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INCENTIVIZING A CARBON-FREE ECONOMY: A METHOD TO IDENTIFY FREE-RIDERS

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Abstract
Top-down approaches to reducing global carbon dioxide emissions have so far met with limited success, even though most countries accept the urgency of mitigating climate change and have entered into various agreements that should help reduce emissions. This article does not dismiss the importance of such “top-down” agreements for developing rational strategies to achieve declining total emissions, but it suggests a complementary approach to encourage immediate “bottom-up” progress on climate goals that do not need to wait for global cooperation. This paper develops a framework to identify free-riding behavior among countries that use three readily measured parameters of the country’s economy: carbon intensity, rate of change of the carbon intensity, and per capita GDP. It then goes on to propose a simple formula to calculate trade sanctions against a free-riding country that could be used in bilateral actions to incentivize carbon emissions reductions. The paper argues that the value of the goods, the difference in carbon intensity between the importer and exporter, and the cost of carbon removal can be used to calculate the unfair trade advantage of a free-riding country. The dynamics of the proposed framework are tested through three case studies, highlighting current free-rider behavior—based on historic emissions for the period 1991–2012; an alternate, hypothetical scenario whereby a subset of countries follow aggressive carbon emission reductions; and a 450 ppm stabilization scenario.

Keywords: climate policy, carbon pricing, free-rider, emissions trading, climate change.
JEL: Q38, Q41, Q56, Q54.

Introduction

The Paris Agreement Parties notwithstanding[1], the repeated failure of international climate negotiations has shown that solutions requiring the consensus of all parties are difficult to agree upon and unlikely to be implemented soon [Victor, 2011]. Since the introduction and adoption of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, the total annual mean concentration of carbon dioxide in the atmosphere has increased from 356 to approximately 410 ppm, highlighting the failure of the existing international treaties at reducing world emissions[2]. Furthermore, the non-binding emission reduction targets, which have resulted from years of negotiations, have been shown to be insufficient to keep the potential warming below the 2°C target [Villarreal-Singer et al., 2013][3] leave alone the more ambitious goal of 1.5°C set at Paris[4]. The world appears on track for more than 2°C of warming unless there are both large emissions reductions and large-scale deployment of negative emissions technologies [Fuss et al., 2014; Sanford et al., 2014].

Stabilizing emissions and eventually driving them to zero will require universal cooperation. Cooperation is difficult: each country benefits from reduced world emissions but can benefit more by not cooperating and relying on other countries to address the problem. This is the classic tragedy of the commons [Hardin, 1968], which can only be resolved if this so-called "free-riding" is suppressed. An international agreement on emissions reductions with trade sanctions for non-participants could address the free-riding problem [Barrett, 2008; 2011; Irfanoglu et al., 2015; Nordhaus, 2015].

On one level, identifying free-riders in the climate arena is easy: some countries are already reducing their carbon dioxide emissions (which are a transparent function of fossil fuel consumption, at least in the absence of widespread carbon capture and storage technology), while others are not. The problem is not as complicated as in venues where behavior can be disguised, such as in peer-to-peer networks, or in ex-ante situations where it is useful to predict who might free-ride [Andreoni, McGuire, 1993]. Yet despite the transparency of ex-post emissions reductions, without an international agreement it is difficult to determine whether countries are lowering their emissions by an appropriate amount.

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[1] https://unfccc.int/process/the-paris-agreement/status-of-ratification.

[2] https://research.noaa.gov/article/ArtMID/587/ArticleID/2362/Another-climate-milestone-falls-at-NOAA%E2%80%99s-Mauna-Loa-observatory.

[3] Energy and Climate Change. Paris, International Energy Agency, 2015. P. 32.

[4] Summary for Policymakers. In: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, H. L. Miller (eds.). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, Cambridge University Press, 2007. P. 12. https://www.ipcc.ch/site/assets/uploads/2018/05/ar4_wg1_full_report-1.pdf.

A more complicated aspect of climate mitigation relates to other greenhouse gases like methane, where emissions are much harder to quantify [Allen et al., 2013]. In a world that has entered an overshoot scenario, the relative importance of these greenhouse gas emissions is rising as they primarily impact the overshoot period. However, even with this caveat, CO_2 emissions are still by far the largest contributor, and developing a mechanism to get a handle on them is useful. Given the very different issues arising in methane emission reductions, it may be beneficial to regulate them separately. Certainly, the difficulties in tracking methane emissions should not become an excuse to avoid regulations of carbon extraction.

The large-scale introduction of carbon capture and storage technologies, either operating at point sources or by removing carbon from the environment, either through bioenergy combined with carbon capture and storage (BECCS) or by removing CO_2 directly from the atmosphere and subsequent storage (DACCS), would introduce an additional term into carbon accounting. Rather than just tracking the consumption of fossil fuels, one would have to subtract the net amount of carbon sequestered. Presumably, carbon sequestration would have to be certified in some manner. Moreover, operators would want to be paid for their effort and thus leave a clear accounting trail. The biggest challenge would be ascertaining the permanence of storage. In effect, operators of leaky storage sites would be carbon emitters. Net sequestration is new sequestration minus the losses from storage sites. Operators would have a direct incentive to hide these losses. Unfortunately, their interest in hiding those emissions could align with the interests of a country to understate their total carbon emissions. On the other hand, most countries that foster carbon sequestration within their borders have demonstrated a willingness to address climate change. Most of these countries could define accounting rules that would have to be adhered to when reporting net carbon emissions. In other words, a country's carbon emission is set by its fossil fuel consumption. If a country wants to claim credit for carbon sequestration, it would have to adhere to generally accepted accounting practice for reporting carbon sequestration.

