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Consumption-based versus production-based accounting of CO_2 emissions: Is there evidence for carbon leakage?

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ABSTRACT

Lately, a controversial debate has evolved regarding consumption-based accounting (CBA) versus production-based accounting (PBA) of CO_2 emissions. So far, the debate has been predominately theoretical and has inspired only a few empirical studies. In this article, we compare production-based versus consumption-based emissions, and for the first time analyze reasons for the differences. In particular, we focus on whether there is evidence for carbon leakage from developed to developing countries. We use the newest available data for 110 countries and analyze whether there are differences between OECD and non-OECD members. Furthermore, we compare the within-country differences for the time span of 1997 to 2011 via fixed effects panel regression models in order to investigate whether increases in GDP per capita result in higher imported emissions. The results suggest that for most countries the differences depending on accounting schemes are small. Furthermore, we find no evidence for carbon leakages. In particular, the ratio of CBA to PBA is not driven by OECD membership or GDP per capita. Instead, the ratio is greater for countries with high energy efficiency and high import rates. Given the small differences between PBA and CBA, we suggest keeping the production-based accounting of CO_2 emissions.

1. Introduction

A controversial debate has recently evolved around the issue of whether national CO_2 emission inventories should be based on territory-related production or consumption (Afionis et al. 2017, Fan et al. 2016, Fernandez-Amador et al. 2017, Davis and Caldeira 2010, Davis et al. 2011, Liu 2015, Peters et al. 2012, Steininger et al. 2015). So far, national CO_2 inventories follow the guidelines of the Intergovernmental Panel on Climate Change (IPCC), which are based on the consumption of fossil fuels within a country. This accounting is called production-based and is relatively straightforward: It estimates the greenhouse gas emissions from all the oil, coal, and gas consumed in a country by private households, industrial production of goods and services, and electricity production. However, production-based accounting has some disadvantages. First, it excludes emissions stemming from international air and sea transportation. Since such emissions do not take place within a specific territory its attribution to specific countries is difficult. Second, energy-intensive industries in countries with strict emission controls, regulations or taxes might move into territories with fewer restrictions and lower energy costs. However, the goods produced in the less restrictive countries might then be exported to the more restrictive countries. Thus, decreasing emissions in one country can be directly linked to increasing emissions in the other country. This type of replacement in response to the environmental policy of a country is often termed “strong carbon leakage”. Third, the emission leakage can also be weak, e.g. if international specialization encourages some countries to outsource the production of carbon-intensive goods to other countries with lower production costs. Strong and weak carbon leakages result only in reallocations of CO_2 emissions, and a decrease in one country is more or less directly related to an increase in another. Consumption-based accounting takes care of these problems. It subtracts from countries all emissions that are contained in exported products, including transportation emissions, and includes the embodied emissions in the inventories of the importing countries (Fan et al. 2016, Peters et al. 2011). If the carbon leakages due to international trade are strong then the difference between consumption-based and production-based emissions might be large. Hence, with respect to production-based

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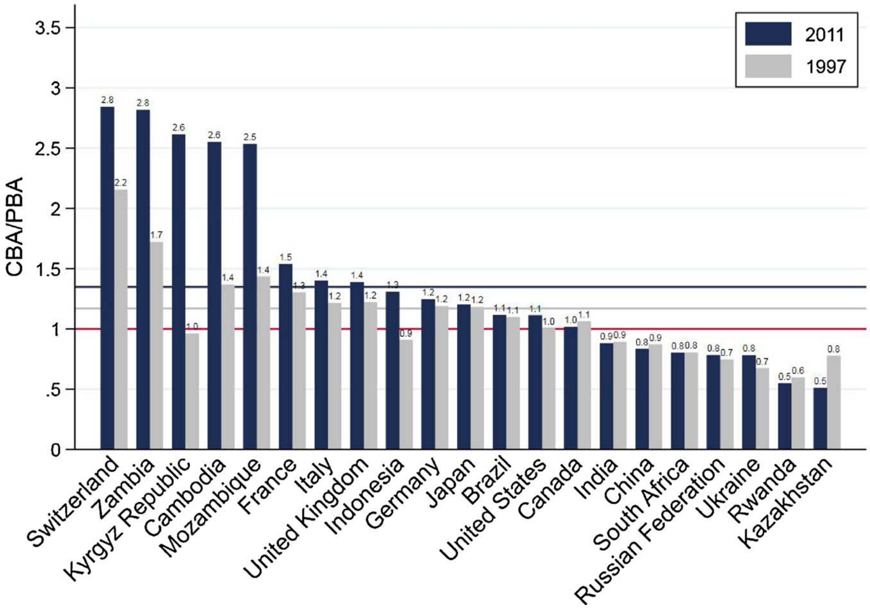

