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Emission Targets, Comparative Advantage and Trade: A New Reading of David Ricardo

Galina Kolev¹

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Abstract

The paper represents a new reading of the traditional Ricardian theory of comparative advantages to tackle current challenges of environmental and climate policy. In the style of David Ricardo, it demonstrates that international trade is a positive-sum game in a two-goods, two-countries world where CO₂ emission targets constrain the production possibilities. Extending the number of goods produced and allowing for transportation costs does indeed question the tradability of a number of goods as in the classical Ricardian world. However, the main findings still apply that international trade extends the consumption possibilities while further enabling policy makers to achieve their CO₂ emission targets. This simple framework is a useful tool to show that the outcome does not depend on the CO₂ pricing method or the price of CO₂ certificates in both countries. The mutual benefit of international trade depends, however, on restraining CO₂ emissions according to the targets set by the Paris Agreement, since the level of CO₂ emissions is the scarce factor of production in the model.

Keywords: Comparative advantage, Environment and trade, Green growth

JEL Codes: F11, F18, Q56

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I. Introduction

The adoption of the Paris Agreement in December 2015 marks a turning point in global environmental and climate policy. Many countries worldwide have now their own long-term goals in terms of CO₂ emissions reduction but at the end the concerted efforts of the international community are needed to restrain the increase in global average temperature to well below 2°C since the aggregated individual intended nationally determined contributions are not sufficient (Höhne et al., 2017).

Whereas emissions in developed countries stabilized since 1990, emissions in developing countries increased several times in the same time (EDGAR, 2019). The widespread belief is that international trade has contributed to this development since it undermines national emission reduction targets (Kanemoto et al., 2014) and therefore hinders achieving global climate policy targets. International trade itself produces CO₂ emissions since it increases the distance between the production site and the consumer. Furthermore, empirical evidence shows that several countries could fulfill their CO₂ emissions reduction commitments only because emission intensive production was displaced offshore (Kanemoto et al., 2014). Adjusting for the additional trade and transport related CO₂ emissions, the data shows that developed countries emissions increased, not decreased. Thus, environmental policy measures produced favorable statistics for the countries implementing them but emission leakage has increased global CO₂ emissions. As the analysis by Peters et al. (2011) indicate, net emission transfers via international trade from developing to developed countries increased four times between 1990 and 2008.

Similar evidence can be found with respect to methane embodied in the international trade of commodities (Subak, 1995). Methane embodied in imports from developing countries accounted as early as in 1990 for between 7 and 9% of emissions in the importing countries. As Guo et al. (2012) summarize, trade creates a mechanism to transfer embodied CO₂ emissions among regions, therefore causing distortion on the global emissions.

The evidence thus shows that under the current setting of emission targets international trade helps developed countries achieve their targets at the expense of global emissions. This does not necessarily imply, though, that international trade is harmful for greening growth. On the contrary, applying Ricardian trade theory insights it is even possible for specialization and international trade to contribute to achieving CO₂ emissions targets or to increase welfare in the presense of CO₂ emissions restraints as the following example should illustrate. Consider a two-country model where two goods are produced, steel and

aluminum. In the home country H both steel and aluminum can be produced with a higher CO₂ efficiency compared to the economy abroad F. In the steel production the CO₂ intensity amounts to 1 ton of CO₂ per ton of steel produced in H and to 3 tons of CO₂ in F. In the aluminum production the CO₂ intensity is 8 tons of CO₂ per ton of aluminum produced in H and 12 tons of CO₂ in F. Assume that both countries have a total CO₂ emissions target of 120 tons for the production of steel and aluminum. In a world without trade H can produce either 120 tons of steel or 15 tons of aluminum or a combination of both. If it needs both goods equally, it will use half of the allowed CO₂ emissions in either industry and it will produce 60 tons of steel and 7.5 tons of aluminum. The same applies for F: the maximal amounts of both goods to be produced under the restriction of CO₂ emissions of below 120 tons are 40 tons of steel and 10 tons of aluminum. If it uses for example half of the allowed CO₂ emissions in either industry as in the case of H, it will produce 20 tons of steel and 5 tons of aluminum.

In a world without trade both countries have to produce both steel and aluminum by themselves in accordance to the relative demand. If H wants to increase the production of aluminum by one ton, it needs 8 tons of CO₂ and has to reduce steel production by 8 tons in order to achieve its CO₂ target. Therefore, the opportunity cost of the production of one ton aluminum is 8 tons of steel in H. In F, on the contrary, the production of one additional ton aluminum requires 12 tons of CO₂ and this amount can be made available if steel production is reduced by 4 tons, since here, CO₂ emission is reduced by 3 tons CO₂ per ton of steel production. Thus, the opportunity cost of one ton aluminum is 4 tons of steel in F.