This article proposes a simple methodology for evaluating the appropriateness of a country's emissions reductions in comparison to other countries. The methodology is based on three economic metrics (GDP per capita, carbon intensity defined as emissions per unit of purchasing parity-adjusted GDP, and the year-to-year change in carbon intensity). Applying this methodology will identify countries that contribute the most to climate change and do the least to fix it. The metrics do not penalize economic growth and exempt poor countries with more pressing poverty issues. They could provide the basis for a generally acceptable rationale for trade sanctions, even in the absence of a formal international agreement. Though rarely used and perhaps difficult to implement, trade sanctions based on environmental standards appear permissible in some situations [Nielsen, 2009]. The focus of this paper is not to analyze the legal and political intricacies of trans-border carbon tariffs or border adjustment fees, but rather to provide a transparent and simple methodology for identifying free-riders, which could become a useful tool for policymakers interested in crafting carbon-based trade sanctions.

1. Defining the Climate Problem

For the scope of this discussion, the climate change problem is intentionally simplified to the release of fossil carbon, rather than other greenhouse gases. Human activities have led to the mobilization of carbon that enters the atmosphere, the biosphere or the oceans. Since these carbon reservoirs are in close contact, their carbon content is readily exchanged, but a net addition to this system will persist for thousands of years [Archer, 2005]. As a result, the mobilization of carbon results in excess CO_2 in the air, acidification of the ocean, and possibly increased biomass stocks altering the ecological balance. For climate change to stop, the CO_2 level in the air must be stabilized, which, in turn, implies net zero CO_2 emissions.

Narrowing the scope to fossil carbon focuses the discussion on the energy sector. In providing energy for electricity generation, heat, and motive power, fossil carbon from the ground is combusted and converted to CO_2, which is typically emitted into the atmosphere. Some CO_2 is absorbed by oceans and terrestrial plants, but as emissions increase, roughly 60% stays in the atmosphere [Hansen, Sato, 2004]. The planet neutralizes carbon emissions on time scales of thousands of years, but on a human time scale of a couple of hundred years, about half the CO_2 will persist in the atmosphere. As a result, CO_2 emissions create a stock problem rather than a flow problem. In order to stabilize CO_2 in the atmosphere, it will be necessary to essentially stop emitting and completely avoid the release of fossil carbon into the environment. This could be accomplished by not using fossil fuels, or by capturing the released CO_2 and storing it safely and permanently [Kharecha, Hansen, 2008].

2. Methods

Measuring a Country's Carbon Footprint

Conceptually, free-riding countries do less than others in similar circumstances toward reducing net carbon emissions. There are many different metrics for assessing a country's carbon mitigation effort, with each metric having its own merit and shortcomings. Among the most used metrics are CO_2 per unit of energy, total CO_2 emissions, CO_2 per capita, and carbon intensity (CO_2 per unit of GDP). In all cases we measure the amount of CO_2 in terms of the carbon content of the fossil fuel extracted or imported minus the amount of CO_2 sequestered by internationally accepted standards.

The first two metrics, CO_2 per unit of energy and total CO_2 emissions, are imperfect measures of a country's contribution to the climate change problem. CO_2 per unit of energy indicates the portion of carbon-free sources of energy used by a country, but even if this metric is low, the total amount of emissions might still be quite large if the country uses a significant amount of energy. Similarly, total CO_2 emissions are an inadequate metric as it does not reflect the size of a country's population or its economic activity.

CO_2 per capita is simply the total emissions of a country divided by its population. This metric normalizes total emissions to the size of a country, which is useful when comparing countries with large populations (e.g. China) with those having small populations (e.g. UK). Although per capita emissions can be a useful indicator, it does not directly describe the structure of an economy, its fuel composition, or its efficiency in using energy and resources. Some have argued for the formulation of an international climate agreement based on equal per capita rights of carbon emissions [Kinzig, Kammen, 1998]. Although this might seem like a straightforward and moral approach to global climate negotiations, the political hurdles associated with its implementation do not make it a useful approach for dealing with the climate problem in the short or medium term.

At the country level, carbon intensity is defined as a unit of emitted CO_2 per unit of GDP, and it is essentially a measurement of the "carbon efficiency" of a particular economy. Carbon intensity (*C*) can be thought of as being the product of two indicators: emission intensity (CO_2/TPES)[5] and energy intensity (TPES/GDP) [Mielnik, Goldemberg, 1999]:

$$C\left(\frac{\mathrm{CO_2}}{\mathrm{GDP}}\right)=\left(\frac{\mathrm{CO_2}}{\mathrm{TRES}}\right)\times\left(\frac{\mathrm{TRES}}{\mathrm{GDP}}\right). \qquad (1)$$

Changes in carbon intensity respond to shifts in the technological composition and efficiency of the energy matrix (CO_2/TPES), as well as to fundamental changes in the structure and nature of the economy, lifestyle, and efficiency of energy use (TPES/GDP). Thus, when thinking about climate change, reduction in carbon intensity is a useful metric as it does not prescribe a specific economic composition, can de-

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[5] Total Primary Energy Supply.

crease while increasing GDP, and incentivizes efficient conversion of resources into energy flows.

