Assessment of Global Emissions and Economic Welfare Impacts of U.S. Withdrawal from the Paris Agreement: A CGE–Machine Learning Analysis

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Abstract

This study aims to assess the global economic and environmental policy implications of the U.S. withdrawal from the Paris Agreement. Specifically, we analyze its impact on U.S. CO_2 emissions, sectoral shifts, GDP, welfare and trade and the spillover effects on U.S. major trading partner economies, such as the European Union and China. With the U.S. withdrawal in 2025, the abatement of its emissions became uncertain and needs to be reassessed to understand how expected reduction in U.S. and global emissions will differ from the Paris Agreement committed levels within the next decade. Therefore, we compare economic and environmental policy implications of U.S. continued participation in Paris commitments with two alternative withdrawal scenarios, one assuming historically observed emissions trends, and the other one employing forecasted emissions trajectories using Bayesian Ridge Regression.

The results indicate significant policy trade-offs. U.S. withdrawal reduces domestic abatement costs while shifting adjustment burdens toward remaining participants with a potential destabilization of multilateral agreements. This emphasizes the need for alternative policies such as coordinated carbon pricing, sectoral agreements, or trade-linked climate clubs. Our findings also indicate that policy evaluations based on solely extrapolation of historic trends may result in inaccurate emissions outcomes following the withdrawal, especially during the periods of rapid technological and structural changes. The results highlight the importance of a robust policy design that explicitly considers uncertainty rather than relies on point forecasts.

JEL classification: C6, E37, Q52, Q56, Q58

Keywords: Paris Agreement, machine learning, CGE model, emissions abatement, welfare effects

1. Introduction

The Paris Agreement, an international treaty, was signed in 2015 by 196 nations to limit global warming and climate change. This study aims to assess the global economic and environmental implications of the U.S. withdrawal from the Paris Agreement. Specifically, we analyze its impact on carbon pricing, emissions trading, and sectoral shifts, with a focus on spillover effects on major trading partners such as the European Union and China. Additionally, we explore whether alternative domestic carbon policies (e.g., state-level initiatives) can mitigate the withdrawal's effects.

According to the United Nations Framework Convention on Climate Change (UNFCCC)[1], the United States would reduce greenhouse gas emissions (GHG) by 61-66% below 2005 levels by 2035 to meet the targets of the Paris Agreement. As shown in Figure 1, this would be in line with the projections of achieving net zero greenhouse gas emissions by 2050. The entire 2035 range is on a straight.

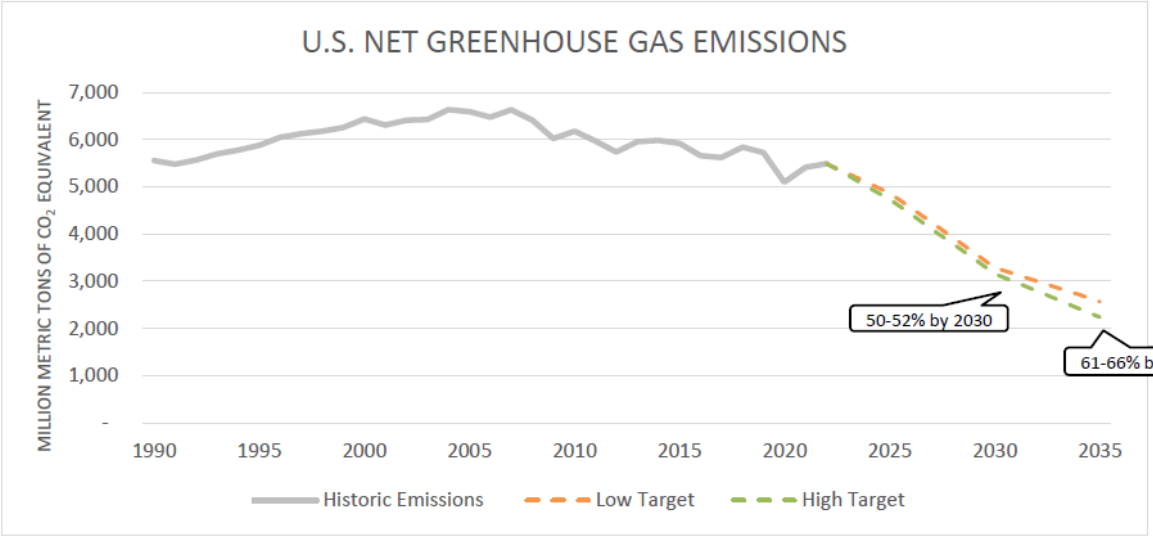


Figure 1. Projected reduction in U.S. GHG emissions by 2050 (source: UNFCCC 2022)

[1] https://unfccc.int/sites/default/files/2024-12/United%20States%202035%20NDC.pdf

To achieve such levels of GHG emissions reduction, short and long-run policy measures should be implemented. There are many economic policy instruments, efficiency improving options and renewable energy options that can be included in the emission reduction measures of each economic sector. Also, long term full decarbonization can be achieved by applying a zero fossil carbon fuels policy. Even with learning and scaling effects, these substitute fuels are expected to be more expensive, and therefore the use of renewable energy options and improvement of energy efficiency will likely play a significant role in the decarbonization of the economy.

To evaluate the impact of U.S. withdrawal from the Paris Agreement in 2025, we consider three counterfactual scenarios. 1) A Baseline Scenario, in which the U.S. remains in the Paris Agreement and follow its Nationally Determined Contribution (NDC) commitments. 2) First withdrawal scenario in which U.S. withdraws from the Paris Agreement and continues to expand oil and gas production leading to potential carbon leakage. 3) Second withdrawal scenario in which we employ machine learning algorithm, Bayesian Ridge Regression (BRR) to forecast mean CO_2 emissions with greater level of accuracy. Our analysis finds some interesting results. When we assume U.S. emission reduction based on historic pre-Paris Agreement average annual changes (Withdrawal Scenario A), we find that the world emissions decline by about 4.4% with relatively smaller negative changes in the U.S. and world GDP and welfare. However, when we consider critical economic, sectoral, and environmental factors using our machine learning algorithm we find more accurate estimates of expected changes in U.S. (-15.8%) and global (-2.32%) emissions after the U.S. withdrawal from the Paris Agreement. Additionally, we also conduct a Welfare change analysis in, to observe how the U.S. and lobal welfare can be affected under each scenario. We decompose the welfare effects into three aspects, allocative efficiency effects, terms of trade

effects, and investment saving effects. We find minimally negative terms of trade and investment-savings effects observed in all three simulations; however, the negative allocative efficiency effects are significant and identical to the GDP impacts for both the U.S. and global economies.