Fig. 1. The ratio of consumption- and production-based CO_2 emissions per capita (CBA/PBA) for 1997 and 2011.
Note: The figure shows the top 5 and the bottom 5 countries with respect to the ratio of CBA to PBA, the five largest emitters of CO_2, and members of the G7 or BRIICS if not already included by the other criteria. Data source is the Emissions Database for Global Atmospheric Research (Olivier et al. 2016) for production-based accounting and the Global Carbon Atlas (Peters et al. 2011) for consumption-based accounting of CO_2. The horizontal grey line denotes the average CBA/PBA ratio for 1997, and the blue line the average for 2011.

inventories, low emission countries might look less “clean” in the consumption-based framework and high emission countries might in reality produce goods for the living standard of low emission countries. Obviously, the difference in accountability of emissions might also have political implications.

In this paper we will take a look at the differences between consumption-based and production-based accounting of emissions. First, after a short literature review in Section 2, we describe the differences by using the most up-to-date data for the 110 countries for which both inventories are available in Section 3. Second, we also analyze the differences by using fixed effects panel regression models for the period of 1997 to 2011 for these 110 countries in this section. Proponents of the consumption-based method often assume (more or less explicitly) that developing countries produce carbon emissions mainly for exports into developed countries. Hence, the former would profit from deducting emissions contained in exports with respect to their CO_2 footprint. In contrast, developed countries might only have low emissions because of leakages and this bias would be corrected by consumption-based accounting. We wonder how big these differences are and whether or not they are driven by GDP. Third, and also in that section, we take a look at the development of the differences of the two inventories for the available time period. If leakages are responsible for the difference, then they should increase over time since regulations became stricter and specialization has also increased over time. The final section concludes with a discussion of the advantages and disadvantages of the consumption-based approach.

2. Literature review

In recent years a number of studies have called attention to the fact that a substantial amount of CO_2 emissions are embodied in international trade. Thus, Davis and Caldeira (2010) report that in 2004 23% of global CO_2 emissions were contained in exports stemming predominantly from developing countries (e.g. China) to developed nations (e.g. Switzerland, Sweden, UK, or the USA). An analysis by Peters et al. (2012) suggests that the proportion related to international trade is increasing over time (to 26% in 2008). These findings have inspired a controversial discussion about the extent to which CO_2 emissions are outsourced by developed nations to developing countries. Some authors propose that since both consumers and producers of goods and services are equally responsible for CO_2 emissions, they should also share mitigation responsibilities (e.g. Steininger et al. 2014, Jakob et al. 2014). How this could be accomplished and whether switching from production-based accounting to consumption-based accounting is beneficial with respect to the efficiency of CO_2 abatement policies is an ongoing debate (e.g. Liu 2015). The consideration of switching to consumption-based accounting depends also on empirical assessments of the size of carbon leakages, and on the reasons for them. So far such empirical investigations are still sparse. Some studies compare consumption-based emissions of Annex I countries (those who committed themselves to CO_2 reductions in the Kyoto Protocol) before and after the commitment. They find very small or no evidence for strong carbon leakages. Similar results hold for studies investigating EU countries before and after the implementation of the European Union Emissions Trading System (EU ETS) (for a review see Branger and Quirion 2014). However, the authors of these studies point out that carbon prices in the EU have been very low so far providing only small incentives for a reallocation of carbon intensive industries such as cement or aluminum production. Furthermore, energy intensive industries received generous emission permits by the EU to avoid reallocation. Hence, outsourcing might increase when the supply of pollution permits is reduced to meet the emission targets.

Other recent empirical studies investigate the question of whether the predictors of CO_2 depend on the accounting scheme. Econometric analyses of production-based emissions usually find that national CO_2 emissions are predominantly driven by population size, GDP, and the energy intensity of a nation’s economy. Moreover, further but smaller predictors are countries’ commitment to environmental protection (measured by ratification of international agreements), non-fossil energy sources, and energy prices (see Franzen and Mader 2016). Fernandez-Amador et al. (2017) compare the effects of GDP per capita on CO_2 per capita of models using production-based data with those of consumption-based data. The estimated elasticity in models using production-based data is 0.65, and the one using consumption-based data 0.81. Similar results are reported by Liddle (2018) who finds an elasticity of 0.57 using production-based CO_2 emissions, and an elasticity of 0.66 analyzing consumption-based data. Hence, the difference of the estimated income elasticity between both accounting schemes is small, and statistically not significant. However, import and export rates also matter if consumption-based accounting is applied. Surprisingly, import and export rates do not matter with respect to production-based emissions. But a country's export rate has a small negative effect on consumption-based CO_2 emissions, while import rates increase them, in line with expectations. None of the two studies finds compelling evidence for an Environmental Kuznets Curve (EKC) independent of the accounting scheme. Thus, CO_2 per capita emissions increase somewhat more slowly at higher income levels than at lower income levels but the diminishing increase is very small, and statistically not significant.