This paper proposes a combination of metrics for deciding whether a country is doing its fair share to reduce emissions, or whether it is a free-rider, which may facilitate the development of trade sanctions on free-riding countries. The metrics are outcome-oriented, and therefore it is not necessary to assess the specific approaches or technologies a country deploys in reducing carbon emissions. Hereafter, a country's carbon footprint is measured by current emissions expressed in terms of carbon intensity (*C*). Focusing on carbon intensity encourages adoption of energy technologies with lower emissions, while not discouraging economic growth or energy use per se.

3. Framework Variables

A country's carbon management effort will be measured by three quantities: (1) the carbon intensity *C*, (2) the relative rate of change in *C*, defined as *R* (2), and (3) the country's wealth (expressed as W = GDP/person). Technically GDP measures a rate of money flow rather than wealth, but we take it as a simple proxy for wealth, as countries with a large domestic product (on a per capita basis) tend to be wealthier than those with low values of *W*. The carbon intensity *C* is defined as the net carbon consumption of a country divided by its GDP (measured in constant purchasing power). Model calculations use an IEA dataset from 1971 through 2012[6], which only includes emissions from fossil fuel consumption and ignores emissions associated with cement production and land-use change. In principle these should be accounted for as well.

The rate of change in *C*, referred to as *R,* requires historic carbon intensity data. The relative change is calculated by the following approximation:

$$R_t = \left(\frac{1}{C_t}\right)\frac{\mathrm{d}C}{\mathrm{d}t} \approx 2\left(\frac{C_t - C_{t-1}}{C_t + C_{t-1}}\right). \tag{2}$$

The rate of change of each country's carbon intensity is calculated for 1971–2012. GDP uses purchasing power parity in constant US$ (2005). Population numbers reported in the same study are used to calculate per capita GDP for each country. For each year in the series, the result is a distribution of all countries in a three-dimensional space spanned by *CRW* (Fig. 1).

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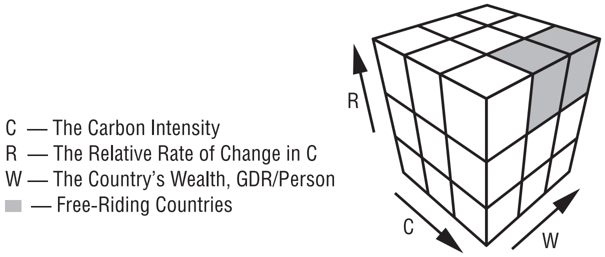
[6] www.iea.org/data-and-statistics.



Source: authors’ estimations based on www.iea.org/data-and-statistics.

Fig. 1. **The CRW Space**

4. Distribution in the *CRW* Space

As a basis for establishing the framework defined in this paper, the *CRW* space is sliced into population-capped terciles in all three dimensions, resulting in 27 sub-boxes encompassing all countries. Splitting the world into terciles allows for classifying each country’s *C*, *R* and *W* into three broad categories: “best”, “middle”, and “worst”. The population terciles identify poor and rich countries, carbon-intensive and carbon-efficient countries, and countries that are improving their carbon intensity and those that are not. For example, the top tercile in carbon intensity contains a subset of all countries, comprising one third of world population that rank highest in carbon intensity (i.e. have the highest carbon consumption per unit of GDP). The bottom tercile is the subset of all countries that rank lowest in carbon intensity and comprise one third of world population. The remaining countries, which also make up one third of world population, constitute the middle tercile. In cases where a country straddles a boundary, it is counted in the tercile containing more than half its population.

5. Identifying Free-Riders

Free-riders are defined by ranking all countries in terms of carbon intensity (*C*), rate of change in carbon intensity (*R*), and wealth (*W*). These metrics consider current performance, rate of improvement, and ability to act. A free-riding country meets the following criteria.

1. The country’s *C* is in the top tercile of all the countries in the world (two thirds of the world population live in countries with lower carbon intensity).
2. The country is in the top tercile in carbon intensity change (*R*). A reduction in emissions shows up with a negative sign. Therefore, the largest values show deterioration or little improvement in carbon intensity.

3. The country is in one of the top two terciles in per capita GDP (W), and therefore can afford to work on the problem.

The first criterion suggests that a free-riding country has high carbon intensity. The second criterion singles out those countries that are slow to improve. The third criterion exempts the poorest countries which need to build their economy. Thus, countries in the bottom tercile in W are never considered free-riders.

These metrics capture the concept of common but *differentiated responsibility*. Developed countries with efficient infrastructures are held to introduce novel technologies to reduce emissions. Emerging economies, with rapid growth and often lower efficiencies in power generation and use, can achieve reductions in emissions by aiming for higher efficiency. Poor countries are simply held to accelerate development until they reach a point where they become responsible for emission reductions.

