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Global costs of US withdrawal: Quantifying the impact on Paris Agreement cooperation

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ABSTRACT

This paper examines the political and economic challenges of addressing climate change under the Paris Agreement, in light of the US decision to withdraw, effective January 20, 2025. As a major greenhouse gas emitter, the U.S.'s withdrawal risks undermining global climate cooperation and may encourage other nations to abandon their commitments. Using a simulation model based on econometric estimation, this study assesses the additional costs incurred by the international community due to non-cooperation, focusing on the implications of the U.S.'s exit. The analysis reveals that global marginal costs for decarbonization are increasing, placing greater burdens on the international community as more countries opt out of their nationally determined contributions (NDCs). The study emphasizes the distinction between conditional and unconditional NDCs, highlighting that non-cooperation by poorer nations exacerbates costs, given their reliance on international support. Conversely, the withdrawal of advanced economies like the U.S. has global implications due to their capacity to influence emissions reductions. Countries are categorized into high- and low-risk groups for free riding, underscoring the necessity of multilateral cooperation. The findings highlight the need for cohesive global action to uphold climate pledges and build trust, particularly in the face of free riding and the pressing threat of climate change.

1. Introduction

In an increasingly interconnected world, collaboration for sustainable development must occur on an international level to strengthen global solidarity and protect the needs of the most vulnerable. Climate change represents a global threat that requires commitment from all nations. The Paris Agreement defines a precise objective: to limit global warming to a maximum of 1.5 °C. Achieving this goal necessitates an energy transition, moving from an energy mix centered on fossil fuels to one based on low- or zero-carbon emissions through renewable energy sources (RES) and improvements in energy efficiency (de Lange, 2024; Shang et al., 2024; Zhao and You, 2020). Meeting the goals outlined in the Paris Agreement requires collaborative action, where cooperation and coordination are essential.

However, the recent withdrawal of the United States from the Paris Agreement on January 20, 2025, disrupts these collaborative efforts, highlighting the challenges of maintaining collective commitment.[1] This policy shift reflects broader concerns about short-term economic costs, which often overshadow the long-term benefits of global climate action. The withdrawal of the world's second-largest emitter of greenhouse gases underscores the dilemma posed by free-riding behavior in international climate agreements. When major economies fail to meet their obligations, cooperative nations face increased financial and environmental burdens, jeopardizing the collective ability to meet decarbonization targets.

The aim of the paper is to provide the first assessment of these dynamics, using econometric models to quantify the additional costs imposed on the international community by non-cooperative actors. Using a simulation model rooted in econometric estimation, this study quantifies the additional costs imposed on the international community due to the lack of cooperation from major economies. The analysis considers both the direct impacts of non-participation and the broader economic ripple effects on global decarbonization efforts.

This pioneering work highlights the critical importance of maintaining multilateral cooperation to counteract the destabilizing effects of such policy reversals and provides actionable insights for policymakers navigating the challenges of global climate governance. The findings provide valuable insights into the economic implications of free riding

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[1] For the formal declaration see White House (2025)

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and emphasize the importance of multilateral cooperation to address the climate crisis effectively.

While the United States has previously withdrawn from the Paris Agreement in 2017, to our knowledge, this approach has not been utilized in the existing literature. For example, Salman et al. (2022) conclude that implementing the Paris Agreement exerted heterogeneous effects on environmental efficiency across countries. Similarly, Cooper (2018) suggests that while the U.S.'s withdrawal poses significant challenges, it could also provide an opportunity to strengthen the Agreement's efficacy and legitimacy through subnational actions within the U.S.

The speed of the global energy transition is highly uncertain (Wang et al., 2024; Fattouh et al., 2019). One of the most serious problems connected to energy transition and the active participation of all countries lies in countries' perception of the costs and benefits of the energy transition itself. While the costs are very often perceived as well calculable and immediate (Qi et al., 2023), the benefits are seen as uncertain and far away. The risk is therefore that the perception of short-term costs could diminish the long-term benefits, negatively impacting the participation of countries in the decarbonization strategy (International Monetary Fund, 2022).

The main novelty of this paper is to provide a quantitative measure of a potential moral threat to the energy transition cooperation process. The international debate has predominantly focused on the percentage of global emissions reductions and the distribution of these targets through nationally determined contributions (NDCs) established under the Paris Agreement. While this framework highlights the committed costs for each participating country, it often overlooks the potential benefits derived from reneging behaviors and the consequent additional burdens placed on others.

In this context, the main innovations of our study are as follows. First, it estimates the global marginal cost function for decarbonization, incorporating both market and social costs while considering the opportunity cost of alternatives. Second, it highlights the importance of implementing enforcement mechanisms to combat free-riding behavior, which are crucial for encouraging compliance and maintaining the integrity of international agreements. Third, it evaluates the additional costs borne by countries when others adopt selfish behaviors, such as the recent U.S. stance. Finally, it quantifies the incentives for free riding with respect to achieving national emissions reduction targets. The findings underscore the importance of collective commitment, monitoring progress, and fostering awareness among countries regarding climate change mitigation efforts.

Climate change has significant international implications for sustainable development. Developing countries are the most vulnerable to the negative impacts of climate change and therefore have a greater interest in developing and implementing mitigation methods (Abbass et al., 2022; Tan et al., 2021; Ravindranath et al., 2002). The energy transition is a long-term process that requires support at the level of politics, society, and industries. Due to economic differences between countries, differences in energy sources and many other factors, energy transition policies and costs differ from country to country. In particular, the energy transition entails high costs for all economies, but clearly developed countries, which have higher financial resources and technological innovation, can transition more easily than developing countries, effectively reducing the cost of RES (Babayomi et al., 2022; Jianchao et al., 2021). However, it is important to underline that the energy transition is not driven by technological improvements but rather by policies. Blazquez et al. (2020) argue that, compared to previous energy transitions, the current one shows that, for example, two identical countries in terms of energy mix and generation cost, can achieve the same level of decarbonization using different policies. Therefore, the importance of new policies is evident so that all countries can shift towards RES and energy efficiency improvements.