In this paper, we are not interested in analyzing the difference of the predicted estimates by the two different accounting schemes but rather in identifying the factors that drive the ratio of CBA to PBA. Put differently, we identify countries with high and low ratios and analyze the differences between them. Hence, we analyze the question of which countries would be affected by shifting the accounting scheme. The literature on consumption-based accounting assumes that wealthy nations are those with stricter environmental laws e.g. higher carbon prices and thereby that they tend to outsource carbon-intensive industries. Hence, if there were carbon leakages, then wealthy nations should have higher ratios than poorer nations. Moreover, assuming that international specialization increases, the ratios should over time become larger in wealthy nations and smaller in poorer nations. In the following we test both assumptions for the first time.

3. Comparing consumption- and production-based emissions

We compare the two accounting methods for CO_2 per capita by using the latest available data; for the production-based accounting (PBA) we take data from the Emissions Database for Global Atmospheric Research (Olivier et al. 2016), and for the consumption-based approach (CBA) data is taken from the Global Carbon Atlas (Peters et al. 2011). Both sources are recognized as the most exact inventories and are commonly used in the literature (Fan et al. 2016, Fernandez-Amador et al. 2017, Franzen and Mader 2016). Consumption-based accounting uses the multi-regional input-output (MRIO) model and depends on the availability of detailed import and export data (Peters et al. 2011). The latest available accounting stems from 2011 and contains 110 countries. First, we compare both inventories by simply calculating the Pearson and Spearman correlations for a country's CO_2 emissions per capita. Pearson's correlation between the two inventories for 2011 is $r = 0.89$. Since both inventories depend on estimates and are not very exact (particularly the CBA), a robustness check of the Pearson correlation is accomplished by also calculating the rank correlation (Spearman's r) which is $r_S = 0.96$. Hence, both correlations are extremely high indicating that statistically CBA and PBA are very similar. On average a country's ranking with respect to CO_2 per capita does not depend on consumption- or production-based accounting. Countries high in production-based emissions are also high in terms of consumption-based emissions. However, there are some differences and they are quite surprising. Fig. 1 displays the ratio of CBA to PBA emissions per capita for 2011 and 1997 (see Fig. 1).

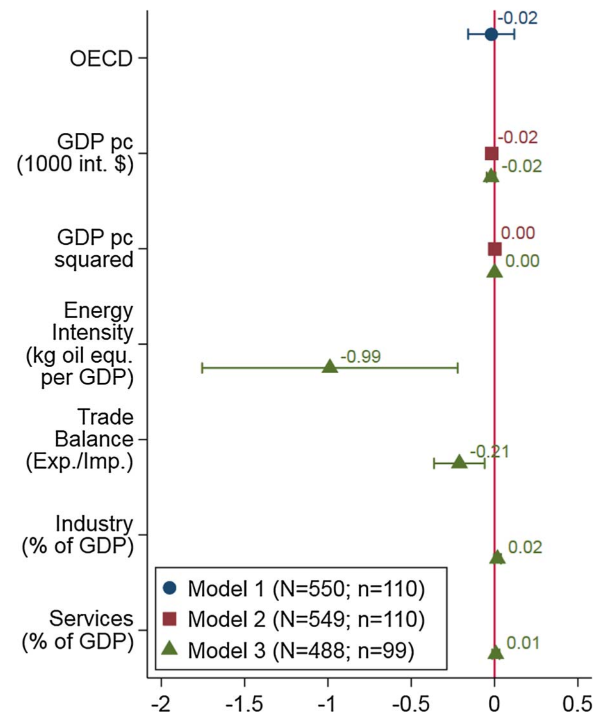

Fig. 2. Regressions of the ratio of CBA to PBA of CO_2 emissions per capita.

