On Sharing Responsibilities for Pollution Embodied in Trade[1]

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October 2018

[1] *Corresponding author*: Marie Françoise Calmette, Toulouse School of Economics. We aknowledge financial support from the *Agence Française pour le Développement* (AFD). We thank Christophe Bontemps for excellent research assistance. We also thank audiences at the African Meeting (Econometrics Society) in Algiers (2017) and AFSE meeting (2018).

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Abstract

In this article, we propose a new way of assessing environmental responsibility at the country level, taking into account their trade balance in terms of carbon. Starting from the fact that the approach based on the respective responsibilities of the producer and the consumer, which are widely promoted and used in the literature, each have their own limitations, we introduce a modified formula for the net trade balance of carbon at the country level. To do this, we examine the extent to which trade flows for a given country increase or decrease global emissions relative to the virtual situation where imports would have been produced in the consumer country. We argue that it would be fair for countries to retain responsibility for the additional emissions they create when trading. We then discuss the incentives provided by the modified liability rule to reduce emission intensity and extend our formula to include trade in intermediate goods. Finally, we illustrate our concept using World Bank and OECD data on trade flows and emission intensity ratios. Finally, we characterize six groups of countries according to the respective order of their producer, consumer and our new liability rule.

JEL : F18, Q54, C67.

Key-words: International trade, carbon trade balance, consumer responsibility, producer responsibility.

Résumé

Dans cet article, nous proposons une nouvelle façon d'évaluer la responsabilité environnementale au niveau des pays en tenant compte de leur balance commerciale en terme de carbone. Partant du fait que l'approche fondée sur les responsabilités respectives du producteur et du consommateur, largement encouragées et utilisées dans la littérature, ont chacune leurs propres limites, nous introduisons une formule modifiée pour la balance commerciale nette du carbone au niveau du pays. Pour ce faire, nous examinons dans quelle mesure les flux commerciaux pour un pays donné augmentent ou diminuent les émissions mondiales par rapport à la situation virtuelle où les importations auraient été produites dans le pays de consommation. Nous soutenons qu'il serait juste que les pays conservent la responsabilité des émissions supplémentaires qu'ils créent lorsqu'ils font du commerce. Nous discutons ensuite des incitations apportées par la règle de responsabilité modifiée pour diminuer l'intensité en émissions et étendons notre formule pour inclure le commerce des biens intermédiaires. Enfin, nous illustrons notre concept à l'aide de données de la Banque mondiale et de l'OCDE sur les flux commerciaux et les ratios d'intensité en émissions. Enfin, nous caractérisons six groupes de pays en fonction de l'ordre respectif de leur responsabilité producteur, consommateur et de notre nouvelle règle de responsabilité.

JEL : F18, Q54, C67.

Mots-clés : Commerce international, balance commerciale du carbone, responsabilité du consommateur, responsabilité du producteur.

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1 Introduction

Why and how to evaluate the international responsibility of a country with respect to its GHG emissions and regarding other countries? First, evaluating the responsibility of a country or a region is necessary to build adequate control and to establish reduction policies of GHG emissions (Peters and Hertwich 2008). For instance, emission targets per country have been set up by the United Nations Framework Convention on Climate Change (UNFCCC) based on emissions produced domestically under the Kyoto Protocol. Countries or regions that currently develop climate policies (like the EU for instance) also base their measures on domestically produced emissions (Lininger 2013, Steininger et al. 2014).

Second, two ways of accounting for emissions, along with other approaches, have been discussed in the literature: producer responsibility and consumer responsibility. According to the principle of producer responsibility, a country is responsible for the pollution emitted when producing domestically goods and services, independently on whether consumption takes place in the country or abroad. This way of evaluating responsibilities has been questioned on the basis of its fairness. One of the difficulties in climate negotiations is clearly the raising importance of CO2 embodied in international trade over the past twenty years. The 5th assessment report of the IPCC (Intergovernmental Panel on Climate Change) points out that overall emissions rose twice as fast in the first decade of the 21th century than during the past three decades and a significant part of this growth is due to international trade. Peters et al. (2011) have found that the emissions from the production of traded goods and services have increased from 4.3 Gt CO2 in 1990 to 7.8 Gt CO2 in 2008. More recently, Shapiro (2016) has estimated that the opening of borders raises global CO2 emissions in the order of 5% compared to a self sufficient situation without any international trade.

The main explanation is that the world's richest countries are increasingly outsourcing their emissions to other rising economies. According to the IPCC, "a growing share of emissions in developing countries is released in the production of goods and services exported, notably from upper-middle-income countries to high-income countries". As a result, the emissions actually produced in a country need not be the same as the emissions that are necessary for consumption. The countries of the OECD, for example, have a carbon footprint greater than the emissions carried out on their territory, while large emerging countries are in the opposite situation: they produce goods using polluting techniques which are then shipped and consumed in developed countries (see Bureau et al., 2017).

It is therefore not surprising that less developed countries and emerging countries often argue that a growing share of their emissions is due to the production of goods exported to rich countries whose consumers should ultimately bear the responsibility from their viewpoint. They do not want to be held responsible for emissions based on their production and would advocate in favor a criterion of responsibility for emissions on the basis of their consumption. In parallel, big emitters like the USA and some other developed countries regularly fear about their economy's competitiveness to be impaired if some other countries do not commit to curb their emissions, because of the possibility of relocation of industries towards pollution havens and of any potential expansion of carbon leakage.

Not only does producer responsibility not account for the possibility for rich countries to outsource their emissions abroad but it also creates some difficulty in assigning responsibility for emissions that occurred during international transportation. Switching to consumer-based national emission inventories has been suggested early in the literature (see e.g. Proops et al. 1993, Munksgaard and Pedersen 2001, Bastianoni et al. 2004, Lenzen et al. 2007, Peters 2008). This approach, very similar to the concept of ecological footprint, amounts to recognize that no matter where the polluting good or service is produced, the impact is global and it is only if the final consumer is responsible for this impact that problems like polluting industries relocations and carbon leakage consequences could be avoided.[1] A first counter-argument against switching to consumer responsibility is that it is simply a shift from one extreme, allocation responsibility to producer only, to another extreme, allocating responsibility to consumer only (Peters 2008). This drawback could be easily alleviated by introducing the notion of shared responsibility (Lenzen et al. 2007) but it is not easy to define the weight to be put respectively on producers and consumers (Steininger et al. 2014) and to avoid double counting in practice (see Gallego and Lenzen 2005 for a method to avoid this latter problem).