Of the 27 sub-boxes formed by the terciles in the three dimensions, nine sub-boxes belong in the top tercile in carbon intensity. Of these, three are also in the top tercile for the rate of change (R). Among those three, two are not in the bottom tercile regarding wealth. Countries which end up in these two sub-boxes are prima facie free-riders. In other words, free-riders occupy two of the 27 boxes in the cube (shaded grey in Fig. 1). It is possible for the free-rider section of the box to be empty and to remain empty as long as all of the carbon-intensive countries are either poor or at least modestly improving their carbon emissions. The number of free-riders will increase over time if some countries start working on emissions reductions while others do not. Many countries already claim to work on reducing their carbon intensity (e.g. China pledged in Paris to reduce carbon intensity by 60–65% from 2005 levels by 2030, and to reduce total emissions starting no later than 2030[7], whereas others, such as the United States, have begun to shift away from coal in favor of less carbon-intensive sources. Differential rates of progress will likely sweep the laggard countries into the free-rider box.

6. Trade Implications: An Example

Free-riding countries will have an unfair advantage in bilateral trades. By establishing the relative position of different countries in the CRW space, it becomes possible for trading partners to establish a basis to account for unfair advantages obtained by free-riders—something that accounting based on total emissions or per capita emissions fails to

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[7] China's INDC. P. 21 https://www4.unfccc.int/sites/submissions/INDC/Published%20Documents/China/1/China's%20INDC%20-%20on%2030%20June%202015.pdf.

provide. The metrics allow for calculating the magnitude of the advantage gained by the free-rider by accounting for the difference in carbon intensity between the exporting and importing countries. This method avoids the complexities of life-cycle analysis and could decrease the total cost of compliance. For an exporting country identified as a free-rider, a carbon trade sanction to account for an unfair advantage could take the following form:

$$CarbonTradeSanction = (C_{exp} - C_{imp})P_c V_c, \tag{3}$$

where C_{exp}represents the carbon intensity of the exporting country (total carbon consumption / GDP), C_{imp} is the carbon intensity of the importing country, P_c is a negotiated or stipulated price per metric ton of CO_2, and V_c is the total value of the imported goods subject to the fee. In addition to dealing with a free-riding country, the following condition must hold for the importing country to be justified in imposing a carbon trade sanction:

$$(C_{exp} - C_{imp}) > 0. \tag{4}$$

The example above is just one possible option for calculating a trade sanction using the free-rider identification methodology proposed in this paper. An effective carbon trade sanction will reflect an approximate cost of carbon mitigation in the importing country. For example, a country that uses a cap-and-trade system internally could very well justify its imposed carbon penalty by using the same carbon price that it charges domestic emitters. One could also consider an implementation where the importing country would not just charge a fee, but actually produce or purchase carbon reductions, e.g. certificates of sequestration to offset the difference in carbon emissions. Over time, a worldwide accepted price for carbon may emerge due to either regulatory steps or technological progress and could form the basis for rational carbon trade sanctions [Nordhaus, 2015][8].

7. Results and Discussion

System Dynamics

In the proposed framework, year-to-year movement between the terciles is not constrained by fixed carbon thresholds, but rather by population boundaries; therefore, there is no absolute carbon intensity that guarantees permanent residence in the "safe zone". If one considers that China and India together represent about one third of the world

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[8] The advent of air capture technology adds a new possibility [Lackner, Brennan, 2009]. The import of goods from carbon-intensive countries could be accompanied by physical capture of CO_2 from the air. This capture plus associated storage would set a well-supported price of carbon [Fox, 2012].

population, their movement between terciles means that many countries get squeezed out as China or India's emissions change, creating an incentive for everyone to improve. On one side, countries have the incentive to always try to be better than China (otherwise they could get pushed out by China's improvement), and at the same time China and India have the incentive to improve in order to stay out of the free-rider space. The actual observed range of *C*, *R*, *W* will ultimately determine the size of the boxes and change from year to year.

Collectively, the world is not reducing CO_2 emissions fast enough. Nevertheless, *R* for many countries is negative (Fig. 2), suggesting that in many cases there is an economic incentive to improve carbon intensity. If, however, a large fraction of the major emitters were to actively pursue more aggressive carbon reductions, the shape and composition of the *CRW* space could change rapidly (Case Study II). Active countries would swiftly lower their *R*, resulting in a gradual reduction in *C*. Non-acting countries would move up in *C* and *R* relative to their neighbors. Assuming a country is not exempt because it is poor (lowest tercile in *W*), it will soon find itself in the free-rider corner of the three-dimensional *CRW* box.

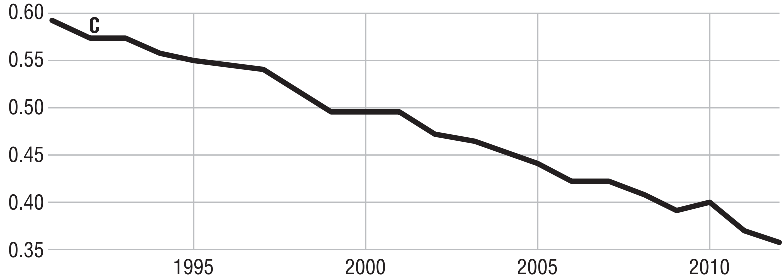
8. Case Studies

Using the rules described in the section above, three case studies were performed using data from the 2014 IEA Emissions report. In Case Study I, a list of free-riding countries was developed for several years in the recent past. In Case Study II, a counterfactual simulation is developed where a subset of randomly selected countries started aggressively improving their carbon intensities in 1991. The purpose of the second case study is to highlight how changes in the *CRW* space occur when countries actively reduce carbon emissions. Sensitivities to the reduction rates are explored. Case Study III demonstrates that the world is still far from producing the carbon intensity reductions required to stabilize atmospheric CO_2 concentrations at or below 450 ppm.