This paper contributes to the literature by providing a comprehensive assessment of the global economic, environmental, and sectoral impacts of the U.S. withdrawal from the Paris Agreement in 2025 using a novel integration of a global computable general equilibrium (GTAP-E) model with machine learning–based forecasting. Unlike existing studies that rely on historical emissions trends, we employ Bayesian Ridge Regression to generate more accurate projections of U.S. CO_2 emissions by capturing complex interdependencies between economic activity, energy consumption, and environmental dynamics. By combining machine learning with a multi-sectoral global equilibrium model, this study offers policymakers improved tools to evaluate trade-offs between climate change mitigation, economic performance, and international competitiveness.

The rest of the study is structured as follows. Section 2 reviews literature. Section 3 describes the methodology and data. The research results and discussion are presented in Section 4. Section 5 presents the conclusions.

2. Literature Review

While the Paris Agreement is considered successful in addressing climate change, it has faced several setbacks and failures, such as the United States withdrawal in 2017 and 2025. Falkner (2016) discussed the agreement's success by arguing that it breaks new ground in international climate policies, as it allows the parties to set their own carbon emission goals to mitigate global warming. Similarly, Streck et al. (2016) celebrate the agreement's success as it represents a step forward by creating a process of engagement, follow-up, and cooperative action at the global

level. In a follow-up study, Liu et al. (2020) analyzed the Nationally Determined Contribution (NDC) pledges by different countries. They found that if nations achieve their NDC targets, CO_2 emissions will be reduced relative to the baseline but not in absolute terms relative to 2015 levels. Likewise, Vrontisi et al. (2020) assessed the trade implications of NDCs to determine nations' trade implications and competitiveness effects. They found a reduction of global trade activity if NDC targets are achieved, mainly due to a rapid decline in demand for fossil fuels. Zhang et al. (2017) addressed the adverse impact of the U.S. withdrawal from the Paris Agreement by discussing its negative effects on the U.S. reputation in the global forum. They stated that while this withdrawal may not change the development of low-carbon technology, long-term transformation trends will be affected by budget cuts in American climate research and the cancellation of multilateral donations by the U.S. Dai et al. (2017) evaluated the impacts of the U.S. withdrawal from the Paris Agreement on emission space and mitigation cost in China, European Union (EU) and Japan. They found that the failure of the U.S. to honor its NDC will decrease its mitigation cost, while increasing China, EU, and Japan's mitigation costs significantly. Sælen et al. (2020) utilized a novel approach to study how U.S. withdrawal will impact global cooperation and found that the severity of the consequences depends on the reaction of other countries regarding their contribution and promises toward the climate accord. Furthermore, the 2°C goal can still be achieved; however, U.S. withdrawal reduces its chances to less than 0.1%. Okorie and Wesseh Jr. (2023) studied the pertinent question: "Are global carbon emission reductions due to reduced production activities, or are production processes becoming more efficient as less carbon is emitted per unit output due to technical progress?" By utilizing difference-in-difference analysis, they showed that the observed reduction is owing to the global increase in technical progress and production efficiency aimed at in the Paris Agreement. These results underscore the importance of complying with the

Paris climate accord. In another recent study, MacNeil (2025) expresses frustration by stating that, due to its repeated withdrawal and re-engagement, domestic political changes, and obstructionism, U.S. leadership in climate mitigation has become a destabilizing factor in global efforts to curb climate change. The author also encourages the U.S. to make its recent withdrawal permanent so that alternate leadership can emerge. Nong and Siriwardana (2018) quantified the impact of the U.S. withdrawal from the Paris Agreement in 2017 and showed that the U.S. GDP would increase by 1.13%, caused by a 0.78% increase in real private consumption. Moreover, U.S. energy prices would decrease significantly, causing a net increase in the U.S. welfare by $97 billion.

3. Model and Data

In this paper we use the Global Trade Analysis Project Energy (GTAP-E) model and version 11 dataset supplemented with the results of our machine learning model to estimate the direct and indirect economic impacts of U.S. GHG emissions reduction under the Paris Agreement. We use the modal substitution approach and estimated elasticities of transport mode substitution from Avetisyan et al. (2021) to modify the GTAP-E model and allow substitution between different modes of transport in response to changes in relative costs driven by various environmental and economic shocks and improvement in energy efficiency. The CES elasticity of substitution, with a typical value of 0.57 to 2.14, governs modal choice changes in response to variations in the relative cost of different transport modes (Avetisyan 2018; Avetisyan et al. 2021).

In the GTAP model the production structure uses Leontief specification to combine labor, capital, land, and intermediate inputs and it also incorporates the energy substitution nest. The latter is based on the constant elasticity of substitution (CES) formulation where the electricity and

non-electricity goods, and non-electricity commodities are joined. In the next level of the production nesting structure the energy sub-product is combined with capital to generate the capital-energy sub-product. The latter is then combined with other factors using another CES function specification. Finally, at the top level of the production structure the final output is formed by combining the value added and intermediate inputs.

The structure of the household consumption is based on a constant-difference of elasticities (CDE) functional form. In the GTAP model consumption, government spending, and savings are combined through a Cobb-Douglas functional specification to form the household preferences. The structure of the standard GTAP model is summarized in Figure 2.