However, a shared responsibility between producers and consumers, could represent a compromise solution in the international negotiations and facilitate the adoption of a consensus (Tuddenham, 2010). This is the goal we are pursuing in this paper: to find a consensual criterion of allocation of responsibilities for country emissions that could be used, for example, for a distribution of the financing burden of the energy transition. It is therefore not to find an optimal taxation of CO2 emissions or assist in the implementation of a trade policy aimed at correcting distortions in competitiveness

[1] See Lenzen and Murray (2010) for an approach applied to carbon footprint.

between countries who practice unevenly stringent climate policies. Nevertheless, both issues are closely related : a huge branch of the literature examining the design of border carbon adjustments and discussing how to quantify emissions embodied in international trade, « indirectly also discusses switching to a consumer-based approach - although in that strand of literature it is usually not termed that way » (Lininger, 2013). In this branch of literature the method widely used to calculate emissions embodied in trade is the Multi-Regional Input-Output analysis, (Arce et al., 2016; Sakai and Barrett, 2016; Rocchi et al, 2018) since the goal is to give an instrument to countries having a carbon pricing mechanism in order to impose a border adjustment on products (Rocchi et al, 2018; Arto et al., 2014) or sectors (Sakai and Barrett, 2016) imported from non-abating countries. For this purpose, Cadarso et al. (2012) had proposed to share the responsibility of emissions along the global product chain depending on the value added of each step of the chain with an application to Spain. Our goal here is different: we aim to find a sharing rule of country responsibility at the global level, taking into account country participation to international trade.

Analyzing GHG emissions embodied in trade requires to compute a trade emission balance as the difference between emissions embodied in exports and those embodied in imports. Serrano and Dietzenbacher (2010) prove that, at the global level, the trade emission balance approach actually coincides with the country responsibility approach where one would compute the difference between emissions produced inside the country and the emissions required by its domestic final consumption.[2]

In this paper, we present first in a highly simplified framework, ignoring for trade in intermediate goods, the concept of producer-based, consumer-based and share responsibilities and exhibit the net carbon trade balance that explain the difference between producer-based and consumer-based responsibilities. The consumer-based rule does not consider that imports from a more emission efficient country actually help in reducing world level emissions. Similarly, the production-based rule includes exports, even if exporting helps decreasing world emissions level when it goes towards less emission efficient countries. To take into account that trade may increase or decrease world emissions level depending on the nature of energy use technologies employed by countries in bilateral trade, we propose a modified definition of the net carbon trade balance. It amounts to affect the trade balance by the best emission intensity ratio in each of these bilateral trade relationships. We then

[2] Besides producers and consumers responsibilities, Marques et al. (2012) have proposed a new nomenclature defined as income based responsibility (also called *downstream* responsibility by opposition to consumer responsibility interpreted as *upstream* responsibility). The idea there is to make primary producers of fossil fuels (e.g. Norway) responsible instead of producers or consumers.

show that, compared to the consumer-based rule, the modified rule will increase (reduce) a country's responsibility when it is creating more (less) emissions by exporting towards cleaner countries than by importing from less clean countries.

We also show that this modified rule for sharing responsibilities has nice efficiency properties for incentives to invest in improving emission intensity at the country level. Note that, as long as consumers are considered as (at least partially) responsible for emissions, the consumer-based responsibility rule may induce countries to make less efforts to limit their emissions by reducing their energy use ratio compared to the pure producer-based rule. Compared to a pure producer-based rule, our modified rule increases the incentives to reduce emissions if and only if the country under scrutiny is a global net importer from less emission efficient countries. However, the modified rule diminishes the incentives to reduce emissions when the country is a global net exporter towards less emission efficient countries. Now, compared to a pure consumer-based rule, the modified rule always increases the incentives to reduce emissions. We see all the properties as rather desirable, especially compared to the diminished incentives for energy savings provided by the consumer-based rule. Furthermore, we extend straightforwardly the concept to the case of trade in intermediate products. Last, we provide an illustrative application on a set of 98 countries, using data from the World Bank and from OECD.

The paper is organized as follows. Section 2 provides notations and an analysis of the difference between consumer, producer and shared responsibilities. It also presents the modified rule taking into account the net impact of each bilateral trade on the world emissions level. Section 3 provides the quantitative illustration. Section 4 concludes.

2 Analysis

2.1 Notations

Let us denote P_i as the measure of production (given by national GDP) for any country indexed by i. Total exports of country i are denoted $X_i = \sum_j X_{ij}$ where X_{ij} denotes exports from country i to some other country j with $X_{ii} = 0$. Similarly, total imports are $M_i = \sum_j M_{ji}$ where M_{ji} denotes imports in country i from country j with $M_{ii} = 0$. By construction, total exports coincide with total imports at the world level ($\sum_i X_i = \sum_i M_i$) and by definition imports in i from j must be equal to export from j to i ($M_{ji} = X_{ji}$).

We also denote E_i country's i emission intensity measure expressed in CO_2 emissions per \$ of GDP and suppose that countries are indexed with $i = 1....n$ such that $E_1 < E_2 < .... < E_n$. This allows to define the *net carbon trade balance* Δ_i for country i as follows:

$$\Delta_i = \sum_j E_j M_{ji} - E_i X_i.$$

The measure Δ_i expresses whether country i is a net CO_2 global importer ($\Delta_i > 0$) or a net CO_2 global exporter ($\Delta_i < 0$).

2.2 Consumer-based versus producer-based responsibilities

Using these notations, we can define the standard producer-based emissions accounting principle as follows:

$$R_i^p = E_i P_i \tag{1}$$

which ignores completely the trade flows for country i.

By contrast, the consumer-based emissions accounting principle is defined as adding the net carbon trade balance to producer-based emissions:

$$R_i^c = R_i^p + \Delta_i \tag{2}$$

where emissions embodied in exports X_i are taken out of the responsibility while emissions embodied in imports (from all partners) are taken into account. The responsibility R_i^c is thus larger than R_i^p whenever country i is a net CO_2 global importer and lower in the opposite case of a net CO_2 exporter.

These two definitions are different ways of allocating emissions responsibilities across countries but their corresponding aggregate responsibilities naturally coincide at the world level:

$$\sum_i R_i^c = \sum_i R_i^p$$

as by construction net carbon trade is balanced at the world level, $\sum_i \Delta_i = \sum_{i,j} E_j M_{ji} - \sum_i E_i X_i = \sum_j E_j X_j - \sum_i E_i X_i = 0$.

The responsibilities R_i^p and R_i^c are clearly polar cases. A natural way to describe all other possible emissions accounting principles between producer-based and consumer-based would be to assume that consumer is responsible for a portion $\alpha \in (0, 1)$ of emissions while the producer is responsible for the remaining portion $1 - \alpha$. This amounts to define the responsibility $R_i(\alpha)$ as follows:

$$\begin{aligned} R_i(\alpha) &= E_i(P_i - X_i) + \alpha \sum_j E_j M_{ji} + (1-\alpha) E_i X_i \\ &= R_i^p + \alpha \Delta_i \end{aligned}$$

so that with $\alpha = 0$, responsibility is producer-based ($R_i(0) = R_i^p$) while for $\alpha = 1$, it is consumer-based ($R_i(1) = R_i^c$). While attractive at first sight, as argued by Steininger et al. (2014) « it is difficult or impossible to determine shares of causal responsibility among them ». Hence, there is no easy way to choose a value for α or to reach a consensus on it.

