to a greener economy can lead to frictional unemployment as workers move to less polluting industries. Stricter carbon policies reduce demand for labor in pollution-heavy sectors, resulting in job losses."

Figure 10. Impacts of Cross-Border Carbon Policy Complementarity ($\varepsilon_{c_{d,u,t}}$) on Labor Employment ($L_{d,t}$) across NGFS Scenarios

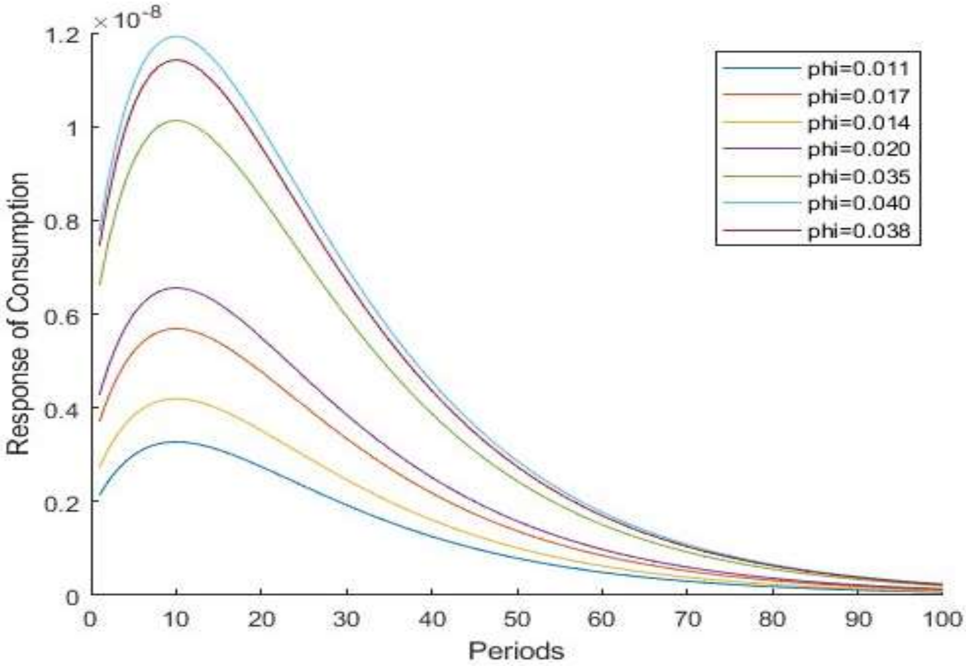


When cross-border carbon policy complementarity increases, coordinated, low-pollution NGFS regimes tend to experience smoother transitions with less employment volatility. Employment remains more stable in these economies, as their labor markets have already adjusted to a greener economy. By the critical adjustment period, coordinated, low-pollution regimes begin to see employment gains from the green transition, as expanding green sectors absorb labor. This sectoral shift is less disruptive, as these economies rely less on pollution-heavy industries and are better prepared for green employment. The critical period thus marks a turning point where the initial employment advantages in high-pollution, less coordinated regimes diminish, while more structurally adjusted, low-pollution economies start benefiting from stable or positive employment growth.

Figure 11 illustrates how consumption responds to a shock in the cross-border carbon policy complementarity across NGFS scenarios. In scenarios such as 'Current

Policies' with lower coordination and higher pollution, the response in consumption initially peaks higher than in more coordinated scenarios. For high-pollution regimes, less aggressive carbon policies would reduce immediate compliance costs for firms and households, resulting in a temporary increase in consumption. Additionally, these economies may benefit from trade or investment from other regions with stricter regulations, creating a short-term positive spillover effect on consumption.

Figure 11. Impacts of Cross-Border Carbon Policy Complementarity Shock ($\varepsilon_{c_{d,u,t}}$) on Consumption (C_t) across NGFS Scenarios



The decline in consumption growth after the peak might reflect the longer-term impact of weak carbon policies, as environmental degradation or climate risks start to offset the short-term consumption gains. As cross-border carbon policies become more aligned, even less coordinated regions start facing indirect pressures through trade, investment, or policy harmonization mechanisms, slowly reducing consumption growth over time. Additionally, the gradual policy alignment increases costs associated with adjusting to a more sustainable trajectory, ultimately dampening consumption.