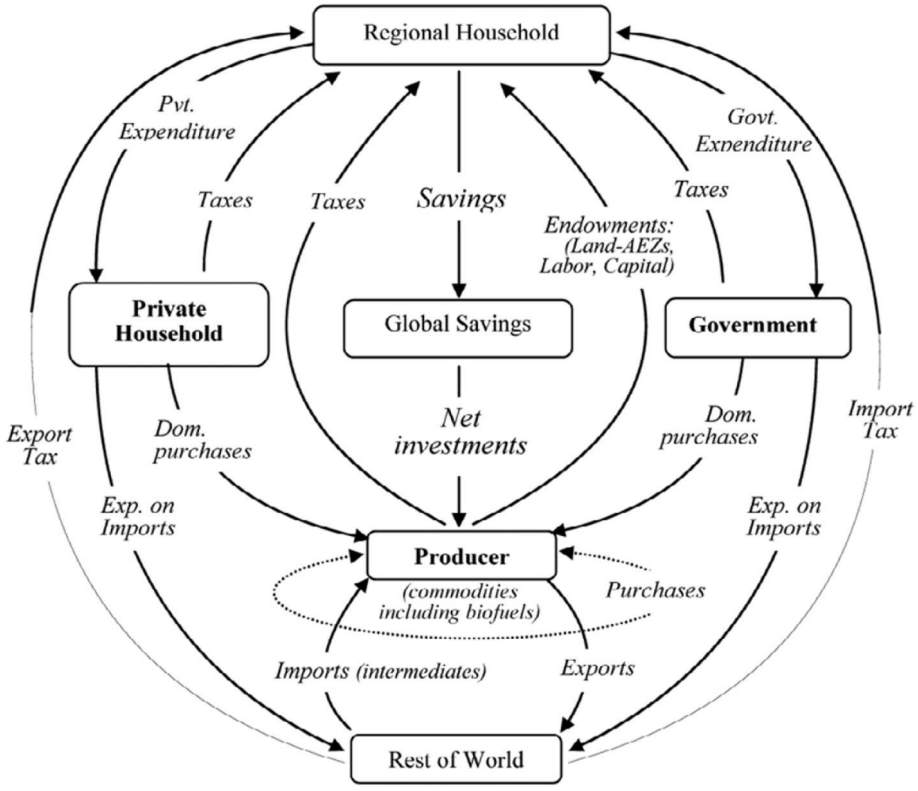


Figure 2. The structure of the standard GTAP model (source: Hertel et al. 2010)

3.1.Scenarios

In our analysis we consider the following three counterfactual scenarios:

1. **Baseline Scenario (Paris Agreement Commitments)** - The U.S. remains in the Paris Agreement and follows its Nationally Determined Contribution (NDC) commitments, aiming to reduce emissions by 61-66% below 2005 levels by 2035.
2. **Withdrawal Scenario A (No Paris Agreement Commitments with historic average 1.6% annual reduction in CO_2 emissions)** - The U.S. withdraws from the Paris Agreement, removing carbon pricing mechanisms and expanding oil and gas production and exports leading to potential carbon leakage.
3. **Withdrawal Scenario B (No Paris Agreement Commitments with forecasted Bayesian Ridge mean CO_2 emissions)** - Capture all critical economic, sectoral, and environmental dynamics by employing machine learning algorithms to generate forecasted Bayesian Ridge mean CO_2 emissions with a greater level of accuracy.

3.2. Machine Learning Model

In this study, we apply Bayesian Ridge Regression (BRR) as a probabilistic supervised machine learning model to project long-term changes in CO_2 emissions. Specifically, we apply our machine learning approach in the *Withdrawal Scenario B*, aiming to capture all critical economic, sectoral, and environmental dynamics by employing machine learning algorithms to generate more accurate forecasts of expected changes in CO_2 emissions. BRR extends classical linear regression by introducing Gaussian priors over the regression coefficients, which helps stabilize estimates when predictors are highly correlated (Bishop et al. 2006; Murphy 2012). Our dataset includes key economic and energy-related variables such as Real GDP, Population, Total Primary Energy Consumption, Total Renewable Energy Consumption, and Natural Gas

Consumption, all of which exhibit strong interdependencies[2]. By incorporating prior information and regularization, BRR provides more robust and reliable coefficient estimates compared to ordinary least squares regression, making it particularly effective in addressing multicollinearity issues (Tipping 2001). Furthermore, BRR produces predictive distributions rather than single-point forecasts, enabling us to quantify uncertainty in the 2035 projections. This capability is especially important for designing evidence-based policy measures and developing effective energy transition strategies.

3.2.1 Model Setup

BRR introduces a Bayesian prior over the regression coefficients to improve estimation stability and handle multicollinearity among predictors. It is particularly well-suited when:

- There are strong correlations among predictors (common in energy and macroeconomic data).
- We need uncertainty quantification for forecasts (e.g., 2035 CO_2 emissions).
- The sample size is moderate but predictors are many.

Given a dataset (X, y) with:

- $X \in \mathbb{R}^{n \times p}$: predictors (e.g., GDP, energy consumption, renewables).
- $y \in \mathbb{R}^{n}$: response (total CO_2 emissions).

The linear regression model can be represented as:

$$y = X\beta + \varepsilon, \quad \varepsilon \backsim \mathcal{N}(0, \sigma^2 I) \qquad (1)$$

[2] Data are available from Total Energy Monthly Data - U.S. Energy Information Administration (EIA) (https://www.eia.gov/totalenergy/data/monthly/index.php) and World Development Indicators, DataBank (https://databank.worldbank.org/source/2?country=IRN&l=en).

3.2.2 Bayesian Prior

Instead of estimating β directly via OLS, BRR assumes a Gaussian prior on the coefficients:

$$\mathcal{p}(\beta|\lambda) = \mathcal{N}(0, \lambda^{-1}I) \qquad (2)$$

where:

- λ controls the **precision** (inverse variance) of the coefficients.
- Larger λ results in stronger shrinkage and helps avoid overfitting.

We also place a **prior on noise precision**:

$$\mathcal{p}(\sigma^{-2}) = Gamma(\alpha_1, \beta_1) \qquad (3)$$

This hierarchical Bayesian setup integrates over uncertainty in both coefficients and noise variance.

3.2.3 Posterior Distribution

Using Bayes' theorem, the posterior over coefficients is:

$$\mathcal{p}(\beta|X, \mathcal{y}) = \mathcal{N}(\mu, \Sigma) \qquad (4)$$

where:

$$\Sigma = (\lambda \mathrm{I} + \alpha X^T X)^{-1}, \mu = \alpha \Sigma X^T \mathcal{y}$$

with:

- $\alpha = \sigma^{-2}$: data precision.
- λ: coefficient precision.

This formulation shows that BRR acts as a regularized regression but also yields posterior uncertainty via Σ.

3.2.4 Predictive Distribution

For a new observation $x_* \in \mathbb{R}^p$, the predictive distribution is Gaussian:

$$p(y_*|x_*, X, y) = \mathcal{N}(x_*^T \mu, \sigma^2 + x_* \Sigma x_*) \qquad (5)$$

- with: Point prediction: $\hat{y}_* = x_* \mu$
- Predictive variance: $\sigma^2 + x_* \Sigma x_*$

This makes BRR ideal for forecasting CO_2 emissions, as we obtain both the mean prediction and a credible interval (e.g., 95% CI).