Let us assume that F reshapes its production pattern in favor of the aluminum production since its opportunity costs are lower compared to H. It can produce a total of 10 tons of aluminum and try to trade half of it for steel. F needs at least 20 tons of steel and 5 tons of aluminum to stand at least as well as without trade. Would H be willing to exchange at least 20 tons of steel for 5 tons of aluminum? It can reduce its aluminum production by 5 tons and thus make 40 tons of CO₂ available which can be used to increase steel production by 40 tons. Therefore, H would be willing to trade even more than 20 tons of steel for 5 tons of aluminum. At the end, both countries have increased their joint amount of steel by 20 tons without giving up their CO₂ emission targets or reducing the amount of aluminum totally available. International trade enables them to grow on a green base and increase welfare. Alternatively, they can decide to leave the total production amount unchanged and do without the additional 20 tons of steel, therefore reducing global CO₂ emission by 20 tons. Both is possible by specializing on the production of goods, where each country has a comparative advantage in terms of CO₂ intensity of production, and trading them

for those goods, where opportunity costs are higher than in the other country. Trade contributes, therefore, to greening growth or growing green and does not undermine national emission reduction targets.

The aim of the present paper is to develop a simple Ricardian style model as shown in the example above to illustrate the role of international trade in achieving global emission reduction targets. Furthermore, the model is used to point out that it is not international trade that undermines national emission reduction targets but the current setting of global environmental policy. Extending the number of goods produced and allowing for transportation costs does indeed question the tradability of a number of goods as in the classical Ricardian world. However, the main findings that international trade is a positive-sum game in the sense of environmental policy objectives still apply. This simple framework is a useful tool to show that the outcome does not depend on CO₂ pricing method or the price of CO₂ certificates in the different countries. However, the mutual benefit of international trade crucially depends on restraining CO₂ emissions according to the targets set by the Paris Agreement, since the level of CO₂ emissions is the scarce factor of production in the model.

The paper is structured as follows: In section two the model framework is presented where CO₂ emissions represent the factor restraining production possibilities. In section three the model is applied to the current challenges of global environmental and climate policy. Section four presents some concluding remarks.

II. Emission targets in a Ricardian style model of trade

David Ricardo's theory of international trade emerged in the light of war, social distress and the Corn Laws (Gerber, 2017). By raising food prices, the tariffs introduced by the Corn Laws hampered growth of other industries in the United Kingdom by reducing disposable income of the broad public (Williamson, 1990). Today, we have to cope with similar challenges. Emerging new protectionism, the call for sustainable development policy measures and even diseases like the virus SARS-CoV-2 (so called Corona virus) increasingly question the concept and the reliability of specialization and international trade.

As Jones and Weder (2017) point out, though, it is rather unusual that an economic theory is still relevant and important after 200 years. The Ricardian theory is a starting point for

many textbooks on international trade since it demonstrates the gains from specialization and trade in a way that “*at least a bright student can absorb quickly*” (Eaton and Kortum, 2012, p. 65). However, having served its pedagogical purpose, it makes room for other theories based on differences in factor endowments and increasing returns to scale as explanations for the benefits resulting from international trade. In the last decades, the Ricardian framework experienced a revival, not only because of its 200th anniversary.

Whereas the Ricardian idea can be applied in a straightforward way to stress the harmful effects of new protectionism, environmental and climate issues were barely included in the *Principles of Political Economy and Taxation* (Ricardo, 1817). Nevertheless, the brilliance and simplicity of the Ricardian idea (Jones and Weder, 2017) make it an excellent starting point for the analysis of international trade in the presence of CO₂ emissions targets as given for example by the Paris Agreement. In the following, a Ricardian style model is presented where the main restriction is not the amount of labor available in the economy but the CO₂ emissions target. The representation is therefore a new reading of the traditional model of David Ricardo as taught by the standard international economics textbooks (see e.g. Krugman et al., 2018). As stressed by Eaton and Kortum (2012), given the opportunity to trade, countries benefit by specializing in the activities they do relatively better. In the model presented below, specialization results not from relative labor productivity comparison as in the traditional Ricardian theory, but rather from the comparison of relative CO₂ intensity at home and abroad.

a. Emission targets and trade in a two-country/two-good model

The starting point of the model framework is an economy (Home, H), whose production possibilities are restrained by a CO₂ emissions target, denoted by C . In the first step the assumption is made that only two goods, x_1 and x_2 , are produced. The production technology is described by the CO₂ intensity, i.e. the required (constant) amount of CO₂ emissions per unit output. The CO₂ emission requirement per unit output are denoted a_1 and a_2 , respectively. Because of the CO₂ emissions target, the production possibility frontier is given by:

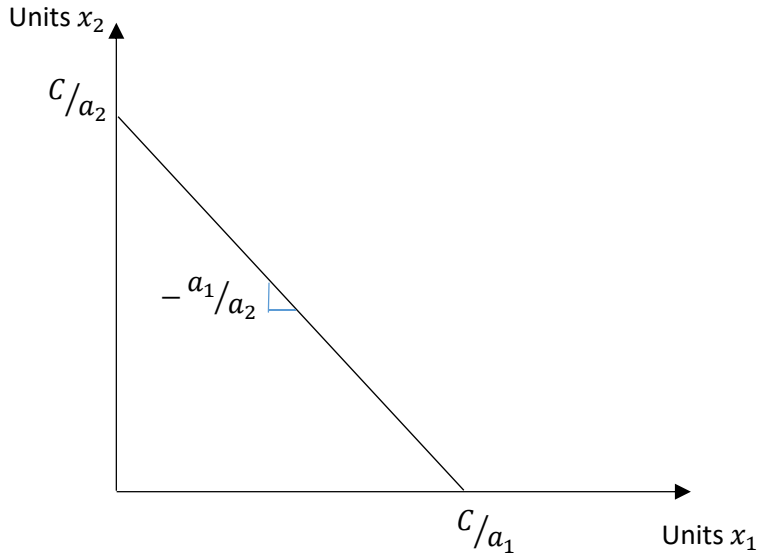
$$a_1x_1 + a_2x_2 \leq C \tag{1}$$

Therefore, the production possibility frontier is a straight line as represented in Figure 1. The total amount of x_1 respectively x_2 that can be possibly produced is given by