Climate change caused by GHG emissions is a global public good, and the impact of climate change linked to emissions from one country affects the entire world.

Climate change caused by GHG emissions is a global public good, and the impact of climate change linked to emissions from one country affects and challenges the entire world. The global effects are compounded by the diversity of emission sources across different sectors. While the energy sector is often at the forefront of mitigation strategies, other sectors such as agriculture and industry contribute significantly to global emissions and present unique challenges.

In agriculture, emissions largely stem from livestock production, rice cultivation, and land use change. Effective mitigation in this sector requires policies such as improved manure management, dietary shifts, agroforestry, and enhanced soil carbon sequestration (IPCC, 2023a, IPCC, 2023b; FAO, 2022). However, political dynamics in agriculture are complex, due to its deep ties to food security and rural livelihoods, particularly in developing countries.

Similarly, the industrial sector, which includes cement, steel, and chemical production, is highly energy-intensive and often lacks cost-effective decarbonization options in the short term. Mitigation strategies include process optimization, electrification, carbon capture and storage (CCS), and material substitution (IEA, 2024; Kaufman et al., 2023). Yet, international coordination is complicated by uneven technological readiness and economic competitiveness concerns.

Integrating mitigation efforts across these diverse sectors reinforces the multidimensional nature of global cooperation. Each sector demands tailored strategies, financial support mechanisms, and capacity building to ensure equitable participation and sustained commitment. However, as happens with most public goods, also in this case, international cooperation on climate change mitigation suffers from incentives to free-ride and renegotiation of agreements in cases of noncompliance (Heitzig et al., 2011). The problem of free riding is therefore pervasive in climate change issues, and most studies show that, as it is a public good, there is no stable coalition of countries that can reduce GHGs (Zhang and Liang, 2020; Paroussos et al., 2019; Kersting et al., 2017).

When small developing countries fail to participate in global efforts, the impact may be negligible due to their limited contribution to global emissions. However, free-riding behaviors from large countries or coalitions could significantly undermine the achievement of global objectives (Lane, 2017). The recent U.S. decision to withdraw from the Paris Agreement raises concerns not only because of its substantial contribution to global emissions but also because it may embolden other nations to follow suit, further weakening international cooperation and amplifying the collective burden on participating countries.

Choices related to the environment very often represent social dilemmas, that is, scenarios in which common resources, in this case the environment, must be protected, and countries are faced with the dilemma of whether to "use" more of them than others, thus making free riding, or sharing common objectives and therefore managing the resource responsibly, with immediate personal benefits, in the short term, smaller than free-rider behavior (Skatova et al., 2016; Irwin and Berigan, 2013). Countries' opportunistic behavior should be handled by appropriate penalties by regulatory authorities which could help align interests of countries, generating positive impact on sustainability goals (You et al., 2018; Schoenmakers et al., 2014).

Combating opportunistic behavior reduces the costs of energy transition and accelerates its progress by encouraging countries to invest in RES (OECD, 2022). International cooperation is thus a critical factor in the green transition (Gu et al., 2022). Ostrom (1990) suggests that cooperation in managing environmental resources is possible when there is mutual trust, supported by mechanisms such as sanctions. While these conditions are easier to implement at a local level, they can also be adapted to address global challenges like climate change. Nordhaus (2015) argues that without sanctions for non-participants, minimal results can be achieved. Trust, supported by enforcement mechanisms, can therefore have a beneficial effect on the energy transition by discouraging free-riding behaviors (Carattini et al., 2015). Also, sanctions could promote social justice, as they aim to correct behaviors that damage the environment and, consequently, the health and well-being of communities, especially the most vulnerable ones.

The energy transition research field is still developing and presents ample opportunities for exploration and growth. The G7 governments have recently launched a climate club, i.e., a global initiative with the aim of accelerating the implementation of the Paris Agreement. The idea behind the construction of a club lies on the fact that a club might discourage free riding behaviors (European Parliament, 2023). At COP28 it has been highlighted how the climate club could be an important institution for cooperation between countries across different geographies (United Nations, 2023).

However, the recent withdrawal of the United States from the Paris Agreement on January 20, 2025, signals a stark departure from the G7 collaborative approach. While the EU members of the G7 continue to champion multilateral initiatives like the climate club, prioritizing coordinated efforts to achieve net-zero emissions, the U.S. position under the current administration seems to focus on national interest priorities. This divergence underscores a growing rift between the EU's commitment to strengthening international cooperation and the U.S.'s prioritization of sovereignty and economic autonomy in addressing climate challenges. The contrast between these positions highlights the fragile nature of global efforts to combat climate change and the critical need for innovative mechanisms, like the climate club, to mitigate the risks posed by free-riding behaviors.

The paper is structured as follows. Section 2 describes the methodology and data. The research results and discussion are presented in Section 3. Section 4 presents the conclusions.

2. Methodology and data

2.1. Model formulation

The model implemented in the paper to simulate the effects of environmental policies considers endogenous feedback from economic activity to the environmental sector.

In a simplified macroeconomic framework for a given country, income equilibrium is considered as a measure of welfare (which is the objective of the government), as a function of private economic activity, cost of achieving the target taxation necessary to finance the target, the externality cost imposed by free rider behavior of others and the net benefit of acting as a free rider. The acronyms and variables used in the paper are listed in Table 1.

This framework can be represented with a general equilibrium set of equations:

$$Y = A(Y) + P \tag{1}$$

$$P = (G, T) \tag{2}$$

$$Z = f\ (Y, G) \tag{3}$$

$$T = T(Y, Z) \tag{4}$$

In eq. (1) the equilibrium is given by supply Y equal to aggregate demand *A(Y)* and the government policy intervention P. In eq. (2) the government policy P is achieved with the instruments of the budget, expenditures G, which represent policy efforts to promote primarily investment toward transition and taxes T, which represent primarily the incentive to decarbonization and the means to finance the transition. In this framework the budget may or may not be balanced in the short term. A temporary deficit may indicate a net public contribution to the acceleration of the transition path or to the promotion of other social policies, such as support to health losses or support to labor losses due to global warming.