4. Results

In our *Baseline Scenario* the U.S. remains in the Paris Agreement and reduces emissions by 63.5% (the midpoint of the 61-66% expected reduction range) below 2005 levels by 2035. According to the U.S. Environmental Protection Agency (USEPA), U.S. emissions were 6.127 million metric tons of CO_2. With 63.5% reduction the expected emission levels will be 2.236 million metric tons of CO_2. Since the GTAP version 11 database is based on 2017, we construct our emissions reduction shock based on the change in emissions from 2017 to 2035. This results in about 57% reduction in GHG emissions for the Baseline Scenario. As illustrated in Table 1, under the Paris Agreement the U.S. GDP decreases by 1.31% assuming no other changes in the economy. We also observe about 11% reduction in total investment. However, with increasing investments in the renewable energy sector and hybrid and electric car production, we expect that in most cases the direct and indirect benefits of emissions reduction policies will exceed the total costs of these regulations, as suggested by the International Panel on Climate Change (IPCC) (2014) report. U.S. exports increase by about 11% and imports decline by around 8% having positive impact on its GDP. Most of the increase in U.S. exports occurs in the oil, coal and natural

gas sectors since it becomes more beneficial to export fossil fuels to other countries not subject to similar regulations.

In this scenario, the U.S. natural gas (50.7%) and coal (44.8%) industries experience the largest output reduction followed by the negative changes in oil products (29.8%) and electricity (29.3%) sectors. Our disaggregation of results shows that changes in fossil fuels usage are mostly driven by reduction in domestic consumption and increase exports. Therefore, we see significant changes in the domestically produced electricity and oil products' output. We also observe 27.3% reduction in the U.S. air transport services output and relatively lower decline of 20.3% in its water transport sector. This can be explained by the fact that in the U.S.-international freight trade, water transport is used for carrying about 80%[3] of the weight and the fuel used in international transportation is partially sourced from other countries that are not subject to the same emission reduction regulation as the U.S. in our baseline scenario. The reduction in U.S. transportation emissions is mostly coming from the air and water transport sectors, because the change in land transport services is about half of those observed for air and water transportation.

[3] https://data.bts.gov/stories/s/International-Freight-Gateways/4s7k-yxvu/

Table 1. Change in macroeconomic variables under the Baseline Scenario, percent

Region	GDP	Investment	Emissions	Exports	Imports
Oceania countries	0.059	2.1	1.34	-0.95	1.4
China and Hong Kong	0.087	2.39	0.46	-3.93	1.4
Japan	0.046	2.16	1.09	-2.47	1.08
East Asia	0.047	2.03	1.11	-0.85	0.73
Rest of South East Asia	0.007	1.46	1.06	-0.28	0.37
Malaysia and Indonesia	-0.015	1.81	0.73	-1.2	0.52
Rest of South Asia	0.003	1.11	0.54	-1.62	0.42
India	0.003	1.94	0.51	-3.21	1.18
Canada	0.291	16.23	-2.36	-6.59	7.56
United States	-1.314	-10.98	-57	11.14	-7.81
Central and Caribbean Americas	-0.009	2	0.75	-0.14	0.97
South and Other Americas	0.008	1.77	1.01	-0.95	0.36
Brazil	0.125	7.17	1.83	-5.68	3.78
European Union	0.123	3.24	1.64	-1.05	0.83
Other East Europe	0.072	1.57	0.57	-0.64	0.63
Rest of European Countries	0.06	1.46	2.3	-0.22	0.46
Russia	-0.006	1.42	0.74	-0.5	-0.46
Middle Eastern and North Africa	-0.041	0.75	0.72	0.21	-0.6
Sub Saharan Africa	-0.013	1.28	1.22	-0.26	0.26
Rest of World	0.078	1.71	3.25	-0.35	0.57
Total	-0.260	0.02	-7.98	-0.20	-0.20

Some countries experience GDP growth under the baseline scenario. We can see that Canada is benefiting the most with a 0.29% increase in its GDP, while middle eastern countries experience the next largest negative impact of 0.04% reduction in their aggregate GDP. Canadian GDP increases mostly because of 16.23% increase in investment. Most of the remaining countries experience relatively modest changes in their GDP values.

Globally, world emissions decline by about 8%. The world GDP decreases by a quarter of a percent. Global exports and imports drop by about 0.2%. Also, there is very little increase in global investment.

In the *Withdrawal Scenario A*, the U.S. withdraws from the Paris Agreement. However, we assume that improvement in technologies over time and use of alternative fuels will result in 1.6% annual reduction (2007-2015) in GHG emissions starting from 2025, based on pre-Paris Agreement average annual reduction in U.S. GHG emissions as reported by the U.S. Environmental Protection Agency[4]. Therefore, the reduction in U.S. GHG emissions from 2024 to 2035 is expected to be about 30.4% under the Withdrawal Scenario A. We observe 0.32% drop in U.S. GDP, which is significantly lower compared to that is the Baseline scenario (Table 2). In this scenario the reduction in investment of 3.81% is substantially smaller than in the Baseline case. Similar patterns are observed for changes in U.S. exports and imports. Specifically, U.S. exports grow by 4.5% while its imports decrease by 2.38% positively affecting the U.S. GDP. The growth in U.S. total exports is mostly driven by the natural gas exports increase by about 80%, followed by 30% increase in oil exports, and around 16% growth in its exports of coal. The largest increases in U.S. exports occur in the oil, coal and natural gas sectors because under this emissions reduction scenario it becomes more beneficial to export fossil fuels to the rest of world countries.

[4] https://www.epa.gov/climate-indicators/climate-change-indicators-us-greenhouse-gas-emissions

Table 2. Change in macroeconomic variables under the Withdrawal Scenario A, percent

Region	GDP	Investment	Emissions	Exports	Imports
Oceania countries	0.014	0.45	0.51	-0.17	0.3
China and Hong Kong	0.03	0.8	0.16	-1.31	0.49
Japan	0.018	0.71	0.48	-0.81	0.39
East Asia	0.017	0.69	0.47	-0.29	0.28
Rest of South East Asia	0.003	0.48	0.38	-0.08	0.14
Malaysia and Indonesia	-0.007	0.52	0.29	-0.33	0.15
Rest of South Asia	0.001	0.34	0.18	-0.45	0.18
India	0.001	0.65	0.21	-1.05	0.44
Canada	0.167	9.16	-4.58	-3.46	4.76
United States	-0.32	-3.81	-30.4	4.5	-2.38
Central and Caribbean Americas	0.001	0.74	-0.19	0.09	0.63
South and Other Americas	0.002	0.46	0.37	-0.2	0.04
Brazil	0.042	2.3	0.8	-1.78	1.23
European Union	0.045	1.05	0.64	-0.33	0.29
Other East Europe	0.029	0.5	0.22	-0.17	0.23
Rest of European Countries	0.019	0.32	0.79	0	0.1
Russia	-0.005	0.31	0.33	-0.08	-0.36
Middle Eastern and North Africa	-0.019	0.07	0.19	0.21	-0.32
Sub Saharan Africa	-0.007	0.32	0.46	0	0.03
Rest of World	0.028	0.54	1.25	-0.1	0.19
Total	-0.056	0.02	-4.43	0.02	0.02