2.3 A new way to measure net carbon trade balance

The consumer-based responsibility rule R_i^c allows to take into account trade impacts in an aggregate way. Indeed, a country that is a global net importer of carbon will see its burden raised compared to the producer-based rule. However, this rule fails to consider that imports from a more emission efficient country actually help in reducing world level emissions. Similarly, exports are included in the producer-based rule R_i^p, even if exporting helps decreasing world emissions level when it goes towards less emission efficient countries.

To see this, consider a world with two countries only indexed by 1 and 2, and assume without loss of generality that country 1 is more efficient than country 2 w.r.t the emission intensity ratio ($E_1 < E_2$). The world emissions level is $R_1^p + R_2^p = E_1P_1 + E_2P_2$ and it depends on the emission intensity ratios E_1 and E_2. In the present example, trade increases (decreases) world emissions by an amount equal to $(E_2 - E_1)(M_1 - X_1)$ when country 1 is a net importer (exporter), compared to the virtual situation where each country would have its consumption entirely produced domestically.

In this example, the consumer-based rule would prescribe the following responsibilities:

$$R_1^c = R_1^p + \Delta_1 = E_1P_1 + E_2M_1 - E_1X_1 \quad (3)$$

$$R_2^c = R_2^p + \Delta_2 = E_2P_2 + E_1M_2 - E_2X_2 \quad (4)$$

Country 1 is thus fully responsible for all its imports from the more polluting country, but country 2 is not responsible for its exports towards a cleaner country. This unbalanced share of responsibility between the two countries could be amended by considering that country 2 should retain full responsibility for the extra emissions $(E_2 - E_1)X_2 > 0$ for its exports X_2 towards the less polluting country 1, compared to the fictitious situation where these exports from 2 to 1 could have been produced in country 1 using the best technology there. We thus define a modified responsibility rule $\hat{R}_2$ for this country as follows:

$$\hat{R}_2 = R_2^c + (E_2 - E_1)X_2$$

which can be rewritten using (4) as:

$$\hat{R}_2 = R_2^p + E_1 \left(M_2 - X_2\right).$$

To keep constant the sum of responsibilities, we then reduce the consumer-based responsibility of the cleaner country 1 by the same amount $(E_2 - E_1)X_2 > 0$. Hence, we define the modified responsibility rule $\hat{R}_1$ for country 1 as follows:

$$\hat{R}_1 = R_1^c - (E_2 - E_1)X_2$$

which can be rewritten using (3) as

$$\hat{R}_1 = R_1^p + E_1(M_1 - X_1)$$

To sum up, in our two countries example, we can express a modified net carbon trade balance, to be added to the producer-based responsibility, as follows, for $i = 1, 2$:

$$\hat{\Delta}_i = (M_i - X_i) \min(E_1, E_2)$$

and the modified responsibility rule for country $i = 1, 2$ is $\hat{R}_i = R_i^p + \hat{\Delta}_i$.

This modified rule can be easily generalized to a world with an arbitrary number of countries: there, a more polluting country i exporting to a cleaner country j creates additional emissions equal to $(E_i - E_j)\, X_{ij} > 0$ compared to the case where the cleaner country would produce what it consumes. Once again, we would like the country i to retain responsibility for the additional emissions (and to reduce by the same amount the responsibility of the cleaner country j). By summing over all bilateral relationships, we define the following modified formula for the net carbon trade balance of country i as follows:

$$\hat{\Delta}_i = \sum_j (M_{ji} - X_{ij}) \min(E_i, E_j)$$

where it is a function of the best emission intensity ratio in each bilateral relationship. Thereby, the emissions responsibility rule for country i would write:

$$\hat{R}_i = R_i^p + \hat{\Delta}_i \tag{5}$$

Each country would be responsible for the emissions created by its production net of its modified net carbon trade balance. Of course, this new rule makes sense if and only if it is balanced at the world level, i.e. $\sum_i \hat{\Delta}_i = 0$, which follows from the fact that it is balanced at each bilateral level by construction. Furthermore, the modified responsibility rule can be straightforwardly generalized to take into account trade in intermediate input products with different sectors and also to multiple pollutants (see Appendix A for a detailed analysis). This is important as trade in intermediates has a major role in explaining recent growth in international trade because it is key to offshoring processes and global value chains (see e.g. Johnson and Noguera, 2012, Koopman et al., 2012, 2014).

Recall that here the responsibility of any country i is increased each times it exports toward a cleaner partner and is reduced each times it imports from a less clean partner. We thus have the following result by comparing Δ_i and $\hat{\Delta}_i$. Without loss of generality, we assume that countries are indexed by i such that $E_1 < ... < E_n$.

Proposition 1 $\hat{R}_i > (<) R_i^c$ *when the sum of emissions created by exporting towards cleaner countries,* $\sum_{j=1}^{i}(E_i - E_j)X_{ij}$*, is larger (lower) than the sum of emissions created by importing from less clean countries,* $\sum_{j=i+1}^{n}(E_j - E_i)M_{ji}$.

Proof: We have:

$$\begin{aligned}
\Delta_i - \hat{\Delta}_i &= \sum_j E_j M_{ji} - E_i X_i - \sum_j (M_{ji} - X_{ij}) \min(E_i, E_j) \\
&= \sum_j E_j M_{ji} - E_i \sum_j X_{ij} - \left[\sum_{j=1}^{i} E_j (M_{ji} - X_{ij}) + E_i \sum_{j=i+1}^{n} (M_{ji} - X_{ij}) \right] \\
&= \sum_{j=i+1}^{n} \underbrace{(E_j - E_i)}_{>0} M_{ji} + \sum_{j=1}^{i} \underbrace{(E_j - E_i)}_{<0} X_{ij}
\end{aligned}$$

■

Compared to the consumer-based rule, our modified rule will increase (reduce) a country's responsibility when it is creating more (less) emissions by exporting towards cleaner countries than by importing from less clean countries.