C/a_1 respectively C/a_2 . The absolute value of the slope shows the opportunity cost of x_1 in terms of x_2 , a_1/a_2 : if Home needs to increase the production amount of x_1 by a unit, CO₂ emissions will increase by a_1 . Thus, Home has to reduce CO₂ emissions in the production of x_2 by a_1 meaning that the output of x_2 will decline by a_1/a_2 .

The production possibility frontier represents the possible combinations of x_1 and x_2 the economy can produce given the CO₂ emissions target. The amount actually produced depends, however, on the demand structure and thus the prices of both goods. In a competitive market economy, the total amount of CO₂ emissions set by the CO₂ emissions target is distributed according to the willingness of the industries to pay for it. The higher the price of the particular product, the higher is the ability of the particular industry to pay for CO₂.

Figure 1. Home's production possibilities frontier



Source: Author.

Note: The straight line represents the production possibility frontier of the home country. The absolute value of the slope equals the opportunity costs of producing an additional unit of good 1 in terms of good 2.

In a simplified economy where CO₂ emissions are the only scarce factor, the compensation of unit CO₂ equals the value of what can be produced with this unit. Assuming perfect competition, the compensation per ton CO₂ will equal p_1/a_1 and p_2/a_2 respectively, where

p_i is the price of good i . As long as the willingness to pay for CO₂ in the production of x_1 is higher, i.e.

$$p_1/a_1 > p_2/a_2, \text{ respectively } p_1/p_2 > a_1/a_2, \quad (2)$$

the CO₂ certificates will flow in the production of that good, and vice versa. The relationship in (2) implies that the economy will specialize in the production of x_1 if the relative price of that good in terms of x_2 exceeds its opportunity costs.

In the absence of international trade, Home has to produce both goods for itself. In the equilibrium with $x_i > 0$ the relative price of x_1 in terms of x_2 equals its opportunity costs:²

$$p_1/p_2 = a_1/a_2 \quad (3)$$

To describe the pattern and effects of international trade a second country, Foreign (F), is introduced with a CO₂ emissions target, denoted by C^* . Asterisks mark the corresponding variables for the foreign country. The CO₂ emission requirement per unit output are denoted a_1^* and a_2^* , respectively, and the production possibility frontier is analogous to (1):

$$a_1^*x_1^* + a_2^*x_2^* \leq C^* \quad (4)$$

In general, the CO₂ emission requirements can follow any pattern. We make the arbitrary assumption that

$$a_1/a_2 < a_1^*/a_2^*. \quad (5)$$

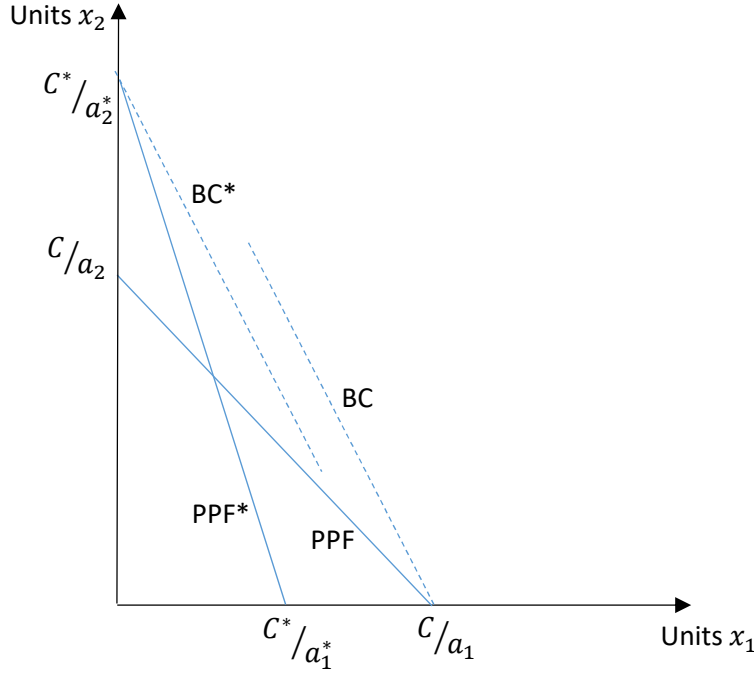
Therefore, turning back to the concept of comparative advantage in the style of David Ricardo, Home has a comparative advantage in the production of x_1 since its opportunity cost in terms of x_2 is lower than in F. From (3) as well as the corresponding relationship for the foreign country and (5) we know that the relative price of x_1 in terms of x_2 is lower in Home in the absence of trade. Once we allow for the possibility to trade, prices will converge, and, given free trade (FT), the two countries can exchange goods at a relative price which quite likely lies somewhere between their opportunity cost:

$$a_1/a_2 < p_1^{FT}/p_2^{FT} < a_1^*/a_2^* \quad (6)$$

² It is also possible to have an equilibrium where only one of two goods is produced and consumed. Since this is a special case that does not change the basic idea of the model, this case is not considered in the further analysis.