In this context, these latter social costs and benefits can be logically considered. However, given the focus on the direct transition costs in this paper, the monetary measures of such indirect costs are not explicitly included. This omission is justified by their temporary nature, as a successful climate change policy would simultaneously eliminate both health losses and temperature increases. Obviously in the long run, the balanced government constraint must be held.

Table 1
Acronyms and Variables list.

Label	Explanation
Y	Gross domestic product of the economy
A(Y)	Aggregate demand of the economy
P	Government policy intervention (net of taxes T minus subsidy expenditure G)
Z	Emissions of total countries
T	Taxation as function of level of activity and level of emissions
Ci	Abatement cost of direct investment for decarbonization (compliance cost of NDC)
g	emissions' reduction rate
α	convexity parameter of the cost function
C	Total cost of all countries
Cp	Cost borne by *p* participating countries (a subgroup of the total countries)
λ	share of CO2 emissions of participating countries
gp = g/λ	emission reduction of participating countries
Zp = λZ	Emissions of participating countries
S	Additional cost factor S that falls on the participating countries
OCj	Opportunity cost of country j
P	international price of fossil fuel
μj	effect on the price of the reduction of 1 % the demand of fossil fuel of country j
ϕj	share of reduction of fossil fuels as pledged by country j NDC
qj	quantity of primary energy consumption of country j
RES	Renewable Energy Sources
NDC	Nationally Determined Contribution
GDP	Gross Domestic Product

In eq. (3) the amount of emissions *Z* is defined as a function of economic activity Y and the policy effort G. In eq (4), the taxation T to finance the climate change policy is a function of economic activity *Y* and of the emission level *Z*. This representation has obviously some limits, because it implicitly assumes that in eq (1) the economic activity A(Y) is satisfying the consumption savings constraints of the consumers, the equilibrium financing of new investment to balance the capital depreciation and is subject to government taxation. In addition, this model implicitly assumes with eq (3) that there exists a productive technology using an energy input which results in some emission level that can be mitigated by some policy intervention. Moreover, the model assumes with eq. (4) that taxation is a function of both economic activity and emissions. In general, the energy sector is a key contributor to global GHG emissions, but not the only one. Agriculture, industry, and waste management also play significant roles in CO2 emissions.

While this paper focuses on energy transition, the broader climate mitigation landscape should be acknowledged. In general, the energy sector is a key contributor to global GHG emissions, but not the only one. Agriculture, industry, and waste management also play significant roles in CO2 emissions. Recognizing the political dynamics and mitigation potential of these sectors can help to reinforce the multidimensional nature of climate cooperation.

The model considers the crucial stylized fact that there exists a target level of emission Z in the economy, that is constituted by the NDCs, which is considered a declaration of intention of countries to achieve specifics targets in terms of reduction of emissions. In a multilateral negotiation framework, the NDCs are the result of political negotiation and are announced in terms of unconditional and conditional options. The first means that the country can achieve certain targets essentially spontaneously on a standalone basis. The second means that if some conditions, namely subsidies or other facilitations are put on the table, the country is willing to achieve a more ambitious emission reduction target.

The achievement of this target is reflected in the model through the relative intensity of the government policy instrument (G) and the external subsidy, which is ultimately implicitly included in the policy instrument (T). In other words, if a country opts for the less ambitious unconditional target, the levels of G and T are sized accordingly. Conversely, if the country aims to achieve the more ambitious conditional target, the level of intervention (G) is increased. In this case, the financial source (T) comprises both internal taxation and external subsidies.

The model considers that international negotiation sets a global target for the world, which is the sum of countries targets. In this framework, there are two types of significant costs for each country that can arise from the international negotiation process toward climate change policies.

The first cost is constituted by direct effort that each country has to set forth in order to comply with the NDCs direct investment (conditional or unconditional). In an ideal scenario, this represents the fair cost each country should bear, assuming all participants maintain loyal behavior. The second cost is constituted by the additional burden, under the hypothetical assumption that negotiation processes could be characterized by some opportunistic behavior, that some not loyal participants can impose on the rest of the world, trying to negotiate a lower assignment ex ante or to achieve a lower target ex post. In other words, this study considers explicitly the implications of the risk that some negative externality is imposed by a country (or a group of countries), acting as a “free rider” on the rest of the loyal participants. The negative externality is given by the fact that these latter must compensate for the missing participation of the former.

The model assumes that to fulfill the worldwide necessary target for achieving the decarbonization target, a lower effort by one country or a sub coalition of countries must result in an increasing effort born by the rest of the world.

In this context, this paper presents a model that considers both the cost of achieving a certain policy target and the externality cost of a free riding behavior. We summarize the main assumptions of the model in Table 2.

In the model there is a cost that a country imposes on others when it implements free riding behavior, reducing its own participation burden. Therefore, this model builds a policy simulation framework that can be used at a macroeconomic level to study the interaction between national objectives, for example on climate change, and the costs of non-participation. In particular, the model highlights the cost of the political process implemented by a country that deviates from the agreement, and which depends on the level of emissions (Z) of the country itself.

Table 2
Main assumptions of the model.

Assumption	Explanation
Free riding	the most important assumption of the model is that countries could free ride in the sense that they can withdraw from the agreement or achieve a lower result. This means that the remaining participating countries will have to bear the extra burden to achieve the overall world target with a fraction of the participant countries
Common technology	a simplifying assumption of the model is that all countries given the common knowledge in the globalized market share the same technology for emission abatement. A more complex model would assume specific abatement technologies for different countries.
Convexity	A crucial assumption of the model is that the abatement cost is represented by a convex function. This means that marginal costs are increasing and therefore if some countries pull out of the global agreement the remaining ones will have to deploy more costly technologies. In other words, the word marginal cost is increasing.
Opportunity cost	Considering that the opportunity cost is represented by the cost of the alternatives not taken, in this model the opportunity cost of deploying low emitting technologies is represented by the cost of abandoning the existing fossil fuel technology.
Emission reduction	The cost of emissions reduction is proportional to emissions

This cost also falls within the taxation T to finance the climate policy. The non-participation of some countries in international agreements implies an increase in costs for those who participate to achieve the CO2 emissions reductions' goal. Given the convexity of the cost function, the marginal costs are increasing. In general, it is plausible to assume that the costs incurred by the countries are different due to the different RES mix and different technologies. Given the global sharing of commercial technologies, we assume identical technology access across countries as a simplifying assumption for the model, because common knowledge of technologies has been spread worldwide while recognizing that actual deployment can vary due to contextual factors.