Furthermore, we can also compare the two rules with respect to the incentives to adapt emission intensity to reduce the responsibility. Take first the rule defined by (2), differentiate R_i with respect to E_i and obtain:

$$\frac{\partial R_i^c}{\partial E_i} = P_i - X_i < \frac{\partial R_i^p}{\partial E_i} = P_i$$

As long as consumers are considered as (at least partially) responsible for emissions, the rule may induce countries to make less efforts to limit their emissions by reducing their emission intensity compared to the pure production-based rule R_i^p. By contrast, the rule $\hat{R}_i$ does not face such an issue as we now expose. Differentiating (5) with respect to E_i we obtain:

$$\frac{\partial \hat{R}_i}{\partial E_i} = P_i + \frac{\partial \hat{\Delta}_i}{\partial E_i}.$$

Rewriting $\hat{\Delta}_i$, we get:

$$\begin{aligned} \hat{\Delta}_i &= \sum_j (M_{ji} - X_{ij}) \min(E_i, E_j) \\ &= \sum_{j=1}^{i} E_j (M_{ji} - X_{ij}) + \sum_{j=i+1}^{n} E_i (M_{ji} - X_{ij}) \end{aligned}$$

and consequently:

$$\frac{\partial \hat{\Delta}_i}{\partial E_i} = \sum_{j=i+1}^{n} (M_{ji} - X_{ij})$$

We thus formulate the following result.

Proposition 2 *Compared to a pure producer-based rule, the modified rule $\hat{R}_i$ increases (decreases) the incentives to reduce emission intensity E_i iff country i is a global net importer (exporter) from countries that are less efficient with respect to emissions.*

Hence, the modified rule has mixed impacts on the incentives to reduce emission intensity compared to the producer-based rule, increasing incentives to be cleaner for some and reducing them for others. But, one can show a more positive result when comparing R_i^c and $\hat{R}_i$ as we now do in the following Proposition.

Proposition 3 *Compared to a pure consumer-based rule R_i^c, the modified rule $\hat{R}_i$ always increases the incentives to reduce emission intensity.*

Proof: To see that $\frac{\partial \hat{R}_i}{\partial E_i} > \frac{\partial R_i^c}{\partial E_i}$, we compute the difference:

$$\frac{\partial \hat{R}_i}{\partial E_i} - \frac{\partial R_i^c}{\partial E_i} = \frac{\partial \hat{\Delta}_i}{\partial E_i} + X_i = \sum_{j=i+1}^{n} (M_{ji} - X_{ij}) + \sum_j X_{ij} = \sum_{j=i+1}^{n} M_{ji} + \sum_{j=1}^{i} X_{ij} > 0.$$

■

3 Application

To illustrate our proposed measure of carbon trade balance, we propose to calculate the responsibilities in global emissions for 98 countries according to the three criteria described in the analysis above. The data used are from the World Bank for GDP and CO2 emissions per dollar of GDP. For bilateral

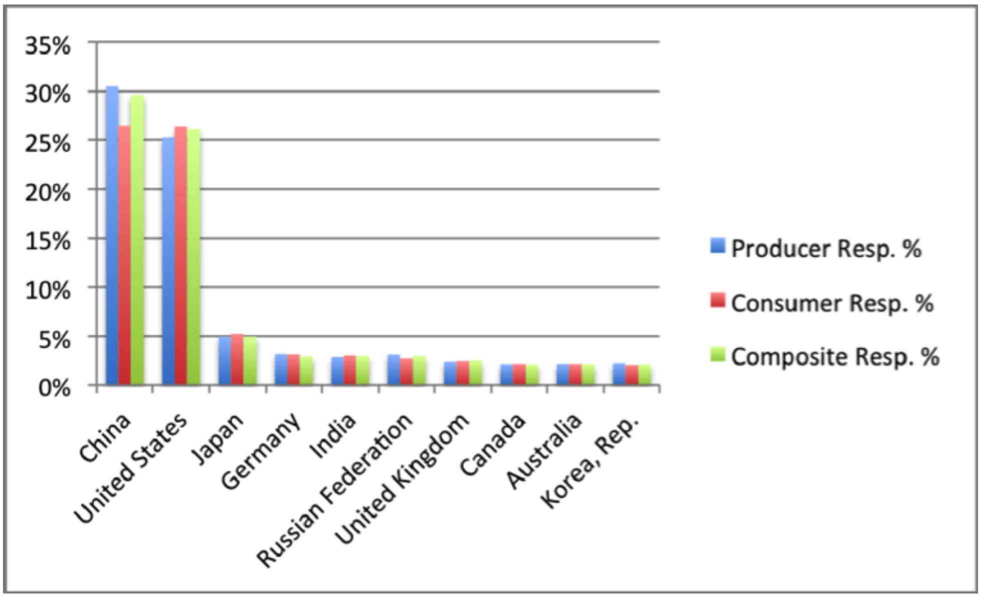

Figure 1: The ten most polluting countries according to their producer responsibility (in % of global emissions).

exports and imports, we used the OECD balanced international merchandise trade statistics.[3] We selected the year 2015, which is the most recent year for which we had all the necessary data. In Table 1 (see the Appendix B), the results are presented in absolute values and as a percentage of countries responsibility for global emissions. Figure 1 shows that, whatever the criterion used, there is a group of ten countries that each account for more than 2% of global emissions, the two largest emitters being by far China and the United States, which together are responsible, whatever the basis used, for more than 55% of global emissions.

Comparing the responsibility of each country based on our composite criterion with that based on their production and consumption leads us to distinguish six possible cases according to the relative ranking between R_i^p, R_i^c and $\hat{R}_i$ or equivalently between 0, Δ_i and $\hat{\Delta}_i$. Figure 2 presents the six groups and indicates for each the number of countries concerned.

As can be seen from Figure 2, the modified rule $\hat{R}_i$ changes the status of countries only in group 4 and 2, compared to the usual formulation R_i of the net carbon trade balance. In particular, while the sample has 74 countries out of 98 that are net importers of CO2, i.e. $\Delta_i > 0$, the modified rule

[3] In theory, the exports of country A to country B should mirror the imports of country B from country A. In practice this is however rarely the case, due to a variety of factors including for example differences in valuation (CIF for imports and FOB for exports), in partner country classification, in customs regimes, and in compilation and dissemination methodologies. The asymmetries between the export and import values for the same trade flow have long been recognised as an important factor that limits the analytical and policy use of international merchandise trade statistics. To tackle this issue, the OECD has developed an approach to reconcile international merchandise trade statistics.

	$R_i^c > R_i^p$ *Net importer of CO2*		$R_i^c < R_i^p$ *Net exporter of CO2*	
$\hat{R}_i > R_i^p$	Group 1 (*58*) $R_i^c > \hat{R}_i > R_i^p$	Group 6 (*0*) $\hat{R}_i > R_i^c > R_i^p$	Group 4 (*8*) $R_i^c < R_i^p < \hat{R}_i$	
$\hat{R}_i < R_i^p$	Group 2 (*16*) $R_i^c > R_i^p > \hat{R}_i$		Group 5 (*4*) $\hat{R}_i < R_i^c < R_i^p$	Group 3 (*12*) $R_i^c < \hat{R}_i < R_i^p$

Figure 2: Classification of countries according to the sign and relative rankings of R_i^p, R_i^c and $\hat{R}_i$. The number in italic between brackets indicates the number of countries in the group.