Notes: Unstandardized regression coefficients with 95% confidence intervals. All models contain dummy variables for each year in order to control for overall time-trends. All standard errors are clustered by country and year, and therefore robust with respect to heteroscedasticity and autocorrelation. Robustness checks comprise FE panel regressions with country-specific constants and slopes (FEIS) (Brüderl and Ludwig 2015), and penalized splines FE models (Ruppert et al. 2003) to test all parameters for linearity. Furthermore, we ran 110 regressions dropping one country each time to test for statistical outliers. In addition, the robustness of standard errors was checked using non-parametric bootstrapping. Moreover, we tested for the influence of omitted variables using the method suggested by Frank (2000). None of these checks had any substantial influence on the estimates. "n" refers to the number of countries, and "N" to the number of observations (number of countries (n) multiplied by the number of years). Table A1 in Appendix A describes all variables and Table A2 lists all countries included in the models. All models as well as all the robustness checks were conducted using the statistical software package STATA 14.2. See also Table A3 for the exact regression results of all three models.

The figure lists the top and bottom five countries with respect to the ratio of CBA to PBA, the ratios for the five largest CO_2 emitters (China, USA, India, Japan, Russian Federation), and members of the G7 or BRIICS if not already contained by the other criteria. A ratio of 1 means that consumption-based emissions are exactly the same as production-based emissions. This is pretty much the case for Canada. A ratio below 1 means that a country would profit (decrease in CO_2 per capita) from switching to consumption-based accounting. Ratios above 1 indicate that inhabitants of a country consume more CO_2 than under the PBA. If carbon leakages exist, then developed countries should have ratios above 1 and developing nations ratios below 1. Inspection of Fig. 1 shows that this is not confirmed by the frequency distribution of CBA/PBA. The top five countries with the largest ratios are almost all developing nations. Switzerland is the only exception. Also, countries with low ratios are mixed and include the Russian Federation and South Africa. The most extreme deviation is observed for Switzerland. The PBA for Switzerland results in 5.4 tons per capita of CO_2 in 2011 and in 15.3 if accounting is consumption-based.

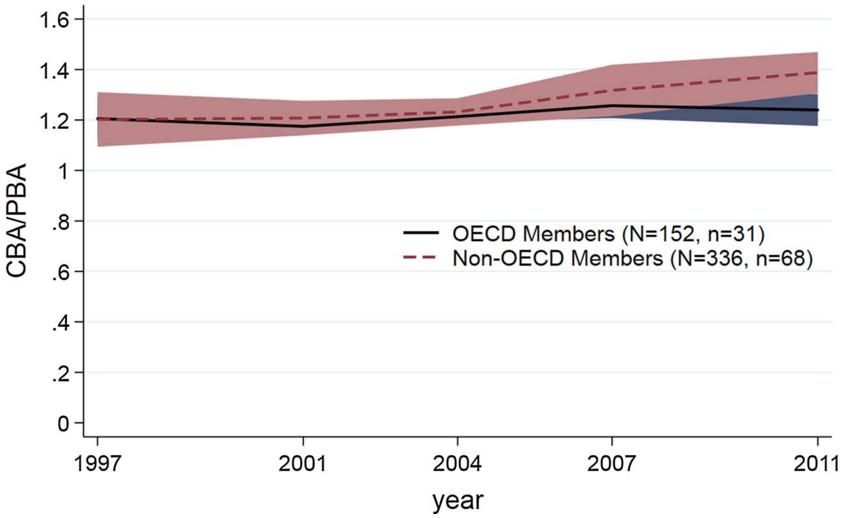

Fig. 3. Growth curves of CBA/PBA ratio of model 3.
Note: The graph displays the predictive CBA/PBA ratios including 95% confidence intervals for OECD and Non-OECD countries. "n" refers to the number of countries, and "N" to the number of observations (number of countries (n) multiplied by the number of years). The analysis (model 3 of Fig. 2) contains 99 countries and five observations (1997, 2001, 2004, 2007, and 2011), however, not all countries have valid measurements for every year.

However, Switzerland's imports stem from Germany (32%), Italy (10%), and France (9%) (World Bank 2017). Hence, Switzerland does not predominantly import CO_2 emissions from developing countries but mainly from developed countries that have higher production-based CO_2 emissions.

Fig. 1 only delivers a first descriptive impression. More reliable insight is obtained by a more rigorous statistical analysis of all 110 countries contained in the database of Peters et al. (2011). Results of such an analysis are depicted in Fig. 2. First, Model 1 of Fig. 2 shows the regression result of a random effects (RE) panel regression (Wooldridge 2010) in which we regress the ratio of CBA to PBA on a dummy variable for OECD membership. The coefficient is almost zero and statistically not significant. Models 2 and 3 use fixed effects (FE) panel regression models in which the ratio of CBA to PBA as well as all independent variables are demeaned (Wooldridge 2010). Model 2 only incorporates countries' GDP per capita (purchasing power adjusted) and its square to control for possible non-linear effects. Again, the coefficients are zero or very close to it and are not statistically significant. Hence, a country's change in GDP per capita does not change the ratio of CBA to PBA.