Figure 2 represents the production possibility frontiers (PPF) of both countries. The absolute value of the slope in F is higher than in H since the opportunity cost of x_1 in terms of x_2 is higher abroad.

Figure 2. Production possibility frontiers (PPF) and budget constraints (BC) of H and F



Source: Author.

Note: The solid lines show the production possibility frontiers of H and F, PPF and PPF*. The slope of PPF* is higher in absolute terms and country H has a comparative advantage in the production of good 1, since its opportunity costs given by the absolute value of the slope of PPF are lower. The dotted line represents the budget constraints of the two countries, BC and BC*. They go through the specialization point and the absolute value of the slope is the relative price of good 1 in terms of good 2.

The pattern of specialization depends on the structure of the relative demand as well as the CO₂ emissions targets of the countries. Assuming that there is sufficient demand for both goods in both countries and that CO₂ emission targets allow for one country to deliver sufficient amounts of the good where it has a comparative advantage, the representation in Figure 2 shows that specialization and trade can benefit both countries.³ Home specializes in the production of x_1 as its opportunity cost is lower than abroad. It can produce a total amount of C/a_1 if it produces only this good and point A in Figure 2

³ A further assumption is the availability of other factors of production that are not considered in the present analysis.

represents its endowment that can be used either for consumption or for trade. It can trade x_1 for x_2 at a relative price that is higher than the opportunity cost of x_1 . Therefore, its budget constraint (BC) that determines the consumption possibilities runs through point A and its slope is higher than that of PPF in absolute terms since it equals the relative price of x_1 in terms of x_2 . As shown in Figure 2, by specializing in the production of x_1 and trading with F the home economy can extend its consumption possibilities, which in the absence of trade were constraint by PPF. The same is true for the foreign country. It specializes in the production of x_2 , produces a total amount of C^*/a_2^* , and extends its consumption possibilities beyond PPF* to BC*.

The assumption we made that there is sufficient demand for both goods in both countries and that CO₂ emissions targets allow for one country to deliver sufficient amounts of the good where it has a comparative advantage is necessary for the representation in Figure 2. However, it is not crucial for the main conclusion to stay valid. If relative demand is biased towards one of the two goods or if the CO₂ emissions targets do not allow for one country to deliver sufficient amounts of the good where it has a comparative advantage, then one of the countries will probably not completely specialize but rather produce also a small amount of the good, where it has a comparative disadvantage. Thought, it will still shift its production towards the industry with the comparative advantage compared to a world without trade. Trade will still benefit both countries, the representation will, however, be slightly different than in Figure 2.

b. Emission targets and trade with many goods

The insights gained above can be extended to a world with many goods in a straightforward way. Assume that H and F stick to their CO₂ emissions targets but consume and are able to produce N different goods. The production technology for good i is again given by the CO₂ intensity a_i in H and a_i^* in F. As in the previous subsection CO₂ intensity can follow any pattern. In the further analysis we order the goods according to the CO₂ emission requirements in a way that is represented as follows:

$$a_1/a_1^* < a_2/a_2^* < a_3/a_3^* < \dots < a_N/a_N^* \quad (7)$$

To determine the pattern of trade we need to take a closer look at the price of CO₂ certificates in both countries.⁴ Let c respectively c^* be the price of CO₂ certificates in H and F. Assuming equal cost for other factors of production in both countries that are not considered here, goods will be produced where it is cheaper to buy the necessary CO₂ certificates. The production of good i requires a_i units of CO₂ in H and a_i^* units in F. The total payment for CO₂ per unit of production is therefore ca_i in the home country and $c^*a_i^*$ abroad. H has an advantage in the production of i if

$$ca_i < c^*a_i^*, \text{ respectively } a_i/a_i^* < c^*/c. \quad (8)$$

Otherwise, it will be cheaper to produce i abroad. According to the relative price of CO₂ certificates we can thus allocate the goods to either Home or Foreign:

$$a_1/a_1^* < a_2/a_2^* < \dots < a_s/a_s^* < c^*/c < a_{s+1}/a_{s+1}^* < \dots < a_N/a_N^* \quad (9)$$

Goods 1 to s will be produced in Home whereas goods $s + 1$ to N will be produced in Foreign. Again, the countries benefit from specializing and trading with each other. The labor costs of producing a good directly in a country are higher than producing another good and trading it for the desired good, if the country has a comparative disadvantage in the production of that good.