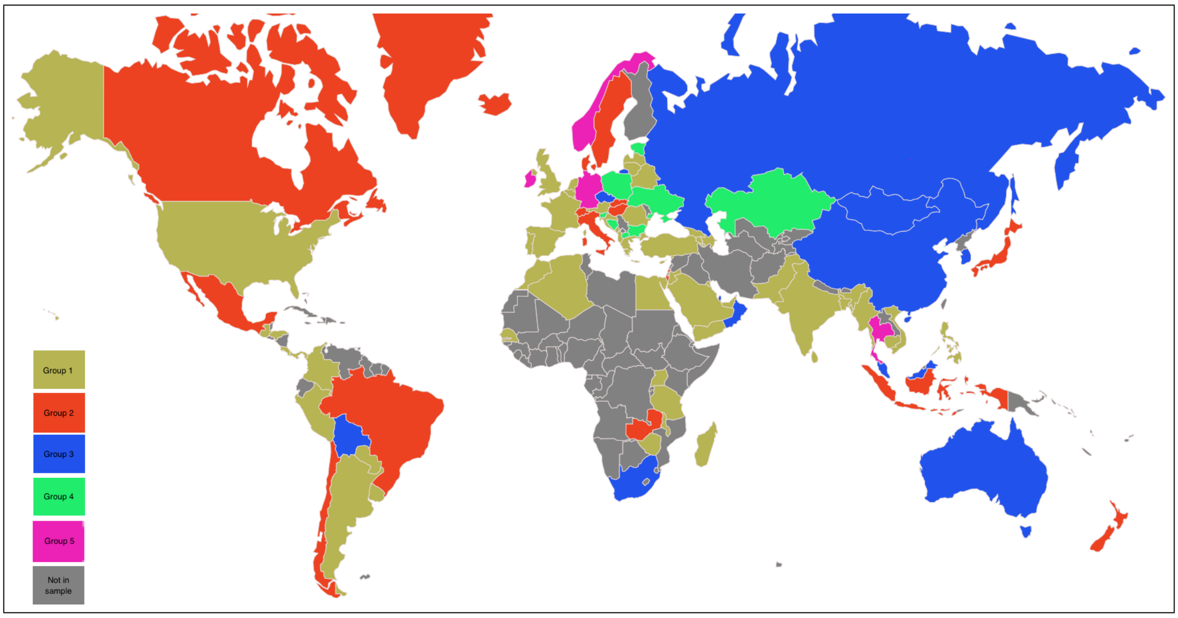

Figure 3: Net importers of CO2 (groups 1 and 2) and net exporters of CO2 (groups 3, 4 and 5).

$\hat{R}_i$ decreases their number to 66. Figure 3 indicates on a world map the group of all countries in the sample.

Consider first the countries that are *net importers of C02* ($\Delta_i > 0$), that is groups 1, 2 and 6. For all these regions, their consumer-based responsibility is greater than their producer-based responsibility, $R_i^c > R_i^p$.

- Among these countries, the *group 1* is made up of countries with trade deficits: they are net importers and consume more than they produce. According to our criterion, their responsibility remains greater than their producer-based responsibility (i.e. $\hat{\Delta}_i > 0$) but is less than their consumer-based responsibility, $\hat{\Delta}_i < \Delta_i$, since part of the responsibility for emissions linked to their imports from more polluting countries is now allocated to the latter. We thus have

$R_i^p < \hat{R}_i < R_i^c$ for *group 1* where one can find among others, by order of importance, the United States, India, United Kingdom, France and Saudi Arabia (see Figure). Note that nearly 60% of our sample (58 countries) belong to this group and it is particularly interesting to find there countries that belong to different classes in terms of national wealth according to the World Bank.

- The *group 2* also concerns net CO2 importing countries ($\Delta_i > 0$). But the modified net carbon trade balance is now negative, $\hat{\Delta}_i < 0$. Thereby, their exchanges contribute to reducing global emissions since they mainly export to more polluting countries. This is the case of Japan, Canada and Switzerland for example.[4] These countries would be penalized by a consumer-based responsibility rule, which attributes to them all emissions linked to their imports and which gives them a status of net importer of CO2 even if some of them have sizeable trade surplus. On the contrary, according to our modified rule, their responsibility is reduced compared to their consumer-based responsibility and their producer-based responsibility: $\hat{R}_i < R_i^p < R_i^c$.
- Note that a third possible case (denoted *group 6*) among net importers of CO2 could be the case where $\hat{\Delta}_i > \Delta_i$ so that the new responsibility rule amounts to increase the environmental liability over the consumer or the producer-based responsibilities: $R_i^p < R_i^c < \hat{R}_i$. There actually none country in this case in our sample.

Now consider the countries that are *net exporters of CO2*, i.e. *groups 3, 4 and 5* for which the net carbon trade balance defined by Δ_i is negative. Their producer responsibility is therefore greater than their consumer responsibility and there are 24 countries out of 98 in this case. Once again, there are three possible cases that we detail below.

- Among these countries, the *group 3* is made up of countries with $\Delta_i < \hat{\Delta}_i < 0$ so that $R_i^c < \hat{R}_i < R_i^p$. We find there China, Russia, South Korea and Australia among others. These countries are often net exporters and among the most polluting countries and therefore they contribute through their trade to an increase in global emissions.[5] According to our rule, their responsibility is increased compared to their consumer responsibility since they now retain part

[4] For example, among the nine largest importing countries from Japan, six countries (United States, China, Korea, Thailand, Australia, Vietnam) that account for more than 56% of Japan' s world exports have a much higher level of emissions per dollar of GDP than Japan. Also, nearly 80% of Canada's exports and 72% of its imports are due to trade with only two countries: the United States and China, that have a much higher level of emissions per dollar of GDP than Canada.

[5] In the ranking of our countries from least polluting to most polluting, in terms of CO2 emissions per dollar of GDP, China ranks 94th out of 98, South Africa 96th, Russia 89th, Korea 86th, Australia 85th.

of the responsibility for emissions linked to their exports to less polluting countries. Nevertheless, since they are major net exporters, their responsibility under our criterion remains lower than their responsibility based on their production since $\hat{\Delta}_i < 0$. Hence, we have .

- The *group 4* also concerns net CO2 exporting countries ($\Delta_i < 0$) but the modified rule entails $\hat{\Delta}_i > 0$ so that $R_i^c < R_i^p < \hat{R}_i$. The modified rule amounts to give them a larger responsibility than under the producer-based rule. The countries concerned are among the most polluting countries and their trade contributes to increase global emissions. This is for example the case of Ukraine which has a positive trade surplus and which is, just before Mongolia, the most polluting country in our country sample.[6] According to our criterion, its responsibility is increased in relation to its consumption-based responsibility (since it retains now a large share of responsibility for emissions related to its exports) and also in relation to its production-based responsibility. There is also Poland, a net CO2 exporting country, but unlike Ukraine, it has a trade deficit. It is its very high level of CO2 emissions per $ of GDP that makes this country, which is a trade deficit region, a net CO2 exporting country ($\Delta_i < 0$).