The U.S. natural gas (26.8%) and coal (25.5%) industries experience the largest output reduction followed by the negative changes in oil products (3.7%) and electricity (12.5%) sectors. In this case again, the changes in fossil fuels usage are mostly based on negative changes in domestic consumption and increase in exports. Therefore, we see significant changes in the domestically produced electricity and oil products' output. We also observe negative changes in the air (9.5%), water (6.7%) and other (3.3%) transport services outputs. The relatively small reduction in the water transport services output is again due to largest share of sea transport used in the U.S.-international freight trade and that the fuel used in international transportation can be

supplied by other trading partner countries with different emission reduction regulations. The relatively lower reduction in land transport usage can be explained by its small share in U.S. international trade.

In this case again, Canada is benefiting the most with about 0.17% growth in its GDP, mostly due to significant increase in its investments (9.16%). The next largest GDP loss -0.019% is observed in the middle eastern countries. Again, most of the other countries face relatively small GDP changes. We find that the global GDP declines by significantly lower amount (0.056%) than in the baseline scenario. Also, the world emissions decrease by about 4.5%, while global investment, exports and imports grow by about 0.02%.

Under the *Withdrawal Scenario B*, using the forecasted reduction in emissions and the modified GTAP-E model we simulate the general equilibrium effects of this scenario (Table 3). We find even lower reduction in the U.S. GDP (-0.11%), investment (-1.71%), and imports (-1.08%). We also observe increasing exports at a lower rate (2.05%) compared to the previous two scenarios. The latter is mostly due to growing natural gas, oil, and coal exports, by about 39%, 12%, and 7%, respectively. The largest export increases take place in the oil, coal and natural gas sectors because under this emissions reduction policy it becomes more profitable to export fossil fuels to other countries.

We observe the largest output reduction in the U.S. natural gas (14.3%) and coal (14%) sectors followed by the negative impacts on the outputs of electricity (6.1%) and oil products (4.6%) sectors, which are mostly driven by growing exports and declining domestic consumption. There are also negative impacts on the air (4.1%), water (2.9%) and other (1.5%) transport services output. Compared to the reduction in air transport services, sea transport experiences relatively small drop in its output. This is again due to the fact that water transport is the main mode of

transportation in the U.S.-international freight trade and that the fuel used in international water transportation can be provided by other trading partner regions not subject to same emission reduction policies. Also, the land transport services output experiences the smallest reduction since it is used for U.S. – Canada and U.S. – Mexico trade representing about 21% of U.S. total exports.

Table 3. Change in macroeconomic variables under the Withdrawal Scenario B, percent

Region	GDP	Investment	Emissions	Exports	Imports
Oceania countries	0.005	0.15	0.24	-0.05	0.1
China and Hong Kong	0.013	0.36	0.07	-0.59	0.22
Japan	0.008	0.32	0.23	-0.36	0.18
East Asia	0.008	0.31	0.22	-0.13	0.13
Rest of South East Asia	0.002	0.21	0.17	-0.03	0.07
Malaysia and Indonesia	-0.003	0.22	0.14	-0.14	0.06
Rest of South Asia	0.001	0.15	0.07	-0.18	0.09
India	0.001	0.29	0.09	-0.47	0.21
Canada	0.083	4.57	-2.75	-1.7	2.41
United States	-0.11	-1.71	-15.77	2.05	-1.08
Central and Caribbean Americas	0.001	0.34	-0.16	0.04	0.29
South and Other Americas	0.001	0.19	0.17	-0.08	0.01
Brazil	0.019	1.02	0.37	-0.78	0.55
European Union	0.02	0.47	0.3	-0.15	0.13
Other East Europe	0.013	0.22	0.11	-0.07	0.1
Rest of European Countries	0.008	0.11	0.32	0.02	0.04
Russia	-0.003	0.12	0.17	-0.03	-0.2
Middle Eastern and North Africa	-0.011	-0.01	0.11	0.1	-0.18
Sub Saharan Africa	-0.004	0.11	0.21	0.02	-0.01
Rest of World	0.013	0.24	0.57	-0.05	0.09
Total	-0.017	0.01	-2.32	0.01	0.01

We can see that the next largest GDP reduction occurs in the middle eastern countries (-0.011%). Like the previous scenarios, Canada is experiencing the largest increase in its GDP (0.083%), which is driven mostly by 4.57% increase in its investments. As before, GDP changes

in most of the remaining countries are relatively small. The world GDP declines by -0.017% which is significantly smaller than the global GDP changes in the previous two scenarios. Finally, global investment, exports and imports increase by about 0.01%, while global emissions drop by about 2.3%.

4.1 Out of Sample Validation for Machine Learning Model

To assess the predictive performance and temporal robustness of the proposed Bayesian Ridge Regression probabilistic supervised machine learning model, we conducted two layers of validation: a chronological out-of-sample test and a forward-chaining time-series cross-validation. In the out-of-sample exercise, our Bayesian Ridge Regression model and three other alternative models, LASSO, OLS, and Random Forest, were trained on data from 1997–2020 and evaluated on the holdout period 2021–2024, ensuring that only historical information was used to forecast future emissions. As reported in Table 4, both the LASSO and Bayesian Ridge regressions achieve high predictive accuracy, with R^2 values above 0.98 and low error magnitudes (RMSE < 25 Mt). However, as shown in Table 5 the Bayesian Ridge model exhibits superior temporal generalization when evaluated across sequential forecasting windows, achieving the highest mean cross-validated R^2 (0.64). This improvement stems from the Bayesian framework's Gaussian priors, which regularize coefficients smoothly and stabilize estimates under multicollinearity, an important advantage when forecasting CO_2 emissions using interrelated macroeconomic and energy variables such as GDP, population, and energy consumption.