The relative price of CO₂ certificates and thus the pattern of specialization depend both on the CO₂ emission targets and the demand for the goods produced. It can be determined by considering the implied relative demand for CO₂ certificates. As indicated by (9), the implied relative demand D/D^* is zero if the relative price of CO₂ certificates c^*/c is lower than a_1/a_1^* since in such a case all goods should be produced abroad. For the purpose of the graphical representation we rearrange as follows:

$$D/D^* = 0 \text{ if } a_1^*/a_1 < c/c^* \quad (10)$$

If a_1^*/a_1 equals c/c^* , then no country has comparative advantage in the production of good 1 and the relative demand can be calculated as follows. The demand for CO₂ certificates in H will lie between zero and a_1x_1 . The demand for CO₂ certificates in F will be a value from the following interval:

⁴ For simplicity, we assume that both countries apply a system of emissions trading. This assumption is, however, not crucial for the analysis and any system of CO₂ compensation payments would deliver similar results.

$$(a_2^*x_2^* + \dots a_N^*x_N^*; a_1^*x_1^* + a_2^*x_2^* + \dots a_N^*x_N^*) \quad (11)$$

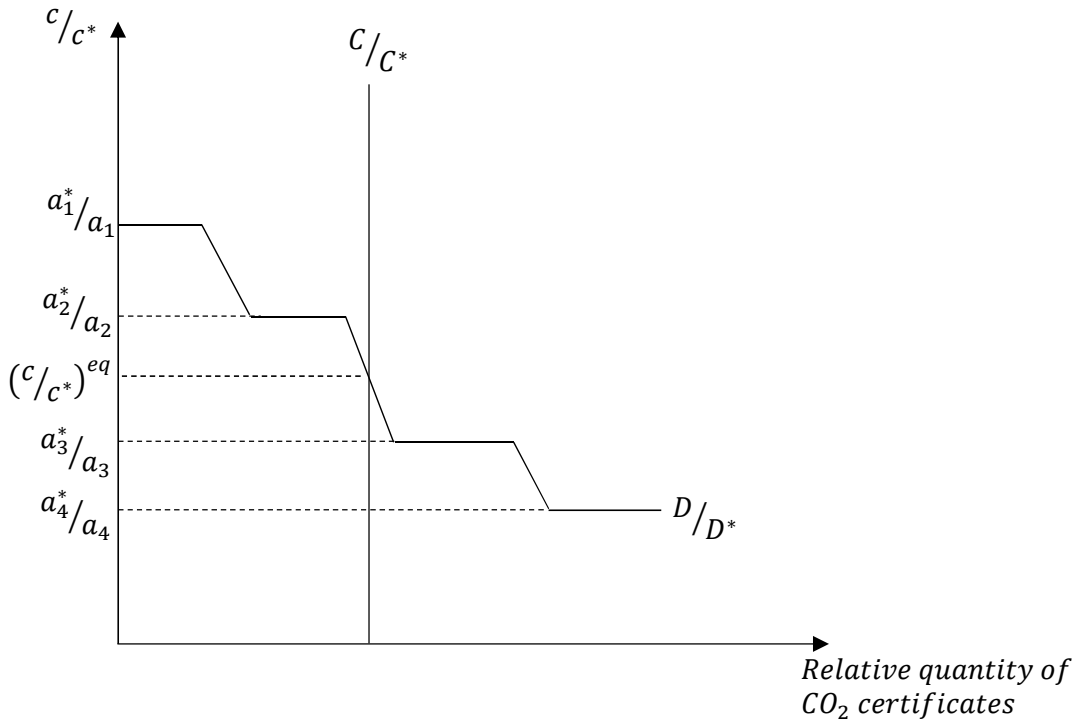
Therefore, the implied relative demand is a horizontal line if relative CO₂ intensity in the production of good 1 equals the reciprocal of the relative certificate price. It lies in this range:

$$D/D^* \in \left(0; \frac{a_1x_1}{a_2^*x_2^* + \dots a_N^*x_N^*}\right) \text{ if } c/c^* = a_1^*/a_1 \quad (12)$$

If the relative price of CO₂ certificates c/c^* lies between the relative CO₂ intensities of good 1, a_1^*/a_1 , and those of good 2, a_2^*/a_2 , then Home will specialize on the production of good 1 and Foreign will produce goods 2 to N . Because the demand for the products change with the relative price, the derived relative demand for CO₂ certificates will be negatively sloped in this range. If c/c^* exactly equals a_2^*/a_2 , then no country has comparative advantage in the production of good 2. Country H will produce good 1, country F will produce goods 3 to N and for good 2 different combinations are possible. Similar thoughts can be applied for the remaining goods. Figure 3 represents the derived demand for CO₂ certificates depending on the relative price for the case of $N = 4$. The equilibrium relative price of CO₂ certificates is determined by the intersection of the derived relative demand and the relative supply of CO₂ certificates. In Figure 3 it is denoted by $(c/c^*)^{eq}$.

The representation in Figure 3 shows further how extensive and intensive margins of trade work in a Ricardian framework where production possibilities are restraint by CO₂ emission targets. Along a riser, a drop in the relative price of CO₂ certificates raises relative demand for good 2 produced in the home country at the intensive margin, since it lowers the price of that good without changing the set of goods that are produced in both countries. Relative demand increases at the extensive margin, when the relative price of CO₂ certificates hits a tread and falls below a_3^*/a_3 , for example.