The fact that less coordinated, more polluted NGFS scenario regimes maintain a higher consumption response even as it declines may reflect that these economies are slower to fully internalize the costs of carbon policies. Economies in highly coordinated regimes, on the other hand, experience immediate adjustments in consumption as stricter policies are implemented earlier, leading to lower consumption growth but more sustainable, long-term outcomes. Essentially, more coordinated economies may be experiencing the effects of front-loaded climate investments that reduce consumption growth initially but aim for longer-term stability.

4. Summary and Policy Implications

This paper examined the environmental and macroeconomic impacts of changes in global value chain (GVC) participation, cross-border carbon emission externalities, environmental considerations in monetary policy, and international coordination in environmental policy based on seven NGFS scenarios through an Environmental Dynamic Stochastic General Equilibrium (E-DSGE) model analysis.

The impulse response analysis of the EDSGE model reveals several key insights: i) Increased Global Value Chain (GVC) participation—reflected in a higher dependency on imported intermediate goods—dampens domestic capital formation and economic growth, with the 'Delayed Transition' scenario experiencing a slightly greater negative impact. ii) Higher cross-border carbon emission externality reduces domestic consumption, employment, and economic growth, with these effects amplified in more polluted regimes during the initial stage, primarily due to larger negative productivity shocks. iii) Greater environmental considerations in monetary policy have minimal impacts on less polluted regimes, such as those in the 'Net Zero 2050' scenario. In contrast, more polluted regimes face more pronounced effects, including increased economic volatility. iv) Stronger cross-border environmental policy complementarity initially benefits more polluted regimes due to lower transition costs, but in the long-term, delayed and accumulated adjustment costs give adverse impacts on these regimes.

Our findings suggest that more reserved approaches, such as the 'Delayed Transition,' may offer short-term benefits, including quicker recovery from negative productivity shocks and reduced adverse impacts from heightened environmental policy complementarity due to lower transition costs. However, these short-term advantages are outweighed by higher long-term transition costs. The results indicate that a more active adoption of 'Net Zero 2050' policy directions is necessary to foster a smoother transition for South Korea's corporate sector. In addition, while the central bank's heightened focus on environmental issues is reasonable and understandable, direct monetary policy measures to address environmental problems have proven less effective. This is primarily due to potential side effects: indirect policy interventions may lead to substantial deadweight losses associated with contractionary monetary policy aimed at reducing carbon emissions.

This study may offer a pioneering analysis of cross-border externalities and policy complementarity in the context of environmental policy. Future research should further refine model parameters for different economic structures and DSGE scenarios to increase the generalizability of findings. Moreover, the current model, which assumes foreign carbon emissions are solely influenced by domestic carbon policies, should be extended to incorporate major foreign macroeconomic variables as endogenous elements, providing a more nuanced characterization of foreign economies.

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Appendix A. Backgrounds and Features of Operation of NGFS

A.1 Backgrounds of the Formation of NGFS and NGFS Scenarios

The NGFS (Network for Greening the Financial System) was launched in December 2017 during the One Planet Summit in Paris, a response to growing recognition that climate change poses significant risks to global financial stability. The network was initiated by a group of central banks and financial supervisors who recognized the need for collective action to integrate climate-related risks into financial supervision and central banking.

The formation of the NGFS was driven by the realization that the financial sector needed to play a crucial role in facilitating the transition to a low-carbon economy and managing the risks associated with climate change. These include both physical risks (e.g., damage from extreme weather events) and transition risks (e.g., economic shifts resulting from climate policies).

Key objectives of NGFS: The primary objective of the NGFS is to enhance the role of the financial system in managing climate and environmental risks and to mobilize capital for green and low-carbon investments. The NGFS provides a platform for central banks and financial supervisors to share best practices, conduct joint research, and develop frameworks and methodologies for assessing climate-related financial risks.

Features of NGFS Operations: One of the central activities of the NGFS is to develop and to refine climate-related scenarios. These scenarios help financial institutions assess the impact of different climate policies and physical risks on their portfolios. The NGFS scenarios are developed in collaboration with leading climate modelers and are based on the latest scientific understanding of climate change. They offer a range of possible future pathways, considering various levels of policy action, technological development, and societal changes.

Membership and Collaboration of NGFS: The NGFS started with a small group of founding members but has grown rapidly to include over 100 members and observers, including central banks, financial regulators, and international organizations. As of May, 2024, 141 central banks and supervisors, and 21 observers are joining the NGFS. The network fosters collaboration between its members through working groups focused on specific areas, such as micro-prudential supervision, macro-financial management, and bridging data gaps.