Table 4. Holdout last 20% Out-of-Sample

Model	R-Squared (Test)	RMSE	MAE
LASSO	0.991	16.285	10.697
Bayesian Ridge	0.982	23.064	17.776
OLS	0.294	144.359	119.206
Random Forest	-4.616	407.049	372.657

Table 5. Time-Series Cross-Validation (forward chaining)

Model	TS-CV R^2(mean)	TS-CV R^2(std)	TS-CV R^2(n)
LASSO	0.641	0.41	4
Bayesian Ridge	0.588	0.397	4
OLS	0.381	0.349	4
Random Forest	-10.083	8.079	4

The visual diagnostics in Figures 2, 3 and 4 further reinforce these findings. In the predicted-versus-actual scatterplots (Figure 1), the Bayesian Ridge and LASSO models produce forecasts that align closely with the 45° reference line, confirming their strong out-of-sample accuracy. The comparative bar charts of R^2, RMSE, and MAE (Figure 3) similarly demonstrate that Bayesian Ridge provides a better balance between fit and stability than both classical OLS and nonparametric Random Forest. Collectively, these results highlight that although LASSO performs competitively in point prediction, Bayesian Ridge achieves greater robustness over time by incorporating parameter uncertainty and probabilistic regularization, making it a more reliable model for long-horizon emissions forecasting and policy simulation.