Figure 3. Determination of relative price for CO₂ certificates: an example

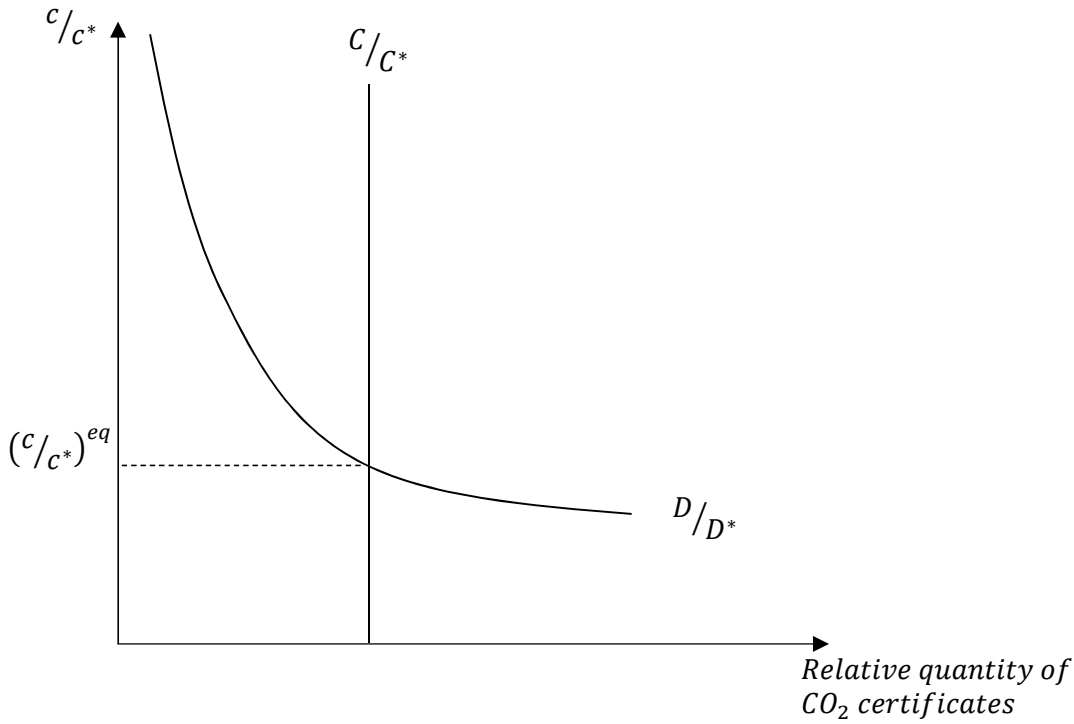


Source: Author.

Note: The solid downward-sloping line is the relative demand curve for CO₂ certificates in Home relative to Foreign. The solid vertical line is the relative supply of CO₂ certificates in the countries. The intersection determines the equilibrium relative price of CO₂ certificates.

The analysis can be further developed to consider the case of a continuum of goods that can be produced in both countries as first introduced by Dornbusch, Fischer, and Smuelson (1977). This renders the gaps between the ratios of CO₂ intensities as shown in a simplified form in Figure 4, the goods remaining sorted according to the comparative advantage of the countries. For any relative price of CO₂ certificates, there is a good s that costs the same whether it is produced in the home country or abroad. Home then produces all goods denoted by a number smaller than s , good s is produced in both countries since no country has a comparative advantage in the production of that good, and all goods denoted by a number greater than s are produced abroad.

Figure 4. Determination of relative price for CO₂ certificates with a continuum of goods



Source: Author.

Note: The solid downward-sloping line is the relative demand curve for CO₂ certificates in Home relative to Foreign. The solid vertical line is the relative supply of CO₂ certificates in the countries. The intersection determines the equilibrium relative price of CO₂ certificates.

As can be seen from Figure 4, a crucial assumption of the model is that both countries pursue CO₂ emission targets. The relationship between the CO₂ emission targets determines the relative price of CO₂ certificates but also the number of goods to be produced in each country in accordance with the concept of comparative advantage. If one country has unreasonably high CO₂ emission target, then the model delivers an outcome where this country should produce most of the goods with high CO₂ intensity of production. This outcome is currently best described by the empirical evidence as presented by Kanemoto et al. (2014) and other related studies. The fact that embodied CO₂ emissions are transferred among regions via international trade can be attributed to lacking or loose CO₂ emission targets in some countries compared to other countries.

c. Emission targets and trade in the presence of transport costs

In the absence of transport costs all goods are tradable and depending on CO₂ intensity of production, relative demand and CO₂ emission targets the range of goods produced is divided between the two countries. The fundamental principles of comparative advantage or the gains from trade do not change by introducing transport costs into the model. In some cases, though, the cost of transportation may be as high as it makes trade less advantageous. High transport cost can lead countries into self-sufficiency in certain sectors, although the CO₂ intensity of production in both countries would motivate specialization and trade.

In the previous subsection production advantage in the home country was given for those goods, where total payment for CO₂ per unit of production, ca_i , was lower than abroad, $c^*a_i^*$. The comparison of CO₂ intensities and payment for CO₂ can be aggravated by transport or other transaction costs associated with international trade. Although transport costs can be very different across industries, we assume that they are a constant percentage share of the CO₂ intensity of a particular product, denoted t . In a two-country model transport costs are independent of the direction of trade.