Case Study I: Free-Riders Across Time

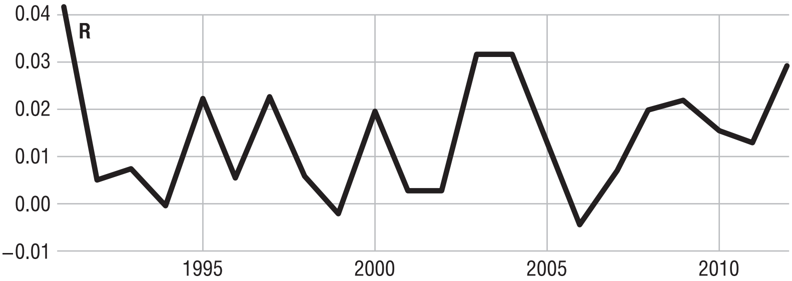
Fig. 2a highlights the top tercile threshold for *C* (carbon intensity) for the years 1991–2012. Shaded region represents free-rider zone for each year. For every year in the time series, countries above the line would qualify as free-riders if they meet the criteria for *R* and *W*. The tercile cutoff value for *C* has been, on average, decreasing during the time period studied, highlighting efficiency gains in the energy sector.

Fig. 2b shows the free-rider threshold for the change in carbon intensity (*R*) across time. Any country falling above this threshold and meeting the criteria for *C* and *W* would be considered a free-rider. In contrast to Fig. 2a, the time-series for the cutoff *R* does not show a distinct downward trend and can fluctuate from year to year. Cases in which the threshold for *R* is negative imply that for these years absolute improvements in *C* would not necessarily exempt a country from falling into the free-rider tercile for *R*.



Source: authors' estimations based on www.iea.org/data-and-statistics.

Fig. 2a. **Threshold for Carbon Intensity, C** (kg(CO_2)/USD)

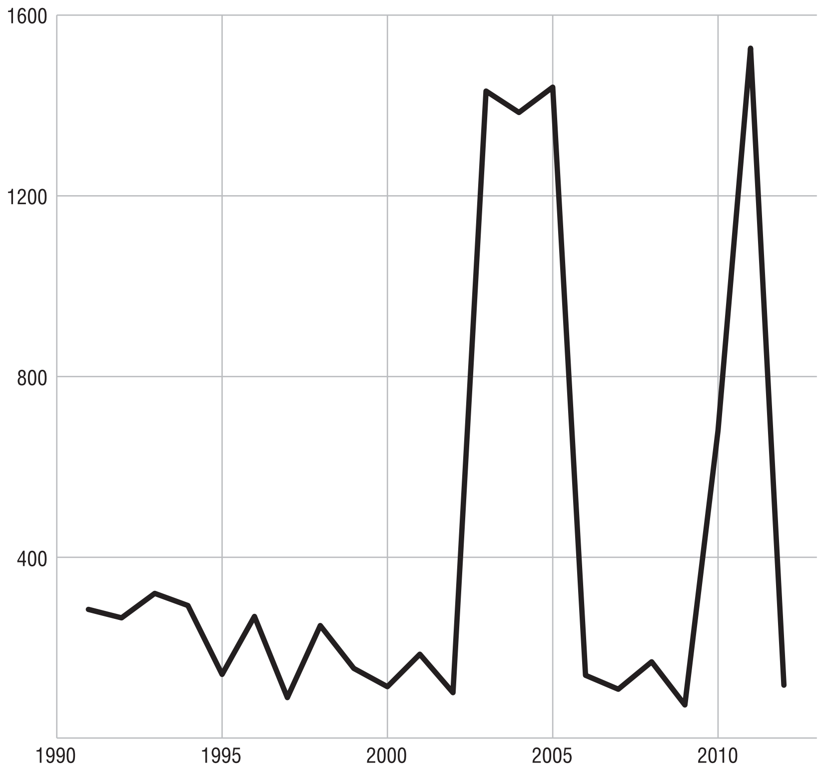


Source: authors' estimations based on www.iea.org/data-and-statistics.

Fig. 2b. **Top Tercile Threshold for the Change in Carbon Intensity, R**

Fig. 3 shows the total free-rider population for the years 1991–2012. The years where the free-rider population is disproportionally high are those for which China ended up in the free-rider zone (2003–2005 and 2011). This highlights the dynamic nature of the framework and how dramatically the year-to-year free-rider population can change.

This framework avoids penalizing countries that have already managed to have low carbon intensities (e.g. France)—and rewards those trying to improve. The dynamics of this scheme are such that as some countries start participating, the group of free-riders will change. This creates an incentive for countries not to fall into this list due to inactivity, and for other countries to work toward removing themselves from the list. As countries start to improve their carbon intensity *C*, those who do not cooperate will eventually be pushed into the free-riding corner.