We assume that C_i is the total cost in monetary terms for $i = 1, \ldots n$ countries that produce Z_i CO2 emissions in relation to their economic activities, expressed in millions of tons. The convexity of the cost function is represented by the $\alpha > 0$ fixed parameter.

According to Nordhaus (2021), the abatement cost is proportional to output (and therefore to the emissions) and it is a non-linear function of the emissions' reduction rate g. In general, this rate is determined by several factors, such as energy savings behaviors, technology improvements and changes in the energy mix. In the model, it assumed that the emission reduction can be achieved, primarily, by increasing the RES share in the energy mix and therefore decreasing the use of fossil fuels. This assumption is a simplification of a more complex interplay of several determinants of the energy transition. We recognize the importance of the Carbon Capture and Sequestration technology that can achieve emission reduction in the atmosphere, which is however at an initial stage of commercial deployment. In this model, we assume that the emission reduction rate is representative of the available technologies.

The model represents a world in which there are n countries that could jointly determine a global agreement for emissions reduction target. Each country contributes voluntarily with her own share. We define λ ($\lambda \leq 1$) the share of emission reduction deployed by the countries that participate in the CO2 emissions reduction target, adopting the specific NDCs. Obviously, full participation implies$\lambda = 1$. We are interested in modeling the consequences of defection by some country or group of countries.

We define the cost function for each country C_i which is necessary for reaching the domestic goal as a function of the emission reduction rate and the amount of emissions:

$$C_i = g^{\alpha} Z_i \tag{5}$$

Then, the total cost C for all i countries participating worldwide to the CO2 emissions reduction target is:

$$C = [\Sigma C_i] = g^{\alpha} [\Sigma Z_i] = g^{\alpha} Z \tag{6}$$

If some country defects from the agreement, we define Cp as the cost borne by a subgroup p ($i = 1, \ldots p$) of participating countries to achieve their original target. Thus, the λ share of CO2 emissions for participating countries is $\lambda = [\Sigma_p Z_i]/[\Sigma_n Z_i] = Z_p/Z$.

Consequently, the cost to achieve global target Z for the participants Cp is defined as:

$$C_p = g_p^{\alpha} Z_p \tag{7}$$

which becomes, by defining $g_p = g/\lambda$ and $Z_p = \lambda Z$:

$$C_p = g^{\alpha} Z \lambda^{1-\alpha} \tag{8}$$

Equations (6) and (8) represent the full and partial participation in the CO2 emissions reduction target by implementing the agreement, respectively. The additional cost factor S that falls on the countries participating in the climate agreement is:

$$S = C_p \,/\, C = \lambda^{-(\alpha-1)} \tag{9}$$

The α parameter is thus crucial because from Eq. (9) it is evident that the degree of convexity of the cost function impacts the amount of costs.

Given that λ < 1 and α > 1, this implies that S > 1. Therefore, there are extra costs, which the countries participating in the agreement must bear to achieve the global target.

2.2. The opportunity cost of the decarbonization target

The data used to construct the model is sourced from official databases. This study relies on publicly available data on primary energy consumption from the World Bank (World Bank, 2023) and the International Energy Agency (IEA, 2023) for 190 countries (Table 1A in the Appendix), expressed in tons of oil equivalent (TOE). The price of Brent is taken from oil is IEA (2023). The percentage of the NDC is taken from IGES (2022). The data for GDP, GDP per capita, CO_2 emission, fossil share, are taken from the World Development indicators of the World Bank (World Bank, 2023), and for nuclear shares are taken from (IAEA, 2023); for conditional and unconditional NDC shares of emission reduction from (IGES, 2022) (Table 2A in the Appendix).

This study employs the concept of opportunity cost in the context of emission reduction. Opportunity cost represents the value of the best alternative relinquished to achieve a particular economic result. It is important to note that this concept does not necessarily align with the market price of a good, even when such a price exists. For instance, the opportunity cost of purchasing a can of orange juice is not merely its market price—the amount of money spent—but rather the potential alternative uses of that money, such as buying a lottery ticket and winning a significant prize. In this context, the opportunity cost of a policy aiming at reducing by X amount emissions, therefore sacrificing the consumption of fossil fuels, is the cost of using the amount of fossil fuels which emit X pollutants. In other words, substituting RES energy, or any other low emitting technology, for fossil fuels by installing new low emitting energy production has an opportunity cost equal to the amount of fossil fuels production that is sacrificed make room for the new technology.

This concept of opportunity cost is not so important when considering the simple market price of the investment in RES or the levelized cost of energy of an investment in RES, but it becomes a relevant concept when considering the policy strategy that each country has to pursue to be part of the decarbonization target of the world. In fact, from a government viewpoint, which is the welfare viewpoint of the country, renouncing to the existing fossil fuel technology has a cost.

This is the opportunity cost of the strategy to invest in new RES or non-emitting technology.

It would also be appropriate, when evaluating the opportunity cost, to consider the potential benefits linked to the use of non-emitting technologies which could positively contribute to the value of the cost itself. Investing in non-emitting technologies means being able to change production and consumption models, satisfying society's needs without damaging the earth's natural resources. Integrating non-emitting technologies in all energy sectors makes countries less vulnerable, and this concerns both developed and developing countries that can escape from a poverty trap in which individuals who do not have access to modern energy services have to pay more for energy they use.

The concept of the opportunity cost developed in this paper is based on the accounting of the following components: the price of fossil fuels, the effect that the reduction of fossil fuel demand exerts on the world equilibrium price of the fossil fuel, the amount of fossil fuel reduction as expressed by the national determined contribution, by each country according to the Paris agreement of 2015.