Figure 2: Predicted versus actual models scatter plots

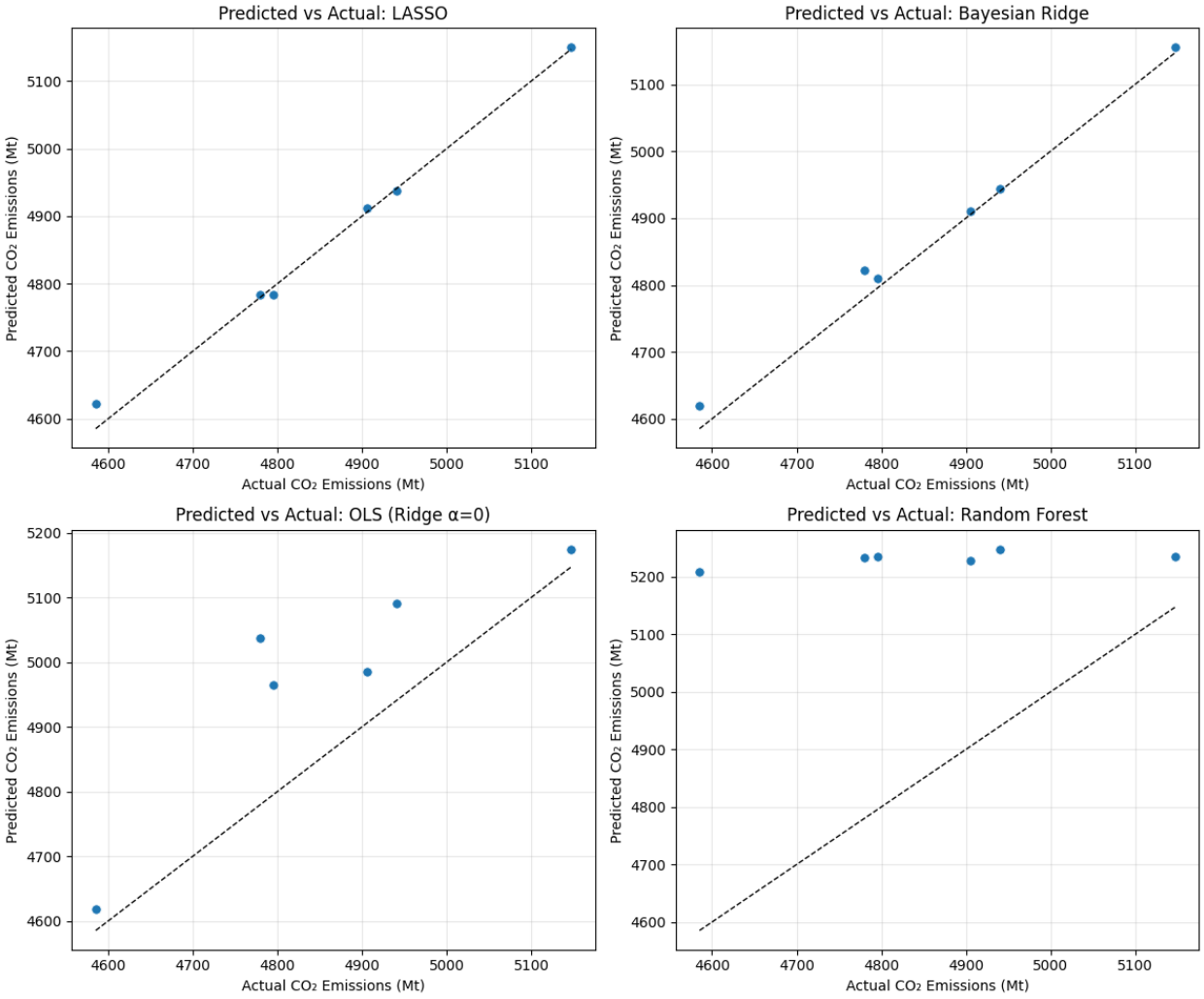


Figure 3: Density plots models

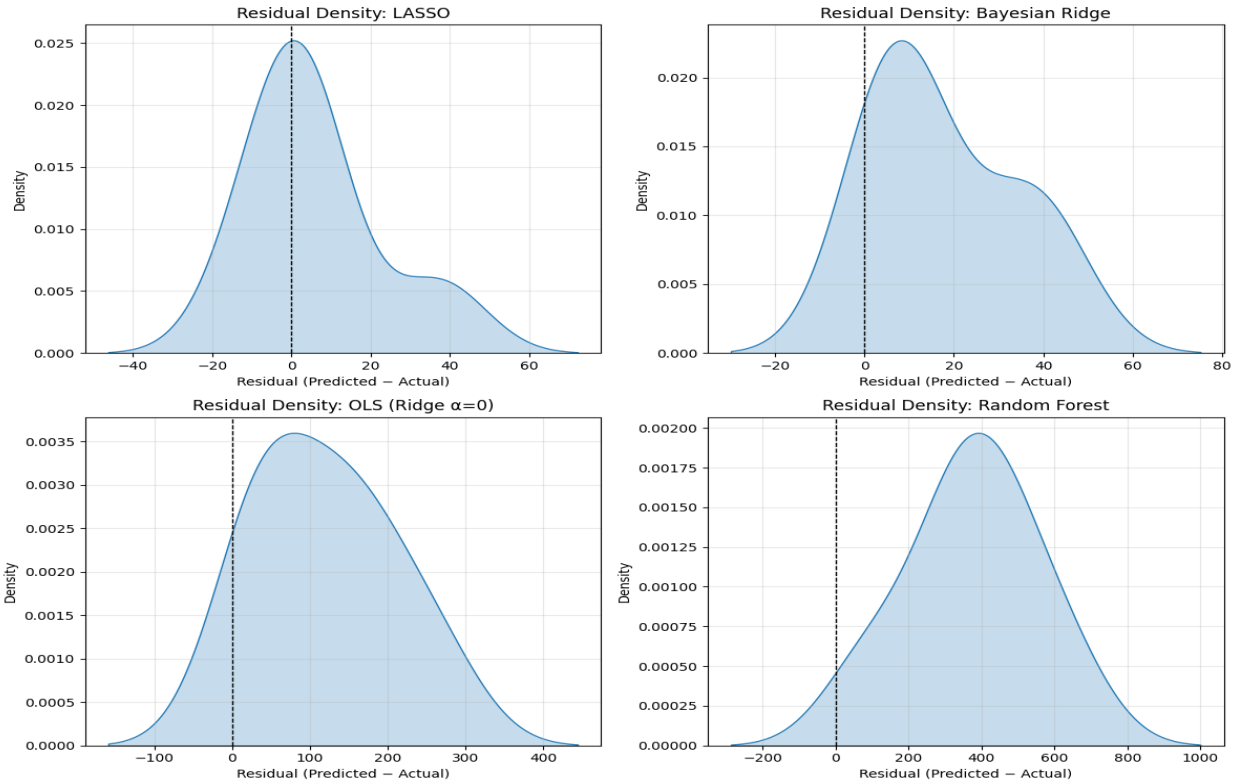
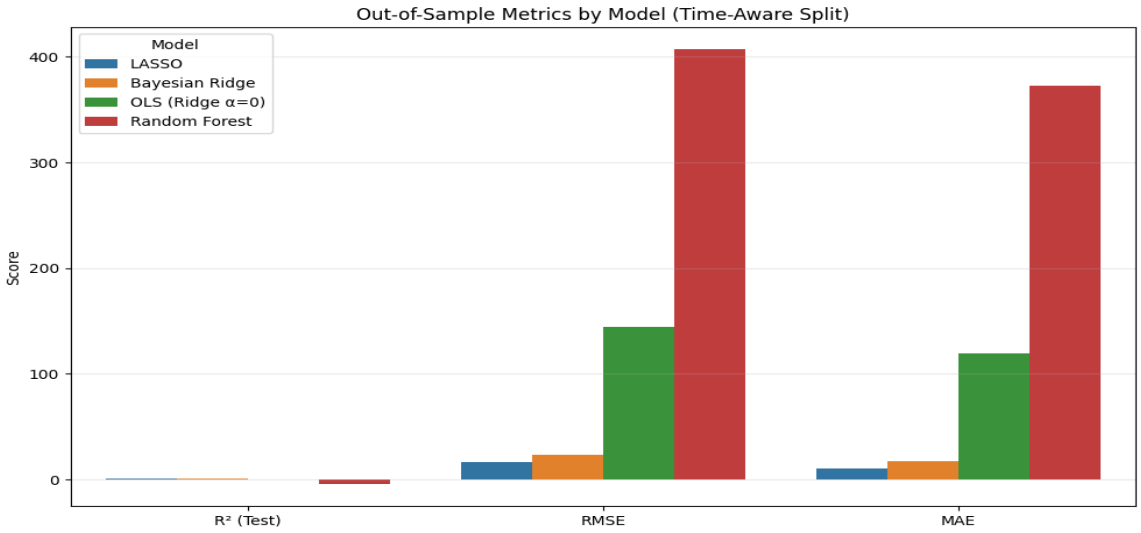


Figure 4: Metrics bar plots



4.2 Welfare Changes

In this section we disaggregate the welfare changes in all three scenarios to better understand how the U.S. and global welfare can be affected under each possible scenario. We decompose the welfare effects into three aspects, and we can clearly see that the largest welfare losses occur in the baseline scenario (Table 6).

In all three simulations the allocative efficiency effects very closely follow the GDP changes for all regions. In the baseline scenario this effect is significant and negative for the United States (-$256 billion) while it is positive in most of the remaining regions, especially in the major trading partner regions of the U.S., such as the European Union ($22 billion), China and Hong Kong region ($11 billion), and Canada ($4.8 billion). In the other two scenarios we observe qualitatively similar but relatively smaller allocative efficiency effects.

The terms of trade effects in the United States are negative and relatively smaller in all three scenarios (-$29 billion, -$13 billion, and -$6 billion). We can however see that in the baseline scenario the terms of trade effects are significantly positive for the European Union ($16 billion), China and Hong Kong region ($6 billion), and Canada ($2.8 billion). This result is qualitatively similar to the terms of trade impacts in the other two scenarios.

The investment savings terms of trade effects are substantially larger and negative for the United States and significantly positive for China in all three scenarios. The global investment savings terms of trade effects are very small since the individual regional effects cancel each other out. The world terms of trade effects also have little impact on the global equivalent variation results in all three scenarios.

Despite the minimally negative terms of trade and investment-savings effects observed in all three simulations, the negative allocative efficiency effects are significant and identical to the GDP impacts for both the U.S. and global economies.

Table 6. Change in U.S. and global welfare under the three scenarios (million US$)