Sourse: authors' estimations based on www.iea.org/data-and-statistics.

Fig. 3. **Free-Riders Across Time** (millions)

Case Study II: Simulating Cooperation

In this case study, a what-if scenario is followed in which the counterfactual assumption is made that some countries started to take climate change concerns seriously a long time ago. Starting in 1991, a subset of countries was randomly selected and a fixed reduction rate was subtracted from their baseline *R* while maintaining their historical GDP[9]. The purpose of this case study is to show how a group of countries actively pursuing carbon reductions can reshape the distribution of countries in the *CRW* space.

Figs. 4a, 4b, 4c, 4d, 4e, and 4f indicate how countries pursuing emission reductions can reshape the *CRW* space. The results highlight two major dynamics: firstly, if reduction rates are large enough, a small number of cooperating countries can push a large population into the free-rider zone; secondly, the results suggests the existence of a cooperating population threshold (~2 billion people) that, once exceeded, increases the likelihood of non-cooperating countries ending up in the

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[9] It is assumed that the economic activities associated with carbon management more or less produce the same change in GDP as the activities that have been replaced.

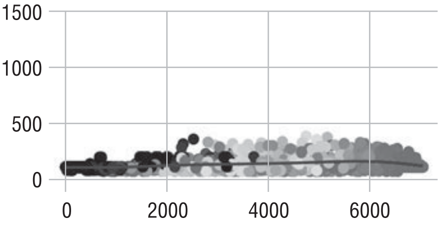

Fig. 4a. **Results for Case Study II, Free-Rider Population to Cooperating Population at Reduction Rate = 0.01** (millions)

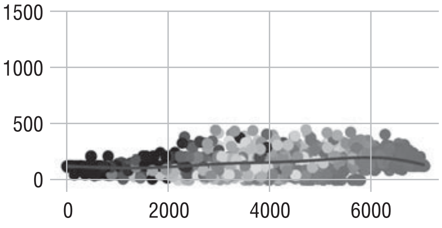

Fig. 4b. **Results for Case Study II, Free-Rider Population to Cooperating Population at Reduction Rate = 0.02** (millions)

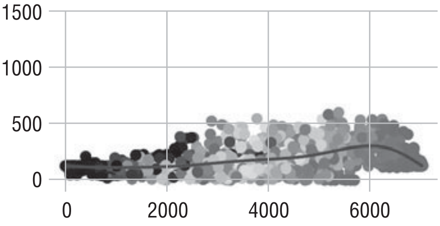

Fig. 4c. **Results for Case Study II, Free-Rider Population to Cooperating Population at Reduction Rate = 0.03** (millions)

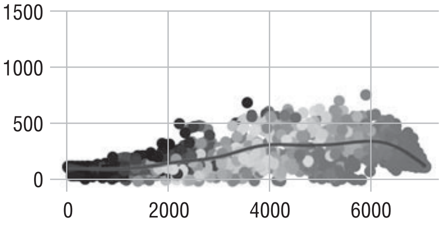

Fig. 4d. **Results for Case Study II, Free-Rider Population to Cooperating Population at Reduction Rate = 0.04** (millions)

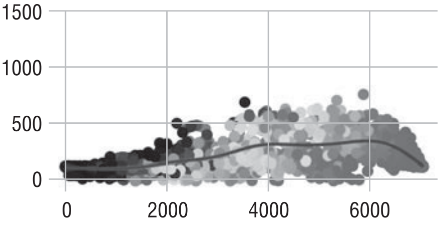

Fig. 4e. **Results for Case Study II, Free-Rider Population to Cooperating Population at Reduction Rate = 0.05** (millions)

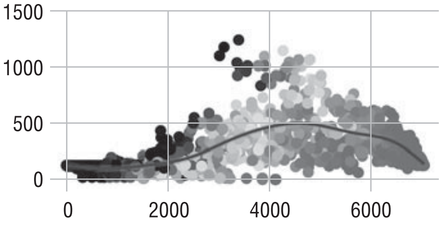

Fig. 4f. **Results for Case Study II, Free-Rider Population to Cooperating Population at Reduction Rate = 0.10** (millions)

Source: authors' estimations based on www.iea.org/data-and-statistics.

free-rider zone. Cooperating countries with large populations can have a significant impact on shaping the free-rider distribution.

Each panel in Figs. 4a and 4b shows the result of 1,000 simulations for the year 2012. Each simulation chose a random set of countries and lowered their carbon intensity change *R* by 1%, 2%, 3%, 4%, 5% and 10% per year starting in 1991. It is worth noting that, since *R* is negative, lowering *R* results in reduced emissions and lower carbon intensity in the counterfactual simulation relative to their actual performance. Each point represents the results of a single simulation. The abscissa of each point indicates the size of the cooperating population, whereas the ordinate indicates the resulting size of the free-rider population. The remainder of the total population is neither cooperating nor seen as a free-rider. The color of the point indicates the total number of cooperating countries in the simulation. It correlates with the size of the cooperating population.