- Last, the *group 5* still concerns net CO2 exporting countries but these countries, which we call *Virtuous Traders*, have a trade surplus and they are among the least polluting countries. Hence, their trade position actually contributes overall to reducing global emissions. According to our criterion, their responsibility is reduced compared to their consumer-based responsibility since part of the responsibility for emissions linked to their imports from more polluting countries is now allocated to these countries. We obtain in this group that $\hat{R}_i < R_i^c < R_i^p$. It is of particular interest to point out that in this small group of 4 countries we have rich countries like Germany and Norway but also intermediary countries like Thailand.

4 Conclusion

In this paper, we propose a new way to evaluate the environmental responsibility of one country by taking into account its carbon trade balance. Starting from the fact that both the production-based and the consumer-based approaches widely promoted and used in the literature have each their own limitations, we want to propose a consensus criterion that would help, for example, to establish a rule for sharing the annual financial burden of the energy transition.

[6] In our ranking of countries from least polluting to most polluting, in terms of CO2 emissions per dollar of GDP, Ukraine is 97th out of 98, Poland is 79th.

This criterion must take into account some national characteristics. In particular, we would like to take into account the wealth of countries, the efforts they have already made to decrease their emissions and the producer versus consumer responsibility.

To have some chance of being accepted by as many countries as possible, a burden sharing rule must be simple and be based on criteria or observable indicators by all, like “hard” data. Remember that, as argued by Peters (2008) the main fault of a consumer-based emissions inventories is that it requires more complex calculations and consequently results may be more often subject to errors, bias and uncertainty. Moreover, even if the regulation of emissions is not the first objective of our rule, it goes without saying that it should not lead countries to more polluting behavior. Finally the burden sharing rule must be such that the sum of countries' responsibility coincides with the world emissions.

We introduce a modified formula for the net carbon trade balance at the country's level, using perfectly observable data: GDP, CO2 emissions per dollar of GDP, bilateral exports and imports. For this, we consider to what extent trade flows for a specific country increases or decreases global emissions compared to the virtual situation where imports would have been produced domestically. We argue that it would be fair for countries to retain responsibility for the additional emissions they create when they trade, if any. The modified formula for a country net carbon trade balance that we propose is a function of the best efficiency use ratio in each bilateral relationship.

We illustrate our concept using data from the World Bank and OECD on trade flows and emission ratios for 98 countries. We characterize six possible groups of countries according to the respective order of their producer and consumer responsibility and according to our composite criterion. As shown in Section 3, where we summarize the main trends of our results, our responsibility criterion allows to distinguish between countries for which trade contributes to decrease emissions and thus their responsibility is attenuated compared to their consumer responsibility and those for which trade contributes to increase emissions so that their responsibility is augmented compared to their consumer responsibility. In each category, emblematic countries oppose and it is particularly interesting to find, in some same groups, countries classified differently by the World Bank in terms of national Wealth, which is a good signal of the acceptability of our rule by countries.

We also find that the incentives brought by the modified responsibility rule to improve on energy efficiency are rather interesting in many situations. Moreover, we extend our formula to include trade in intermediate input goods. It could be interesting to apply our concept to evaluating emission responsibility by distinguishing between trade in final and intermediate goods in a world with N countries with S sectors and compare the results to our aggregated calculations considering each economy to consist of just a single sector with one single economy-wide emission intensity.

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Appendix

A Generalization to trade in intermediate input goods

Similarly to e.g. Serrano and Dietzenbacher (2010), consider a world with N countries with S sectors (indexed by $s = 1...S$) in each. Each sector produces one good that can be used as a final consumption good or as an intermediate input for other sectors. Production P_i in country $i = 1...N$ thus writes:

$$P_i = C_i + X_i + \sum_j A_{ij} P_j \tag{6}$$

where C_i is the domestic consumption of final goods produced in i, X_i denotes the final goods exported in the rest of the world. Matrix A_{ij} denotes the matrix of domestic inputs consumed at home (when $j = i$) or exported to be used in production elsewhere (when $j \neq i$).

By considering the system $\mathbf{P} = \mathbf{C} + \mathbf{X} + \mathbf{AP}$ obtained from (6), it follows that:

$$P_i = \sum_j B_{ij}(C_j + X_j)$$

where B_{ij} is an element of matrix $\mathbf{B} = (\mathbf{I} - \mathbf{A})^{-1}$. Denote E_i the vector of emissions coefficient for all sectors in country i and an element of E_i is e_{is} which indicates the domestic emission of CO2 per unit of output in industry/sector s in country i.[7]

We can now define the producer responsibility as:

$$R_i^p = E_i P_i = \sum_j E_i B_{ij}(C_j + X_j). \tag{7}$$

Similarly, the consumer responsibility is defined as follows:

$$R_i^c = \sum_j E_j B_{ji} C_i + \sum_j (\sum_k E_k B_{kj}) X_{ji} \tag{8}$$

where the first term denotes the emissions needed to produce domestically the final consumption C_i using domestic and foreign intermediate inputs while the second term represents all the emissions needed to produce the imports coming from partner j, equal to X_{ji}, via the use of inputs produced both domestically and abroad.[8]

[7] For simplicity, we do not consider here the possibility of having $M > 1$ pollutants but extending the model to this context is straightforward. In such a case, E_i is a matrice whose generic element is e_{is}^m that represents the domestic emissions for pollutant m per unit of output in sector s in country i.

[8] Recall that by convention $X_{ii} = 0$.