Region	Baseline Scenario				Withdrawal Scenario A				Withdrawal Scenario B			
	Allocative efficiency effect	Terms of trade effect	Invest-savings effect	Total equivalent variation	Allocative efficiency effect	Terms of trade effect	Invest-savings effect	Total equivalent variation	Allocative efficiency effect	Terms of trade effect	Invest-savings effect	Total equivalent variation
Oceania countries	941.0	1,377.7	84.5	2,403.2	228.1	168.5	41.6	438.2	82.6	7.5	21.5	111.6
China and Hong Kong	11,021.2	16,027.5	2,290.8	29,339.5	3,740.2	5,962.2	956.3	10,658.6	1,686.6	2,757.0	454.2	4,897.8
Japan	2,293.6	4,417.8	472.3	7,183.6	900.4	1,835.6	190.6	2,926.6	413.9	882.4	89.7	1,386.1
East Asia	1,077.2	3,542.0	149.8	4,769.1	389.2	1,553.5	63.3	2,006.1	179.5	743.4	29.6	952.6
Rest of South East Asia	105.8	502.5	244.3	852.7	49.7	277.0	104.8	431.5	24.9	130.8	50.0	205.8
Malaysia and Indonesia	-197.2	641.5	3.4	447.6	-97.5	129.8	22.1	54.3	-45.8	38.4	13.5	6.1
Rest of South Asia	25.2	123.8	276.4	425.4	6.8	80.2	98.7	185.7	2.2	42.2	44.5	88.9
India	71.2	3,646.4	891.4	4,609.0	34.1	1,464.9	331.2	1,830.2	18.1	684.4	152.6	855.2
Canada	4,820.9	8,241.4	734.9	13,797.2	2,764.9	5,959.1	525.3	9,249.3	1,374.2	3,092.2	236.7	4,703.2
United States	-255,462.0	-28,796.0	-5,904.5	-290,162.5	-62,236.0	-12,708.1	-2,717.6	-77,661.6	-21,448.9	-6,023.2	-1,289.6	-28,761.8
Central and Caribbean Americas	-159.3	-189.5	139.3	-209.6	20.5	750.7	60.6	831.9	13.4	411.4	28.9	453.7
South and Other Americas	159.1	-1,905.9	66.2	-1,680.5	43.2	-836.4	24.9	-768.3	16.8	-390.1	11.8	-361.5
Brazil	2,570.0	2,101.9	-357.9	4,313.9	860.7	649.9	-151.4	1,359.2	385.1	290.9	-72.1	604.0
European Union	21,541.5	16,052.5	-425.9	37,168.0	7,807.3	6,043.6	-186.3	13,664.6	3,543.8	2,829.2	-89.4	6,283.6
Other East Europe	1,132.3	-291.9	382.8	1,223.3	453.0	-106.0	137.5	484.5	207.5	-44.2	61.9	225.3
Rest of European Countries	676.6	-834.5	110.9	-47.0	219.6	-475.0	49.5	-205.9	91.0	-253.1	24.3	-137.8
Russia	-91.1	-4,839.6	173.1	-4,757.6	-70.9	-2,183.5	160.9	-2,093.6	-41.8	-1,064.8	93.7	-1,012.8
Middle Eastern and North Africa	-1,317.5	-17,406.0	506.4	-18,217.1	-614.9	-7,484.1	241.0	-7,857.9	-345.0	-3,589.3	121.5	-3,812.9
Sub Saharan Africa	-216.5	-2,709.1	133.2	-2,792.4	-121.7	-1,149.2	40.3	-1,230.6	-67.3	-561.7	15.3	-613.8
Rest of World	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	-211,007.8	-297.6	-28.7	-211,334.1	-45,623.0	-67.3	-6.7	-45,697.1	-13,909.1	-16.3	-1.5	-13,926.8

5. Conclusions and Policy Implications

This study evaluates the economic, trade, and emissions consequences of U.S. withdrawal from the Paris Agreement using an integrated framework that combines a modified GTAP-E computable general equilibrium model with machine-learning-based emissions forecasting. The results highlight a clear policy trade-off. Continued U.S. participation in the Paris Agreement yields the largest global emissions reduction (approximately 8%), but at the cost of a substantial domestic adjustment, including a 1.3% contraction in U.S. GDP and a welfare loss exceeding USD 290 billion. By contrast, withdrawal scenarios significantly attenuate these domestic costs but weaken global mitigation outcomes, particularly once emissions trajectories are conditioned on data-driven forecasts rather than historical averages.

The results indicate that U.S. withdrawal from the Paris Agreement, when not accompanied by compensating domestic climate policy, substantially weakens global mitigation through export-driven carbon leakage. While withdrawal reduces domestic adjustment costs relative to continued Paris participation, it leads to a pronounced expansion of U.S. fossil fuel exports—particularly natural gas and oil—which offsets emissions reductions achieved elsewhere and explains why global emissions decline by only 4.4 percent under historical-trend assumptions and just 2.3 percent under machine-learning-based forecasts, compared to nearly 8 percent under continued participation. From a policy perspective, this finding implies that withdrawal without domestic carbon constraints is environmentally inefficient, even if it alleviates short-run welfare losses. It reinforces the case for maintaining domestic climate instruments—such as carbon pricing, clean electricity standards, or emissions performance regulations—to address the leakage channel identified in the model, a conclusion consistent with the broader climate policy literature emphasizing the cost-effectiveness of carbon pricing when paired with complementary measures and revenue recycling (World Bank, 2023; IPCC, 2022; Aghion, 2016).

A central policy implication of the analysis concerns the interaction between climate policy and international trade under asymmetric commitments. Under the withdrawal scenarios, major U.S. trading partners—including the European Union, China, and Canada—experience positive welfare gains driven largely by improvements in terms of trade and investment reallocation, as shown in the equivalent variation

decomposition, while simultaneously importing a greater volume of emissions-intensive goods from the United States. This combination of economic gains and increased imported carbon intensity creates a clear incentive for trade-based leakage mitigation measures, most notably border carbon adjustments. The relevance of this channel is underscored by recent policy developments such as the EU's Carbon Border Adjustment Mechanism, which has been explicitly motivated by concerns over leakage and competitiveness under unilateral climate ambition. The results provide quantitative support for the view that carbon border adjustments represent a second-best but increasingly salient policy response when large trading partners relax climate constraints, particularly when targeted at emissions-intensive, trade-exposed sectors and designed in line with international guidance (IPCC, 2022; Böhringer, 2012; Jakob, 2021).

The redistribution of welfare observed in the model also has important implications for international climate cooperation. U.S. withdrawal lowers domestic mitigation costs while shifting adjustment burdens toward remaining participants that maintain stricter climate policies, reinforcing free-riding incentives and weakening collective ambition. This asymmetry helps explain why unilateral withdrawal can destabilize multilateral agreements and strengthens the case for alternative cooperative arrangements that internalize spillovers. In particular, club-based approaches—such as coordinated carbon pricing, sectoral agreements, or trade-linked climate clubs—emerge as practical mechanisms for sustaining cooperation when universal participation cannot be achieved. The results thus lend empirical support to theoretical and applied work arguing that conditioning trade or investment benefits on climate policy alignment can help stabilize cooperation and limit leakage in an increasingly fragmented global policy environment (Nordhaus, 2015; Vrontisi et. al, 2020).

Finally, the integration of machine-learning-based emissions forecasting with a CGE framework has direct policy relevance in the presence of uncertainty. The substantial difference between historical-trend and data-driven emissions projections demonstrates that policy evaluations based solely on extrapolation of past trends may systematically understate emissions outcomes following withdrawal, particularly in periods of rapid technological and structural change. This finding underscores the importance of adaptive and robust policy design that explicitly accounts for uncertainty rather than relying on point

forecasts. Integrated modeling approaches that combine structural economic mechanisms with probabilistic forecasting can improve policy calibration, enhance stress-testing of climate strategies, and reduce the risk of unintended outcomes, a conclusion that aligns with recent calls for the use of multiple modeling frameworks to inform climate policy under deep uncertainty (Hepburn, 2025).

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