Case Study III: Stabilizing at 450 ppm

It is worthwhile to estimate the size of the necessary reduction of CO_2 emissions to stabilize at a particular level. Starting from the observation that stabilization of CO_2 in the atmosphere requires emissions to go to zero implies a fixed budget for the remaining carbon. It takes roughly 4 GtC to raise the atmospheric concentration by 1 ppm[10]. This assumes that approximately half of the emissions are absorbed by the ocean and the biosphere [Lackner, 2009]. While this number would need to be fine-tuned for the actual time scale considered, it is roughly correct for a broad set of assumptions.

Assuming a stabilization goal of 450 ppm[11], which is slightly less ambitious than the 1.5°C target discussed in the IPCC Special Report on Global Warming of 1.5°C[12], the world would be allowed a total cumulative carbon budget E_w of approximately 160 GtC before emissions have to reach a level of zero[13]. This implies a world annual emission reduction necessary to reach this stabilization goal. The annual world emission $\varepsilon_w(t)$ can be described as an exponential decay:

$$\varepsilon_w = \varepsilon_{w_0} e^{t/\tau}. \tag{5}$$

Here ε_{w_0} is the annual carbon output at the start time $t = 0$. τ is the characteristic time over which emissions have to drop. The cumulative carbon budget is therefore:

$$E_w = \varepsilon_{w_0} \int_0^\infty e^{t/\tau}\,\mathrm{d}t, \tag{6}$$

$$E_w = \varepsilon_{w_0} \tau. \tag{7}$$

With $E_w = 160$ GtC and $\varepsilon_{w_0} = 10\ \mathrm{Gt}\frac{\mathrm{C}}{\mathrm{yr}}$, the characteristic time constant is $\tau = 16$ yrs. This translates into a required annual emission reduction of 6.06%[14].

ε_w can be rewritten in terms of the world population (p_w), average world carbon intensity (C_w) and average world GDP per capita (W_w), such that:

$$\varepsilon_w = p_w \times C_w \times W_w. \tag{8}$$

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[10] 1 ppm in the atmosphere represents 2.14 GtC based on the total mass of the atmosphere, a little less than half of the CO_2 ends up in relatively short order in the surface ocean or the biosphere.

[11] Summary for Policymakers. P. 16.

[12] Global Warming of 1.5°C. Geneva, IPCC, 2018. P. 4.

[13] Assumes the starting atmospheric CO_2 concentration is 410 ppm.

[14] An even simpler calculation backs this up: currently CO_2 rises at about 2.5 ppm per year; the remaining budget to reach 450 ppm is 40 ppm, or 16 years. Since most of the rise in CO_2 is due to fossil fuel emissions, these two numbers should indeed agree.

Therefore, the relative rate of change in ε_w can be expressed as:

$$\left(\frac{1}{\varepsilon_w}\right)\frac{\mathrm{d}\varepsilon_w}{\mathrm{d}t}=\left(\frac{1}{p_w}\right)\frac{\mathrm{d}p_w}{\mathrm{d}t}+\left(\frac{1}{C_w}\right)\frac{\mathrm{d}C_w}{\mathrm{d}t}+\left(\frac{1}{W_w}\right)\frac{\mathrm{d}W_w}{\mathrm{d}t} \tag{9}$$

or

$$R_w\equiv\left(\frac{1}{C_w}\right)\frac{\mathrm{d}C_w}{\mathrm{d}t}=\left(\frac{1}{\varepsilon_w}\right)\frac{\mathrm{d}\varepsilon_w}{\mathrm{d}t}-\left(\frac{1}{p_w}\right)\frac{\mathrm{d}p_w}{\mathrm{d}t}-\left(\frac{1}{W_w}\right)\frac{\mathrm{d}W_w}{\mathrm{d}t}. \tag{10}$$

The world's rate of change in carbon intensity has to overcome continued growth in population and world GDP. Assuming the average world population keeps growing at 1.1%/yr, with an average growth in world GDP per capita of ~2%/yr, a reduction in the world carbon intensity that keeps to the remaining carbon budget is determined:

$$\left(\frac{1}{C_w}\right)\frac{\mathrm{d}C_w}{\mathrm{d}t}=-6.06\%/yr-1.1\%/yr-2.0\%/yr, \tag{11}$$

$$R_w=-9.16\%/yr. \tag{12}$$

Throughout this paper, free-riders have been defined in terms of what the rest of the world is doing. A framework has been created where free-riders are determined by comparing their economic circumstances and efforts with the efforts put forth by other countries around the world. However, at present the efforts of all countries together are insufficient to stabilize emissions at 450 ppm. Given the global nature of the climate problem, the free-rider problem can be framed in terms of the average world effort required for emissions to asymptotically converge toward 450 ppm. Under this interpretation of the problem, the world would need an $R=\left(\frac{1}{C_w}\right)\frac{\mathrm{d}C_w}{\mathrm{d}t}$ that is greater than or equal to the 9.16%/yr reduction outlined above. Any country not meeting this metric would automatically be considered a laggard. It is worth noting that if this definition is used to identify a free-rider in 2012, there are only 13 countries (with a combined population of 121 million people) that have an R below the required downward trend. Every other country in the world is free-riding on its allowed annual carbon emissions. This small subset of countries gives an idea of the magnitude of the problem, and highlights the disconnect that exists between the actions required to stabilize at 450 ppm and the actual behavior of most countries around the world.