Under these circumstances, good i will be produced at home if

$$ca_i < (1 + t) \cdot c^*a_i^*, \text{ respectively } a_i/a_i^* < (1 + t) \cdot c^*/c. \quad (13)$$

The same good will be produced abroad if

$$(1 + t) \cdot ca_i > c^*a_i^*, \text{ respectively } a_i/a_i^* > 1/(1 + t) \cdot c^*/c. \quad (13)$$

The pattern of specialization is less straightforward compared to the previous subsection since there is a range of goods where transport costs make full specialization less recommendable.

$$\begin{aligned} a_1/a_1^* < \dots < a_{K-1}/a_{K-1}^* < 1/(1 + t) \cdot c^*/c < a_K/a_K^* < \dots < a_S/a_S^* = c^*/c < a_{S+1}/a_{S+1}^* < \dots < \\ \dots < a_L/a_L^* < 1/(1 + t) \cdot c^*/c < a_{L+1}/a_{L+1}^* < \dots < a_N/a_N^* \end{aligned} \quad (9)$$

Goods 1 to $K - 1$ still will be produced in the home country, goods $L + 1$ to N will be produced abroad. For the remaining goods K to L no clear-cut specialization recommendation is possible and both countries will produce those goods for themselves.

An example for such a good is cement: the costs of transportation both in economic and CO₂ terms are as high as they question the tradability of this good.

As in the traditional Ricardian model, some goods appear non-tradable because of high transport costs that make it impossible to identify a country with a clear comparative advantage. For the remaining goods, though, the idea of comparative advantage and the the home country still will profit from specializing on for example good $K - 1$ and trading it against, say, good $L + 1$.

III. Discussion

The theoretical model described thus far can be used to discuss a range of practical issues, which emerge in a world of international trade in the presence of CO₂ emission targets. In the first place, it appears plausible that high CO₂ intensity of production may lead to disadvantages for some countries on the global market. The CO₂ intensity of production may indeed vary between countries. Hasenbeigi et al. (2016) report that the production of one ton of crude steel is associated with CO₂ emissions amounting to 1080 kg of CO₂ in Mexico, 1708 kg of CO₂ in Germany, 1736 kg of CO₂ in the U.S. and 2148 kg of CO₂ in China. Does this mean that China has a disadvantage in steel production according to kg of CO₂ emissions? This would be the case if trade flows were based on the concept of the absolute advantage. However, an absolute advantage in the production of a particular good is neither a necessary nor a sufficient condition for having a comparative advantage. The comparative advantage of a country depends both on its CO₂ intensity in the production and the price of CO₂ certificates relative to other countries. The price of CO₂ certificates depends on the relative price of CO₂ intensity in other industries. Lower prices of CO₂ certificates can compensate for high CO₂ intensity in the production and vice versa.

China also exhibits a higher CO₂ intensity in aluminum production compared to other countries. The association European Aluminium in Brussels reports that CO₂ intensity in aluminum production lies at about 7 tons CO₂ equivalent per ton aluminum produced in Europe and 10 tons CO₂ equivalent per ton aluminum produced in China (European Aluminium, 2019). Combining these data with the findings of Hasenbeigi et al. (2016) delivers some insights about comparative advantages in China and Europe. In Europe⁵, opportunity costs of producing one ton of aluminum amount to about 4 tons of steel (=

⁵ For Europe CO₂ intensity of German production calculated by Hasenbeigi et al. (2016) is applied.

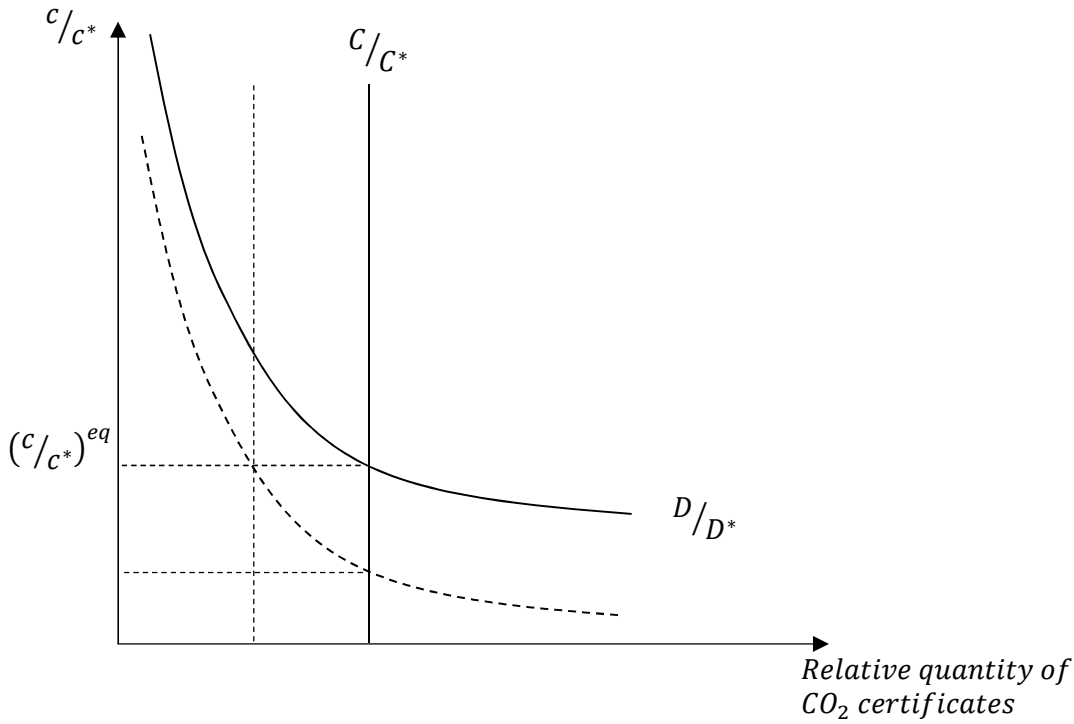
$\frac{7000}{1736}$). In China, the corresponding value is 10 tons of steel per one ton of aluminum ($= \frac{20000}{2148}$). According to this data, Europe has a comparative advantage in the aluminum production and China has a comparative advantage in the production of crude steel, although Europe has absolute advantage in the production of both goods. Although this example is rather simple and does not consider other goods, it illustrates that countries with different CO₂ intensity levels may benefit from international trade if the concept of comparative advantage is applied.