In this context, consider a 1 % reduction in primary fossil fuel consumption in country j. This has a marginal effect on the international fuel price that needs to be accounted for. This price effect can be quantified as (p – Δp). i.e. the current price minus the effect of 1 % reduction of country's j consumption on the world supply. Let's define μ_j is the effect on the price of the reduction of 1 % the demand of fossil fuel of country j. In order to quantify this effect, define the relative size of each country's energy consumption as $s_j = q_j/q$.

Then the quantity μ_j, is given by:

$$\mu_{-}\left(j\right) = (1 - \frac{\partial p}{\partial q}\frac{\Delta q_j}{p}\bigg) = \left(1 - \frac{\partial p}{\partial q}\ \frac{\Delta q_j}{p}\ \frac{q}{q}\ \frac{q_j}{q_j}\right) = \left(1 - \frac{s_j}{\varepsilon_S}\right) \tag{10}$$

where $\frac{\Delta q_j}{q_j} = 1\%$ and ε_S is the world supply elasticity.

In order to achieve the emission reduction target, set by the NDC pledged by country j, let's define as ϕ_j the implied share of reduction of fossil fuels of each country (United Nations, 2025).[2] Given the above definitions, the monetary value of the opportunity cost for each country *j*, *OCj*, can be expressed as the product of the change of the international price of fossil fuel (p μ_j) times the percentage reduction applied to the level of quantity q_j, where q_j is the quantity of primary energy consumption of country j.

Formally, we have:

$$OC_j = p\ \mu_j\ \phi_j\ q_j \tag{11}$$

Equation (11) represents the monetary measure of the opportunity cost to implement the policy strategy that each country has to pursue to be part of the global decarbonization target.

3. Results and discussions

The opportunity cost computed for each country is used to estimate the marginal cost of RES deployment, for 182 observations in total. This study estimates the marginal cost parameter (α- 1) for both the case d unconditional NDC and conditional NDC, defining a logarithmic cost function[3] (Table 3). Notice the high significance of the coefficients, showing that empirically the cost function is convex. In particular, the convexity parameters of the marginal cost function, (α- 1), are 1.66 for unconditional and 1.43 for conditional NDC. This pattern is an interesting empirical result, which demonstrates the importance of considering different efforts, in order to consider the political commitment of the countries.

Our findings are in line with the latest assumptions of the DICE model, simulated by Barrage and Nordhaus (2024), who estimate the convexity parameter equal to 1.6.

By estimating the cost function, the additional cost factors linked to the non-participation of some countries can be computed. This additional cost will fall on the countries that instead participate in the climate agreement. Indeed, the non-linearity if this function shows that, as some countries adopt free riding behavior, others face even greater efforts to achieve the common goal of CO2 emissions' reduction.

The model is used to assess the additional cost induced to all others

Table 3
Estimated marginal cost function parameter for RES deployment.

	No obs.	R Squared	Estimated (a-1)
UNCONDITIONAL NDC	182	0.11	1.66
CONDITIONAL NDC	182	0.12	1.43

Note: all coefficients are significant at 1 %.
Source: our calculation from World Bank (2023) IEA (2023).

[2] For instance, according to the official declaration, Brazil (United Nations, 2025) commits to an absolute net greenhouse gas emission target in 2030 of 1.20 GtCO2e, consistent with a reduction of 53.1 % in comparison with 2005, according to the latest inventory data. We use this percentage reduction for each country.

[3] The differentiation of the cost function of eq. (5) and taking logs: log*(C)'* = α_0 + *(α– 1)* log*(g)* allows us to estimate econometrically the marginal cost parameter *(α– 1)*.

by any potential free riding country, which avoids complying with the NDC targets.

Obviously, the size of the countries in this model varies from very large emitters to very small emitters. To assess the relative importance of the hypothetical reneging country, we report the share of each country in total world CO2 emissions, the unconditional and conditional target and the GDP per capita in constant USD. It emerges that top emitters in 2021 are Russia (0.0473), India (0.0730), United States (0.1349) and China (0.3090). These countries alone count for more than half of total global CO2 emissions. The group of the bottom 5 % emotes is constituted by 65 different small countries. The bottom 1 % of the emissions accrued to 40 different small countries In other words, less than two thirds of the countries (precisely 116) are responsible for 95 % of the emissions, while the other third (precisely 65) are responsible for only 5 % of the world emissions.

In Table 4 we report in column 1 the share of world emissions of selected groups of countries. Next, we report three quantities that are potentially associated with the free-rider behavior of a non-participating country. These are reported as percentagt are computed. The first is the measure of the additional cost imposed on all the others according to eq (9). This is the additional cost that the loyal countries would have to bear to maintain unchanged targets. The second is the benefit that accrues to the non-participation country and the third is the ratio of the potential benefit of a country to the cost imposed on the others.[4]

The convexity of estimated cost function shows that the additional cost increases more than proportionately with respect to the non-participating country's share. In other words, if a country reduces its effort to decarbonize by a certain amount, which has a certain cost, the additional effort that must be made by the other countries will have a cost that is more than proportionate, because the convexity of the cost function implies that the additional effort put in place has a higher marginal cost. The same computation for selected groups of countries is reported in Table 4.

In Table 4, to further highlight the consequences of free riding behavior, there are shown groups of some countries and the four largest emitters in the world. The country list is in Column 1, the share of the emissions is in Column 2, and the additional cost imposed by each non-participating country for reneging their commitment to unconditional and conditional NDC, respectively, are in Columns 3 and 4. Table 4 reports also the benefits (avoided cost of the NDC) are in Column 5 and 6, and the ratio of the benefit of the free rider (avoided cost of participation) to the cost imposed to others are in Column 7 and 8, in the cases of unconditional and conditional NDC, respectively. Finally, there is the check whether this ratio is more convenient for the conditional case with respect to the unconditional one in Column 9 (1 means "yes" and 0 means "no").

Among the largest emitters, the United States' recent withdrawal from the Paris Agreement on January 20, 2025, exemplifies how non-participation by major economies exacerbates the financial burden on cooperative nations. Representing 14.01 % of global emissions, the U.S.'s decision imposes additional costs of 18.74 % and 20.59 % on participating countries under unconditional and conditional Nationally Determined Contributions (NDCs), respectively. These figures illustrate how the non-participation of high-emitting countries leads to disproportionate cost increases for the remaining participants, jeopardizing collective climate targets.