On the other hand, it may be easier to agree on a means of identifying free-riders when, under current conditions, most countries (and especially the most powerful countries) are not among the free-riders. The United States and China both have high carbon intensity but have also experienced large reductions in carbon intensity. These reductions may not have been driven by climate change concerns, but they nevertheless represent a positive outcome. In the U.S., per capita emissions have declined over the last two decades. Australia and Russia have usually been close to the free-rider box, and occasionally moved across that line. Right now, the typical free-rider is a resource-rich country with large revenues and little incentive for improving efficiency, and often receives substantial subsidies for fuels. Saudi Arabia is a good example.

Conclusion

Eliminating free-riding on the effort to reduce the world's carbon intensity to zero will require a means of identifying free-riders. This paper suggests a particular metric, which compares the outcome of any reduction effort across countries. While a case can be made that today there is virtually no country that does enough to avoid excessive climate change, free-riders are countries that underperform compared with the low average performance. By identifying free-riders and plausibly threatening action against them, it becomes possible to incentivize action in these countries. This, in turn, removes the excuse that action is futile for those who are undecided. If free-riding can be discouraged, the motivation to act will increase for everyone. This will also raise the average level of effort and, therefore, mark inaction as free-riding.

By encouraging a country to consider a trade-related action toward a free-rider, one turns the dynamic around. Up to this point free-riding simply required inaction; now it requires challenging an action, for example in front of the World Trade Organization (WTO), which in the court of public opinion is likely to be justified. This justification is even stronger if the border adjustment fee is not simply a tariff, but is used to pay for negative emissions that offset the imputed carbon emissions associated with the imported goods.

The rules of the WTO explicitly allow for certain forms of tariffs, such as anti-dumping and countervailing duties, which are designed for market distortions. The absence of a carbon price is distortionary, as the market price of fossil fuels does not fully reflect their social costs [Muller et al., 2011; Stiglitz, 2006]. As a result, charging for carbon reductions as proposed in this paper could be made compliant with the free trade principles of the WTO. There are other examples where WTO rules allow interference with free trade. For example, it is not considered an attack on free trade if individual countries unilaterally prohibit the import of shrimp when their capture kills a significant number of sea turtles [Nielsen, 2009]. Ignoring the hazards to sea turtles achieves an unfair cost advantage. Similarly, ignoring the emissions of carbon dioxide in the production of goods obtains an unfair cost advantage by ignoring a global threat to the environment. Rather than consider the border adjustment fee as a tariff interfering with free trade, one could consider it a service fee to recover the excess carbon that the free-riding country emitted. This option becomes even more powerful if negative emission technologies like BECCS or direct air capture coupled with sequestration could be deployed [Lawrence et al., 2018].

As some countries put a price on these social costs (either with an explicit carbon price or via regulatory actions), it will become important to identify free-riding countries. This paper proposes a fair methodology to identify those free-riders, and it is envisioned that international trade theorists could use such a methodology to devise a simple and straightforward system of carbon-based trade sanctions.

The free-rider identification methodology is based on three simple metrics: a country's carbon intensity (C), relative change in carbon intensity ($R = \left(\frac{1}{C_w}\right)\frac{\mathrm{d}C_w}{\mathrm{d}t}$), and wealth ($W$) using GDP per capita as a proxy. These variables are sorted into population-based terciles, and a country may be considered a free-rider if it is contained within the top terciles in terms of carbon intensity (C) and rate of change in carbon intensity (R), and it is not in the bottom tercile of wealth (W). A free-rider country has high overall carbon intensity, is not rapidly improving its carbon intensity, and is not among the poorest countries in the world.

By accounting for income or wealth, the proposed scheme is compatible with the concept of differentiated responsibility. By never labelling a country in the bottom W-tercile as a free-rider, it exempts poor countries from being subject to free-rider sanctions. Moreover, the emphasis on progress reflected in the R-tercile makes it relatively easy for middle-income countries to stay out of the free-rider box. One characteristic of rapidly growing middle-income countries is a relatively low efficiency of their energy infrastructure. Improving this efficiency is a desirable policy even without climate change concerns, and, as a co-benefit, it will reduce carbon intensity, which prevents the country from being labelled a free-rider. Moreover, it would also incentivize developing countries to leapfrog the fossil carbon era and move more aggressively to renewable energy. This is important as the long-term trajectory of carbon intensity must be moving to zero, and much of the available carbon storage capacity may be spoken for by large-scale need for negative emissions.

In addition to identifying free-riders, the *CRW* metric for assessing a country's carbon mitigation behavior can be used to push toward a more aggressive carbon trajectory. Case Study III points to world average requirements on R to keep atmospheric CO_2 concentrations below the 450 ppm threshold recommended by the IPCC. This critical R-value, which depends on observed economic growth, is exceeded by virtually every country.

In sum, the proposed methodology can accelerate action on climate change by (1) giving first-mover countries a straightforward way to identify free-riders and potentially provide a justification for eliminating their economic advantage by using carbon-based trade sanctions, and (2) possibly convincing free-riders that internal action on climate change is a more cost-effective strategy. This methodology therefore creates a path toward action for countries that are concerned about climate change and tired of waiting for a top-down international agreement.

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