Publications and Guidance: The NGFS regularly publishes reports, technical documents and guidelines to support the integration of climate-related risks into financial supervision and central bank operations. Key publications include guidance on scenario analysis, best practices for green finance, and recommendations for central banks on managing climate risks.

A.2 Relationships between NGFS and Central Banks

Incorporating Climate Risks into Supervision: Central banks are supposed to use NGFS scenarios and guidance to integrate climate-related risks into their supervisory frameworks. This includes assessing the resilience of financial institutions to climate risks and ensuring they have appropriate risk management practices in place.

Scenario Analysis and Stress Testing: Central banks should apply NGFS scenarios in their macroeconomic modeling, stress testing, and risk assessment exercises. This helps evaluate the potential impacts of different climate pathways on the financial system and the broader economy. By conducting scenario analysis, central banks can better understand the potential vulnerabilities in the financial sector and develop strategies to mitigate these risks.

Supporting Green Finance: Central banks are encouraged to promote green finance by supporting the development of sustainable finance markets and integrating environmental considerations into monetary policy operations where appropriate. The NGFS provides a framework for central banks to explore how they can align their own portfolios with sustainability goals and encourage the financial sector to support the transition to a low-carbon economy.

Appendix B. Details of Seven Scenarios of NGFS

The details of seven NGFS scenarios are given in terms of major assumptions of the policies adopted and predictions on economic and physical impacts.

1. Net Zero 2050

This scenario assumes the world takes aggressive and immediate action to reduce greenhouse gas emissions, achieving net-zero emissions by 2050. The scenario aims to limit global warming to 1.5°C by the end of the century, with minimal overshoot. This scenario is characterized by i) Rapid decarbonization across all sectors, ii) significant technological innovation and deployment, particularly in renewable energy, carbon capture, and energy efficiency, iii) a strong policy framework including carbon pricing, regulations, and subsidies for green technologies.

It is predicted that economic impacts include relatively high transition costs upfront but minimized long-term economic damages due to avoided severe climate impacts. Physical impacts predicted include limited physical risks due to effective mitigation of climate change.

2. Below 2°C

This scenario assumes a less aggressive but still coordinated global effort to reduce emissions, aiming to limit global warming to below 2°C by 2100. The pace of transition is slower than in the Net Zero 2050 scenario. This scenario is featured by i) gradual implementation of climate policies and slower technological change compared to Net Zero 2050, ii) moderate carbon pricing and sectoral policies aimed at reducing emissions, iii) gradual phase-out of fossil fuels, with increased reliance on renewables and energy efficiency improvements.

In terms of economic impacts, moderate transition costs are predicted with some industries facing higher costs due to delayed action. In physical impacts, moderate physical risks are expected as some climate impacts are avoided but others remain due to the slower pace of emissions reductions.

3. Low Demand

This scenario assumes a significant reduction in global energy demand due to structural changes in the economy, technological advancements, and behavioral shifts. This leads to a smoother transition with lower emissions. The scenario is featured by i) major reductions in energy demand driven by energy efficiency, digitization, and shifts in consumption patterns, ii) lower reliance on fossil fuels and a faster transition to renewables due to reduced overall energy needs, iii) global temperature rise limited to around 1.5-2°C, depending on the extent of demand reduction.

For economic impacts, lower transition costs are predicted due to reduced energy demand, less pressure on energy infrastructure, and fewer stranded assets. For physical impacts, lower physical risks are expected compared to other scenarios, as reduced demand leads to lower emissions and less severe climate impacts.

4. Delayed Transition

This scenario reflects a delayed global response to climate change, where significant policy action is postponed until after 2030. As a result, emissions reductions need to be much more aggressive later, leading to higher transition costs. This case is characterized by i) slow initial response with little to no emission reduction efforts before 2030, ii) sudden and sharp policy changes in the post-2030 periods, resulting in rapid decarbonization efforts, iii) higher economic disruption due to the need for rapid changes in energy infrastructure and industrial processes.

For economic impacts, high transition costs are expected due to the sudden shift in policies, leading to stranded assets and economic dislocation in carbon-intensive sectors. For physical impacts, higher physical risks are predicted in the near term, with some risks of overshooting climate targets before emissions are brought under control.