Table 4 further demonstrates that the additional costs imposed on participants increase with the size of the non-cooperative economy. For instance, the Brics10 coalition, representing 50 % of global emissions, would impose costs of 276.17 % (unconditional) and 228.30 % (conditional) on others, should it fail to meet its commitments. Similarly, China, responsible for 32.09 % of emissions, would impose a staggering 80.69 % and 72.00 % additional costs, under unconditional and conditional NDCs, respectively, if it were to adopt free-riding behavior.

The findings also underscore how free riding from smaller emitters, like the 104 countries collectively representing 1 % of emissions, imposes relatively minor additional costs (2.38 % and 3.15 %, in the case of unconditional or conditional NDC, respectively). Their benefit would be 1.46 % and 1.92 %. In other words, in the case of unconditional NDC, they would save 1.46 % of the world cost but they would impose a higher additional cost, equal to 2.38 % to the rest of the world.

In contrast, large economies like the U.S., with a benefit-to-cost ratio of 0.54 under both NDC scenarios, may find non-participation economically appealing, as their avoided costs significantly outweigh their share of collective emissions reductions.

In the sixth row, the reneging behavior of the GCC is simulated. These countries represent 5.44 % of the world emissions. In this case the additional cost for the rest of the world would be 8.8 % and 8.2 % (in the case of unconditional or conditional NDC, respectively). From our findings, it emerges that largest countries in terms of GDP are those whose non-participation would impose very high costs on the participating countries. Brics10, for instance, would impose additional costs for defaulting unconditional and conditional NDCs of 276.17 % and 228.30 %, respectively. Their free riding incentives in terms of avoided costs for addressing the NDCs would be 56.31 % and 52.43 %, respectively.

Notice that the additional cost imposed to other participants is an increasing function of the country's importance in terms of CO2 emissions, as Fig. 1 shows, separately for the small countries and the top 5 emitters (China, United States, India, Russia and Japan).

This study shows how tempted a country can be to adopt free riding behavior. To this end, the savings that the country would obtain by not participating in the CO2 emissions reduction target can be compared to the additional cost it imposes on other countries. If this ratio is less than one, the country could find convenience in non-participation and therefore behave as a free rider. The simulation also allows us to measure the additional burden that countries participating in the agreement would have to bear, when some countries do not participate. Consequently, we can label high-risk and low-risk for free riding countries with the above ratio with values above one and below one, respectively.

In addition, we show the cascading effects of non-participation, particularly when the U.S. withdrawal could encourage similar actions by other nations. The simulation underscores that global climate efforts rely heavily on the active participation of major economies.

This case identifies a potential opportunistic behavior, elaborating further the lines of Nordhaus (2015) discussion of the climate club formation, which can be exercised by a country which can negotiate a discount/compensation in the assigned target, knowing that the others would be prepared to concede it, because in the end the additional cost that they suffer is higher than compensation required by the country threatening to free ride. The climate club would therefore allow the introduction of obligations and sanctions related to free riding (Nordhaus, 2021). Climate club could improve the effectiveness of environmental agreements enhancing cooperation across industrialized and developing countries, with common but differentiated responsibilities in the context of climate change mitigation (Prakash and Potoski, 2007).

There are three interesting considerations, stemming from the interpretation of the empirical results of the model.

Firstly, as expected, China is the most important country in the NDC policy framework. A hypothetical withdrawal of China would impose an additional cost of 80 % ad 72 % on all others, in the cases of unconditional and conditional NDC, respectively (Table 4 Columns 3 and 4). The cost share (unconditional) borne by China accounts for about 31 % of total cost of the NDC policy (Table 4 Column 5) although her share of total emissions is 32.1 % (Table 4 Column 2).

These figures underscore China's central role in the global

[4] The results for all the individual countries are available upon request. Units of measurement: share of emissions: percentage; additional cost: percentage increase of burden if the countries group free ride.

Table 4
Penalties and free riding for groups of countries and some specific countries.

Countries year 2021	Share of emissions %	Addit. cost uncond %.	Addit. cost cond. %	Benefit uncond. %	Benefit cond. %	Ratio benefits/costs uncond.	Ratio benefits/ costs cond.	Ratio cond. > ratio uncond.
Brics10[a]	50.00	276.17	228.30	56.31	52.43	0.20	0.23	1
Brics4[b]	44.00	126.44	152.87	40.00	44.00	0.32	0.29	0
Brics10 (No China)	17.91	59.81	54.10	25.40	23.68	0.42	0.44	1
104 countries (1 % emiss)	1.00	2.38	3.15	1.46	1.92	0.61	0.61	0
32 poorest GDP PC	0.60	0.76	0.98	0.47	0.61	0.62	0.62	0
GCC	5.44	8.79	8.15	5.13	4.78	0.58	0.59	1
Russia	4.91	16.56	15.26	9.13	8.50	0.55	0.56	1
India	7.58	10.44	9.65	6.02	5.60	0.58	0.59	1
United States	14.01	18.74	20.59	10.18	11.04	0.54	0.54	0
China	32.09	80.69	72.00	30.91	28.75	0.38	0.40	1

Note.
[a] Brics10 is an intergovernmental grouping which, from 2024, includes Brazil, Russia, India, China, South-Africa, Saudi Arabia, Iran, the United Arab Emirates, Egypt, Ethiopia.
[b] Bric4 is the original group: Brazil, Russia, India, China.