One can check immediately that $\sum_i R_i^p = \sum_i R_i^c$ as:

$$
\begin{aligned}
\sum_i R_i^c &= \sum_{i,j} E_j B_{ji} C_i + \sum_{i,j} (\sum_k E_k B_{kj}) X_{ji} \\
&= \sum_{i,j} E_j B_{ji} C_i + \sum_{j,k} E_k B_{kj} X_j \\
&= \sum_i R_i^p
\end{aligned}
$$

We can express the emissions needed for the exports of final products and intermediate inputs for country i :

$$
\sum_j E_j B_{ji} X_i + \sum_{j \neq i} E_i B_{ij} (C_j + X_j) \tag{9}
$$

where the first term denotes the emissions needed to produce and export final products X_i (using domestic and foreign inputs) while the second term denotes the emissions needed to produce intermediary inputs to be exported elsewhere in order to produce final products. Similarly, we can express the emissions needed for the imports of final products and intermediate inputs for country i :

$$
\sum_{j \neq i} E_j B_{ji} (C_i + X_i) + \sum_j (\sum_k E_k B_{kj}) X_{ji} \tag{10}
$$

where the first term denotes the emissions needed to produce foreign intermediary inputs that are imported to produce domestic consumptions and exports while the second term denotes the emissions needed to produce all final products imports X_{ji} from domestic and foreign inputs. The net carbon trade balance Δ_i for country i can then be computed by subtracting (9) to (10):

$$
\begin{aligned}
\Delta_i &= \sum_{j \neq i} E_j B_{ji} (C_i + X_i) + \sum_j (\sum_k E_k B_{kj}) X_{ji} \\
&\quad - \sum_j E_j B_{ji} X_i - \sum_{j \neq i} E_i B_{ij} (C_j + X_j)
\end{aligned}
$$

which simplifies into:

$$
\begin{aligned}
\Delta_i &= \sum_{j \neq i} E_j B_{ji} C_i + \sum_j (\sum_k E_k B_{kj}) X_{ji} - E_i B_{ii} X_i - \sum_{j \neq i} E_i B_{ij} (C_j + X_j) \\
&= \sum_{j \neq i} \left(E_j B_{ji} C_i + (\sum_{k \neq i} E_k B_{kj}) X_{ji} \right) - \sum_{j \neq i} E_i \left(B_{ii} X_{ij} + B_{ij} \left(C_j + \sum_{k \neq i} X_{jk} \right) \right)
\end{aligned}
$$

where the last line follows from collecting all the terms in E_i. Note that by inverting k and j the second term in the first bracket rewrites:

$$
\sum_{j \neq i} \sum_{k \neq i} E_k B_{kj} X_{ji} = \sum_{j \neq i} \sum_{k \neq i} E_j B_{jk} X_{ki}
$$

Replacing, we get the following expression for the net carbon trade balance:

$$\Delta_i = \underbrace{\sum_{j\neq i} E_j \left(B_{ji}C_i + \sum_{k\neq i} B_{jk}X_{ki} \right)}_{\substack{\text{foreign emissions needed for imported} \\ \text{intermediary inputs and imports of final products}}} - \underbrace{\sum_{j\neq i} E_i \left(B_{ii}X_{ij} + B_{ij} \left(C_j + \sum_{k\neq i} X_{jk} \right) \right)}_{\substack{\text{domestic emissions needed for exports} \\ \text{of final products and intermediary inputs}}} \tag{11}$$

Note that in this net carbon trade balance, all the foreign emissions that are first imported and then exported again have naturally disappeared by cancelling each other out. This is also the case for all domestic emissions that are first exported and then imported again.

Finally, one can check easily that, by using (7), (8) and (11), the usual relationship between producer, consumer and net carbon trade balance continue to hold in this generalized context:

$$R_i^c = R_i^p + \Delta_i.$$

We are now in a position to derive our composite sharing rule for responsibilities $\hat{\Delta}_i$. Adapting our rule, we define a new vector of emissions coefficients as follows:

$$\hat{E}_{ij} = (\min(e_{i1}, e_{j1}), .., \min(e_{is}, e_{js}), .., \min(e_{iS}, e_{jS}))$$

where to each sector $s = 1...S$ we associate the least polluting technology among the two trade partners i and j. We can thus define $\hat{\Delta}_i$ as follows:

$$\hat{\Delta}_i = \sum_{j\neq i} \hat{E}_{ij} \left(\underbrace{B_{ji}C_i + \sum_{k\neq i} B_{jk}X_{ki} - B_{ii}X_{ij} - B_{ij} \left(C_j + \sum_{k\neq i} X_{jk} \right)}_{\text{net trade balance}} \right)$$

and the proposed composite sharing rule is now:

$$\hat{R}_i = R_i^p + \hat{\Delta}_i.$$

B Results for the application

Table 1: **Pollution responsibilities in absolute values (tons of CO2) and in percentage.**

Name	R^p	R^c	$\hat{R}$	R^p %	R^c %	$\hat{R}$ %
Albania	1790964425	2671648005	2252270831	0,01%	0,01%	0,01%
Algeria	42059569270	46512890723	45228536536	0,19%	0,21%	0,20%
Argentina	1,29E+11	1,33E+11	1,30E+11	0,58%	0,60%	0,59%
Armenia	2501118330	2980543507	2691908567	0,01%	0,01%	0,01%
Australia	4,80E+11	4,75E+11	4,77E+11	2,17%	2,15%	2,15%
Austria	58084060243	68424955822	58320139695	0,26%	0,31%	0,26%
Azerbaijan	11692864436	12894750053	12067677367	0,05%	0,06%	0,05%
Bahrain	17121530282	12580526071	16514687177	0,08%	0,06%	0,07%
Bangladesh	29076363810	40368844867	30779093848	0,13%	0,18%	0,14%
Belarus	20807141079	24298281979	23208677217	0,09%	0,11%	0,10%
Belgium	87768739695	1,02E+11	88307206328	0,40%	0,46%	0,40%
Bolivia	9917518833	9508597338	9909061542	0,04%	0,04%	0,04%
Bosnia Herzegovina	9092565316	8111310383	9721724838	0,04%	0,04%	0,04%
Brazil	2,81E+11	3,02E+11	2,77E+11	1,27%	1,37%	1,25%
Bulgaria	16421594599	15537875386	17346485499	0,07%	0,07%	0,08%
Cambodia	2181738460	6128765417	2424994037	0,01%	0,03%	0,01%
Canada	4,76E+11	4,80E+11	4,75E+11	2,15%	2,17%	2,15%
Chile	50544891439	57335153624	50228364056	0,23%	0,26%	0,23%
China	6,76E+12	5,82E+12	6,56E+12	30,53%	26,31%	29,67%
Colombia	43452728155	53235661655	45192018414	0,20%	0,24%	0,20%
Costa Rica	6044854226	9049012892	6462475409	0,03%	0,04%	0,03%
Croatia	9354468186	12078407864	10841809764	0,04%	0,05%	0,05%
Cyprus	4409374147	5762962323	5385825167	0,02%	0,03%	0,02%
Czech Republic	56939622427	46771748829	56269284990	0,26%	0,21%	0,25%
Denmark	43677432498	50479071255	43328175654	0,20%	0,23%	0,20%
Egypt, Arab Rep.	77324399982	97239971121	88672201762	0,35%	0,44%	0,40%
Estonia	12359056534	10307196550	13886398220	0,06%	0,05%	0,06%
France	3,09E+11	3,72E+11	3,15E+11	1,40%	1,68%	1,42%
Georgia	3251709920	5010106208	4291178115	0,01%	0,02%	0,02%
Germany	6,98E+11	6,83E+11	6,50E+11	3,15%	3,09%	2,94%