5. NDCs (Nationally Determined Contributions)

This scenario is based on the climate commitments made by countries under the Paris Agreement, known as Nationally Determined Contributions (NDCs). These commitments are assumed to be implemented, but they fall short of the goals needed to limit global warming to well below 2°C. This case is characterized by i) climate action aligned with current NDCs, leading to a global temperature rise of approximately 2.5-3°C by 2100, ii) moderate policy interventions with varying levels of ambition among countries, iii) continued reliance on fossil fuels with some expansion of renewable energy and energy efficiency measures. For economic impacts, moderate transition costs are expected with uneven impacts across regions and sectors. For physical impacts, significant physical risks are predicted due to insufficient global action, leading to increased frequency and severity of extreme weather events.

6. Current Policies

This scenario assumes no further strengthening of climate policies beyond those already in place. It represents a business-as-usual pathway where the world continues on its current trajectory. It is featured by i) limited additional policy action beyond what is currently implemented or announced, ii) continued growth in fossil fuel use with gradual increases in renewable energy and energy efficiency, iii) global temperature rise of around 3-3.5°C by 2100.

For economic impacts, relatively low transition costs are expected in the short term but higher long-term economic damages due to severe climate impacts. For physical impacts, high physical risks are predicted with severe impacts from climate change, including extreme weather events, sea-level rise, and disruptions to ecosystems.

7. Fragmented World

This scenario envisions a world where climate policies are implemented unevenly across regions. Some countries or regions take strong action, while others lag behind, leading to a fragmented global response. This scenario is featured by i) regional differences in climate policy ambition and implementation, ii) limited global cooperation, resulting in varying carbon prices and regulatory environments, iii) continued reliance on fossil fuels in regions with weaker policies, while other regions transition to greener energy sources.

In terms of economic impacts, mixed economic outcomes are expected with high transition costs in regions with strong policies and competitive disadvantages for regions with weaker policies. For physical impacts, high physical risks are predicted globally, as fragmented action is insufficient to prevent significant climate impacts.

Appendix C. Steady State Equilibrium of the Model and Parameters

C.1 Parameter Values

$\alpha = 0.3$ // Labor's output elasticity
$\beta_1 = 0.65$ // Capital's output elasticity
$\gamma = 1 - \alpha - \beta$ // Imported intermediate goods' output elasticity
$\beta = 0.99$ // Discount factor
$\delta = 0.025$ // Capital depreciation rate
$\phi_0 = 1$ // Frisch labor supply elasticity
$\sigma = 1$ // Inverse of the elasticity of intertemporal substitution for consumption
$\varphi = 1$ // Carbon intensity
$\gamma_0 = 1.3950\text{e-}9$ // Parameter of the constant in the environmental damage function
$\gamma_1 = 6.6722\text{e-}6;$ // Parameter of the linear term in the environmental damage function
$\gamma_2 = 0.001$ // Parameter of the square term in the environmental damage function
$\phi_1 = 0.1850$ // Emission abatement cost parameter
$\phi_2 = 2.8$ // Cost parameter as an exponent of abatement effort
$\gamma_{u,t} = 0.4$ // Parameter of cross-border externality of foreign emission
$\theta = 0.75$ // Calvo pricing rigidity share
$\varepsilon = 0.75$ //Elasticity of substitution in Calvo price rigidity term
$\eta = \frac{(1-\theta)(1-\beta\theta)}{\theta}$ // Parameter for the slope of New Keynesian Phillips Curve (NKPC)
$\chi_{\Pi_u} = 1.5$ // Taylor rule inflation weight
$\chi_{Y_u} = 0.5$ // Taylor rule output gap weight
$\chi_{D_u} = 0.3$ // Taylor rule emissions weight steady state value

C.2 Steady State Values

λ = 0.676122589360656; //Steady state shadow price of carbon emissions
C = 1.479021727325519; //Steady state consumption
W = 1.389615689635382; //Steady state wage rate
L = 0.939550558292468; //Steady state labor employment
R = 0.03; //Steady state real interest rate
K = 17.167345501345505; //Steady state capital
I = 0.429183637533638; //Steady state investment
Y = 2.008637226167533; //Steady state production
P = 1; //Steady state price level
γ = 0.05; //Steady state output elasticity of imported intermediate goods
$y_{u,t}$ = 0.100431861308376; //Steady state foreign intermediate goods
M_d = max(1e-4, 0.02008637226167533); // Steady state emissions
D_d = max(1e-6, 4.03462350634600e-06); // Steady state environmental damages
e_d = max(0.01, 0.01); //Steady state emission abatement efforts
τ_d = max(0.05, abs($\phi_1\phi_2 e_d^{\phi_2 - 1} / \varphi$)); //Steady state carbon tax