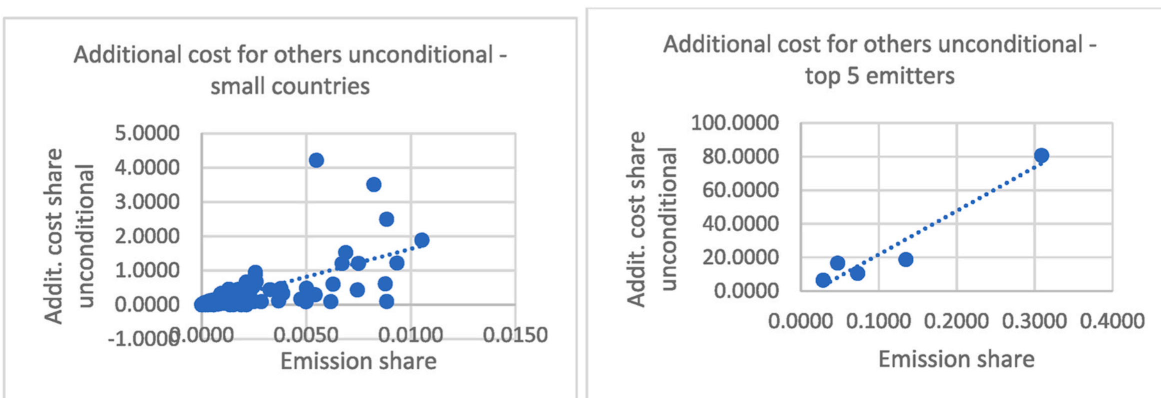

Fig. 1. Additional cost and CO2 emissions.

decarbonization effort—its active participation is crucial for meeting global climate targets, and any withdrawal or reduction in its commitment would significantly undermine collective progress.

In contrast, the United States, while also a major emitter, contributes a smaller share of global emissions at 14.01 % (Table 4, Column 2). Despite this, the consequences of U.S. non-participation are still considerable, imposing additional costs of 18.74 % and 20.59 % on the remaining participants under unconditional and conditional NDC scenarios, respectively (Table 4, Columns 3 and 4). These additional costs, while lower in magnitude than those associated with a hypothetical Chinese withdrawal, still represent a significant burden on cooperative nations. However, the cost share borne by the U.S. under its unconditional commitment is only 10.18 % (Table 4, Column 5), which is notably less than its share of global emissions. This lower proportion suggests that the U.S.'s potential to bear the costs of decarbonization is underutilized relative to its emissions footprint.

The contrast between China and the U.S. highlights key differences in their roles within the NDC framework. While China's participation is indispensable due to the sheer scale of its emissions and the proportionality of its commitments to its emissions share, the U.S. plays a critical role in setting an example for other advanced economies. The recent U.S. withdrawal from the Paris Agreement exacerbates global challenges, not only because of the additional costs it imposes on others but also due to the risk of setting a precedent that may encourage other nations to disengage. Unlike China, which has committed to ambitious renewable energy investments and is a global leader in the deployment of solar and wind energy, the U.S. withdrawal signals a retreat from international climate leadership and risks undermining the credibility of multilateral climate efforts.

These differences also reflect diverging domestic and international strategies. While China has tied its economic development to large-scale investments in renewable energy and climate technologies, the U.S. decision to prioritize short-term economic interests, as evidenced by its withdrawal, reveals a focus on domestic priorities over global cooperation. This divergence in strategy not only affects the direct financial burdens on cooperating countries but also highlights the broader geopolitical implications of differing approaches to climate change.

In summary, while both China and the United States are critical players in the NDC framework, their impacts and roles differ significantly. China's active participation is essential due to its emissions magnitude, and its withdrawal would create unparalleled challenges for the global community. Meanwhile, the U.S. withdrawal, although less impactful in absolute terms, has far-reaching consequences for global cooperation and the willingness of other nations to fulfill their commitments.

Secondly, the cost incurred in countries to achieve the NDC goal is different among countries, and this also depends on the type of RES that each country uses in the energy mix. For example, countries with high insolation can exploit solar energy more efficiently than other countries. Although solar panel costs have fallen globally, installation can be cost-effective in countries with low labor costs for installation, and government support. In the case of wind, coastal regions or those with large open spaces can benefit from an abundant wind resource, reducing costs compared to countries with less consistent wind.

Thirdly, the effects of non-participation in climate agreements are non-linear, implying that the cost imposed by a group of non-participating countries is not simply the sum of the individual effects of each country. For instance, considering the emissions contributions of the Gulf Cooperation Council (GCC) countries, Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates, the findings demonstrate that the collective cost imposed by this group is distinct from and greater than the aggregated costs of each country acting alone. This highlights the compounding impacts of collective non-cooperation on global climate efforts.

The study underscores the critical importance of maintaining multilateral cooperation to counteract the destabilizing effects of such policy reversals and offers actionable insights for policymakers navigating the challenges of global climate governance. Additionally, it emphasizes the necessity of addressing free-riding behaviour through enforcement mechanisms, which are essential for fostering compliance and sustaining the integrity of international agreements.

China therefore plays a key role in the fight against climate change and in achieving the goals of the Paris Agreement. According to the NDC, China has committed to achieve the peak CO2 emissions in 2030, decreasing CO2 emissions per unit of GDP by 65 % from the 2005 level (Zhou et al., 2021). Although China is among the world's leading contributors of GHG emissions, the country is making impressive efforts towards climate change mitigation. In fact, as of 2023, more than half of all new solar and wind power in the world has been installed in China. China is the world's leading producer of RES and is producing and using technologies for the energy transition at a rapid pace, such as photovoltaic panels and batteries for storage, and is developing projects aimed at capturing the carbon dioxide released by the fumes of large plants. The implementation of projects to produce hydrogen with low environmental impact is also continuously increasing, and plants are being developed for the generation of "green" hydrogen, which is obtained through the electrolysis of water in special electrochemical cells powered by electricity produced by RES. China represents a complex case in terms of economic development and respect for the environment. Although it has made significant progress in promoting renewable energy and implementing more stringent environmental policies, the country continues to face far-reaching environmental challenges due to its rapid industrialization and urbanization.

Free-rider behaviors prevent international environmental agreements from being effective and this basically can happen when policy makers only care about the welfare level of their respective country. In this framework, enforcement mechanisms should include clearly defined penalties for non-compliance and rewards for adherence. Financial sanctions, trade restrictions, or exclusion from international benefits could deter free-riding behaviours, while access to green financing or preferential trade terms could reward compliance. The creation of climate clubs, as proposed by the G7, offers a promising path forward. Membership in such clubs could be contingent on meeting specific emissions reduction targets, with benefits such as shared technology, reduced tariffs on green goods, and collective funding for green projects tied to active participation. These clubs could also impose penalties on non-member states to discourage free riding.