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Table 1 – continued from previous page

Name	R^p	R^c	$\hat{R}$	R^p %	R^c %	$\hat{R}$ %
Greece	47045547046	52715065019	50364636309	0,21%	0,24%	0,23%
Guatemala	7672149295	11373626177	8465686208	0,03%	0,05%	0,04%
Honduras	4945601183	6211454322	5571718259	0,02%	0,03%	0,03%
Hong Kong SAR, China	36207154008	2,21E+11	45414810061	0,16%	1,00%	0,21%
Hungary	20905371063	27087889688	19797051123	0,09%	0,12%	0,09%
Iceland	2391774592	2710532195	2296226107	0,01%	0,01%	0,01%
India	6,32E+11	6,55E+11	6,47E+11	2,86%	2,96%	2,93%
Indonesia	1,64E+11	1,79E+11	1,60E+11	0,74%	0,81%	0,72%
Ireland	44613840370	38854306611	34529928720	0,20%	0,18%	0,16%
Israel	77079641863	78348613933	76128574988	0,35%	0,35%	0,34%
Italy	2,88E+11	3,24E+11	2,83E+11	1,30%	1,46%	1,28%
Japan	1,10E+12	1,14E+12	1,08E+12	4,96%	5,15%	4,90%
Jordan	12206993385	16104140599	15156876495	0,06%	0,07%	0,07%
Kazakhstan	1,20E+11	1,04E+11	1,20E+11	0,54%	0,47%	0,54%
Korea, Rep.	4,95E+11	4,47E+11	4,62E+11	2,24%	2,02%	2,09%
Kuwait	40494081136	46160490424	45832970353	0,18%	0,21%	0,21%
Latvia	4187996499	7639154141	5057899695	0,02%	0,03%	0,02%
Lithuania	6622329927	10556699912	7213830539	0,03%	0,05%	0,03%
Luxembourg	11137100319	13625537709	12491564508	0,05%	0,06%	0,06%
Macedonia, FYR	3181823841	3112756981	3400403639	0,01%	0,01%	0,02%
Madagascar	924205797,1	1917537820	1015734330	0,00%	0,01%	0,00%
Malawi	447190762,1	1125196562	509394722,4	0,00%	0,01%	0,00%
Malaysia	98146911106	81289447421	88570438796	0,44%	0,37%	0,40%
Malta	1626246536	5722300507	3351238777	0,01%	0,03%	0,02%
Mauritius	1895389471	3018566068	2230043870	0,01%	0,01%	0,01%
Mexico	2,73E+11	3,00E+11	2,69E+11	1,24%	1,36%	1,22%
Mongolia	15342252956	10957665097	14889489866	0,07%	0,05%	0,07%
Montenegro	969344247,9	1347680705	1228753707	0,00%	0,01%	0,01%
Morocco	23700499180	27215043770	26142452859	0,11%	0,12%	0,12%
Myanmar	3324187163	11648907333	3646843379	0,02%	0,05%	0,02%
Netherlands	1,56E+11	1,93E+11	1,63E+11	0,70%	0,87%	0,74%
New Zealand	36684698849	40301737172	36384970973	0,17%	0,18%	0,16%

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Table 1 – continued from previous page

Name	R^p	R^c	$\hat{R}$	R^p %	R^c %	$\hat{R}$ %
Norway	67719619590	64691618860	60164796476	0,31%	0,29%	0,27%
Oman	26532718595	25388014464	26384399255	0,12%	0,11%	0,12%
Pakistan	49520237012	63109900838	53798534579	0,22%	0,29%	0,24%
Panama	7136461255	18245992844	11457386590	0,03%	0,08%	0,05%
Paraguay	2447297028	4349446703	2580545198	0,01%	0,02%	0,01%
Peru	29894216729	35819457421	30362084307	0,14%	0,16%	0,14%
Philippines	44698648334	65495171947	48298536404	0,20%	0,30%	0,22%
Poland	1,53E+11	1,44E+11	1,57E+11	0,69%	0,65%	0,71%
Portugal	31544460685	36818986003	33671672951	0,14%	0,17%	0,15%
Qatar	49011271995	35577329407	37512194567	0,22%	0,16%	0,17%
Romania	31689430307	37801725185	33173052202	0,14%	0,17%	0,15%
Russian Federation	6,87E+11	5,78E+11	6,47E+11	3,10%	2,61%	2,93%
Saudi Arabia	2,29E+11	2,60E+11	2,57E+11	1,03%	1,17%	1,16%
Senegal	3577070649	5641480741	4892274701	0,02%	0,03%	0,02%
Singapore	33938950367	91309152238	35298064689	0,15%	0,41%	0,16%
Slovak Republic	19442264248	22320551598	19362948648	0,09%	0,10%	0,09%
Slovenia	10144543509	10103859206	10158874829	0,05%	0,05%	0,05%
South Africa	2,16E+11	1,78E+11	2,08E+11	0,98%	0,80%	0,94%
Spain	1,86E+11	2,12E+11	1,89E+11	0,84%	0,96%	0,85%
Sri Lanka	6047786634	11719048907	6735889037	0,03%	0,05%	0,03%
Sweden	50065364880	65923274800	49176669182	0,23%	0,30%	0,22%
Switzerland	55909694967	87491062269	52373763584	0,25%	0,40%	0,24%
Tanzania	4162436868	8295999357	4775958571	0,02%	0,04%	0,02%
Thailand	1,15E+11	1,08E+11	1,06E+11	0,52%	0,49%	0,48%
Turkey	1,58E+11	1,85E+11	1,70E+11	0,72%	0,84%	0,77%
Uganda	2122481762	3248918014	2314394393	0,01%	0,01%	0,01%
Ukraine	62578502203	49373052359	64074966109	0,28%	0,22%	0,29%
United Arab Emirates	1,08E+11	1,40E+11	1,31E+11	0,49%	0,63%	0,59%
United Kingdom	5,23E+11	6,00E+11	5,55E+11	2,36%	2,71%	2,51%
United States	5,60E+12	5,84E+12	5,80E+12	25,33%	26,42%	26,20%
Uruguay	5980370922	8094841645	6293276527	0,03%	0,04%	0,03%
Vietnam	62107545775	72472134358	65389307320	0,28%	0,33%	0,30%

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Table 1 – continued from previous page

Name	R^p	R^c	$\hat{R}$	R^p %	R^c %	$\hat{R}$ %
Yemen, Rep.	9330384429	12148566184	11136603659	0,04%	0,05%	0,05%
Zambia	1442533858	3453150848	1248549931	0,01%	0,02%	0,01%
Zimbabwe	7652306325	8584491579	8507577242	0,03%	0,04%	0,04%
Total Sample	2,21E+13	2,21E+13	2,21E+13	100%	100%	100%