A second issue regards the pricing of CO₂ in the different countries. Many developed countries are concerned that different arrangements to achieve CO₂ emission targets can distort competition and lead to comparative disadvantage for countries where the price of a unit CO₂ is higher than in other countries. This is a widespread view that has a great influence on policymakers. As illustrated by the example above, comparative advantage does not depend on the price of CO₂ certificates but rather on the relative CO₂ intensity of production. It is often claimed that the price of CO₂ certificates is lower in China therefore creating advantages for Chinese producers. The comparative advantage in aluminum production in Europe in the above example is independent of the price of CO₂ certificates.

In the multi-goods model this outcome is less obvious but still valid. What matters to a country is that it is cheaper for it to produce the goods where it has a comparative advantage and trade them for other goods instead of producing those other goods by itself. The relative price of CO₂ certificates determines the number of goods where a country has a comparative advantage. Gains from trade can be achieved even with a small number of good produced in the home country, though. The crucial assumption is that all countries pursue CO₂ emission targets as given for example by the Paris Agreement.

The analysis above delivers also valuable insights about the incentives for innovation. Improving technology in terms of the CO₂ intensity of production at home shifts the derived relative demand for CO₂ certificates as shown by the dotted downward-sloping line in Figure 5. Given unchanged CO₂ emission targets in both countries, the price of CO₂ certificates decreased in H relative to F and the number of goods produced in the home country increases. Alternatively, it is possible to keep the set of goods produced in both countries unchanged by reducing the CO₂ emission target of the home country, as represented by the dotted vertical line in Figure 5.

Figure 5. The impact of technology improvement in H



Source: Author.

Note: The dotted downward-sloping line is the relative demand curve for CO₂ certificates in Home relative to Foreign after CO₂ reducing innovations in Home. The dotted vertical line shows how relative supply of CO₂ certificates can be decreased by introducing a more rigorous CO₂ emissions target in Home. The new emissions target is possible to achieve without changing the set of goods produced if combined with CO₂ reducing innovations.

In the present analysis, other factors are left out, the underlying assumption being that the decision to trade or not is solely made based on CO₂ emissions targets. Moving closer to the real world, one should consider also other restrictions given for example by factor endowments. There is a range of Ricardian style trade models that can be used to extend the analysis and consider additional production factors (see e.g. Costinot and Vogel, 2014, Roy, 1951, Ruffin, 1988). Further steps in this direction are left for further research.

IV. Concluding remarks

The analysis in this paper relies on the brilliance and simplicity of the Ricardian idea (Jones and Weder, 2017) to stress the potential positive contribution of international trade in the presence of CO₂ emissions targets as given for example by the Paris Agreement. The paper represents a new reading of the traditional Ricardian theory of comparative advantage and demonstrates in the style of David Ricardo that international trade is a positive-sum game in a two-goods, two-countries world where CO₂ emissions targets constrain the production possibilities. Extending the number of goods produced and allowing for transportation costs does indeed question the tradability of a number of goods as in the classical Ricardian world. However, the main findings still apply that international trade extends the consumption possibilities while enabling policy makers to achieve their CO₂ emissions targets. This simple framework is a useful tool to underline that the outcome does not depend on CO₂ pricing method or the price of CO₂ certificates in the different countries. The mutual benefit of international trade depends, however, on restraining CO₂ emissions in the sense of the targets set by the Paris Agreement, since the level of CO₂ emissions is the scarce factor of production in the model.

Specialization, international trade and globalization are complex processes, encompassing many different aspects. As Frankel (2009) stresses, it would be surprising if all of them and at any time were favorable or unfavorable to the environment. As the model presented in this paper indicates, international trade can be made climate-friendly and can contribute to greening growth or even growing green. The highest priority should therefore be to implement CO₂ emissions targets at the individual country level. This will not only stop carbon leakage by means of offshoring and international trade but will also open up the possibility of international trade to contribute to achieving lower levels of global CO₂ emissions.

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