4. Conclusions

This study has presented a theoretical model and an empirical analysis of the costs that might arise for a community of countries to reach the global goal of reducing CO2 emissions when a single country or a group of countries adopts free-riding behaviors. The analysis focused on the Paris Agreement and the Nationally Determined Contributions (NDCs) submitted by countries to meet global emissions reduction targets.

The relevance of this model lies in its ability to provide policymakers with quantitative measures related to the energy transition cooperation process, going beyond traditional metrics like emissions reduction percentages. By considering the costs of free-riding and the additional burden imposed on cooperative countries, the model highlights the need for stronger global mechanisms to ensure equitable burden-sharing in decarbonization efforts.

The recent decision by the United States to withdraw from the Paris Agreement on January 20, 2025, brings new urgency to these findings. As one of the largest greenhouse gas emitters, the U.S.'s non-participation increases the financial and environmental burden on other countries, particularly those that remain committed to their NDC targets. Beyond the direct costs, the withdrawal also risks undermining global trust and cooperation, potentially encouraging other nations to prioritize short-term economic gains over long-term climate commitments. The risk of a domino effect—where the U.S.'s withdrawal inspires other countries to follow suit—highlights the fragility of voluntary agreements like the Paris Agreement and underscores the need for binding mechanisms.

This study demonstrates that additional costs induced by free-riding behavior increase disproportionately with the size of the non-participating country's share of global emissions. Wealthier nations with higher GDPs, which contribute significantly to emissions, impose the greatest burden when they renege on their commitments. The U.S.'s withdrawal illustrates this dynamic, as it not only imposes financial costs on other participants but also weakens the collective momentum necessary to achieve global climate goals.

To address these challenges, new policy measures are essential to strengthen global cooperation in tackling climate change and ensuring smooth energy transition. Enforcement mechanisms are pivotal in curbing free-riding behaviors and fostering compliance. A robust global monitoring framework is essential for tracking progress and ensuring accountability. Enforcement mechanisms should also consider the disparities between developed and developing countries. Financial penalties could be paired with increased international support for developing nations, ensuring equitable opportunities to transition to renewable energy sources, reducing perceptions of unfair burdens, and encouraging broader participation. One critical approach is the introduction of sanctions and incentives to align national actions with international goals. Policymakers could implement financial penalties, carbon border adjustments, and trade restrictions to discourage free-riding behaviors by non-participating countries, while offering economic or technological support to reward nations that uphold their commitments. These measures would create tangible costs for non-compliance and provide meaningful benefits for active participation.

Additionally, future international agreements should move beyond the voluntary frameworks exemplified by the Paris Agreement, which are vulnerable to non-compliance. Incorporating legally binding targets and enforcement mechanisms would ensure accountability and equitable burden-sharing among nations, reinforcing the reliability of collective commitments. Such binding commitments would mitigate the risks of free-riding and encourage countries to take more decisive actions toward emissions reductions.

Innovative initiatives like climate clubs and regional coalitions, such as the G7 Climate Club, offer another avenue for strengthening global collaboration. These groups can foster cooperation among like-minded nations by providing preferential trade terms, facilitating technology-sharing agreements, and offering financial incentives. By creating an inclusive and supportive structure, climate clubs could establish a stable foundation for collective action while effectively isolating countries that choose not to comply.

Efforts must also focus on reengaging major emitters, such as the United States and other large economies that may have withdrawn from multilateral agreements. Diplomatic strategies should highlight shared economic opportunities in renewable energy markets and underscore the long-term economic and environmental costs of climate inaction. Reintegrating these key players into global agreements is critical for maintaining momentum and achieving meaningful progress.

Furthermore, supporting developing countries is vital to ensuring the inclusivity of global climate action. Emerging economies often face significant challenges in transitioning away from fossil fuels, including high costs, inadequate infrastructure, and societal resistance to change. Expanding mechanisms for technology transfer, reducing trade barriers for green technologies, and increasing climate finance can enable these countries to bypass traditional development models and transition directly to sustainable and resilient economic systems.

The findings also emphasize the indispensable role of multilateral cooperation in reducing global emissions. Achieving decarbonization targets is significantly more cost-effective when all countries participate, compared to fragmented efforts that place undue strain on cooperative nations, even if they are the most advanced economies. The energy transition must therefore prioritize inclusivity, fostering partnerships between developed and developing countries to ensure sustainable growth that benefits all. This collective approach is essential not only to achieve emissions reductions but also to establish a more equitable and united response to the shared challenge of climate change.

The limitations of this study, such as the availability of detailed data on technological programs and the social and health costs of climate change, highlight opportunities for future research. More granular data would allow for a deeper understanding of the economic and social dimensions of decarbonization policies. Additionally, scenario analyses could explore the cost implications of different policy pathways, identifying the most cost-effective strategies for achieving emissions reductions. Future research could build on our framework by expanding it to incorporate cross-sectoral cooperation mechanisms, which would further highlight the multidimensional nature of climate governance, considering explicitly agriculture, heavy industry and new technology sectors.

The recent U.S. withdrawal underscores the urgent need for innovative policies and mechanisms to maintain momentum in global climate efforts. While emerging economies currently contribute a small share of CO_2 emissions, their reliance on fossil fuels for development could make them the primary sources of climate-changing emissions by 2050 if left unaddressed. International cooperation, backed by clear incentives, sanctions, and support mechanisms, is essential to ensure that all countries, regardless of economic status, can contribute to the energy transition.

Ultimately, the energy transition represents not only a challenge but also an opportunity to redefine global economic and social priorities. Cooperation can foster a sustainable future, but achieving this vision requires decisive action to address the risks of free-riding and strengthen the institutions that support collective climate action.

CRediT authorship contribution statement

Simona Bigerna: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Silvia Micheli:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.126733.

Data availability

Data will be made available on request.

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