Model 3 extends the model by including four variables, energy intensity, trade balance, and an economy's share of the industrial or service sector. Energy intensity is obtained by calculating the ratio of a country's energy consumption per unit of GDP. The larger the ratio the more energy is used per unit of GDP. Hence, the variable can also be interpreted as a country's energy inefficiency. The results suggest that energy inefficiency is negatively related to the CBA/PBA ratio. If the energy consumption per unit of GDP increases the CBA/PBA ratio decreases. Put the other way round, if the energy efficiency increases over time (energy/GDP decreases) then the import of CO_2 increases as well.

A negative effect is obtained for the ratio of exports to imports. If exports increase in comparison to imports, the CBA/PBA ratio decreases. Or put the other way round, if the imports are large in comparison to exports then the CBA/PBA ratio increases. Hence, this effect is very intuitive. Finally, an economy's share of the industry or service sector is not related to the CBA/PBA ratio.

Furthermore, we take a look at the growth curve of the CBA/PBA ratio for OECD members and non-members (see Fig. 3). The graph shows no clear trend for both types of countries. Hence, it is not the case that OECD members increase in CBA over time, at least not for the observation period at hand. If anything then OECD members decrease imports of CO_2, but this trend for 2011 is not statistically significant.

4. Conclusion and discussion

An analysis of the CBA/PBA ratio reveals that there is no empirical evidence for carbon leakage from developed to developing countries. On average, countries increase imports of CO_2 if they become more energy efficient. A good example is Switzerland, which has high energy efficiency and also a very high ratio of CBA to PBA. Countries also increase consumption-based CO_2 emissions if they do have large imports in relation to exports, which is a very intuitive effect. However, on average OECD members or countries with high levels of GDP per capita do not have larger CO_2 imports or have increased them over time. In fact, the difference in accounting is rather small for most large emitters such as China (6.1 vs 7.3 or -16%) or the USA (19.2 vs 17.3 or + 11%).

Given these small differences should we switch to consumption-based accounting? Consumption-based accounting has the advantage of incorporating CO_2 emissions from international transportation. It also incorporates carbon leakages and attributes them to the countries who more or less directly externalize CO_2 emissions. However, the empirical analysis reveals that there are no systematic carbon leakages from developed countries. Furthermore, the consumption-based approach also has some disadvantages.

It is based on rather complicated input-output matrices, and thus, involves more assumptions than the production-based approach. This makes the consumption-based accounting more inaccurate than the production-based approach. The consumption-based approach also violates the principle of product liability, which states that producers are responsible for the quality and safety of their products. Of course, this principle applies to companies and it is less clear whether it should also apply to countries. However, the balance of small advantages and large disadvantages would suggest keeping the production-based approach.

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Declaration of interests

None.

Appendix A

Table A1
Variable description.

Variable	mean/ share	within ($\bar{x}_i$)			between ($x_{it} - \bar{x}_i + \bar{\bar{x}}$)			N (n x T)	n	Description	Data Source
		sd	min.	max.	sd	min.	max.				
PBA CO_2 p. c. (metric tons)	3.75	.63	-1.17	8.02	4.26	.05	19.99	875	175	PBA CO_2 emissions p. c. of fossil fuel use and industrial processes (cement production, carbonate use of limestone and dolomite, non-energy use of fuels and other combustion) attributed to the country in which goods and services are produced. Excluded are: short-cycle biomass burning (such as agricultural waste burning) and large-scale biomass burning (such as forest fires).	EDGAR
CBA CO_2 p. c. (metric tons)	5.48	.93	1.56	12.43	5.48	.06	25.50	550	110	CBA CO_2 emissions p. c. of fossil fuel use and industrial processes attributed to the country in which goods and services are consumed (CBA CO_2 = PBA CO_2– CO_2 exports + CO_2 imports).	GCA
CO_2 Trade Balance	1.25	.23	.14	3.09	.38	.57	2.49	550	110	Ratio of CBA to PBA (CBA/PBA).	
OECD Member-ship	.18	0	.18	.18	.37	0	1	920	184	Dummy variable for OECD membership (1) and non-membership (0)	OECD
GDP p. c. (1000 internatio-nal dollars)	11.65	3.54	-14.42	33.14	12.65	.47	73.86	871	178	Gross domestic product (GDP) p. c. based on purchasing power parity (PPP). PPP GDP is GDP converted to international dollars using PPP rates. Data are in international dollars based on the 2011 International Comparison Program (ICP) round.	IMF
Energy Intensity	.18	.07	-.29	.88	.13	.01	.90	687	158	Energy intensity level of primary energy is the ratio between energy supply and PPP GDP. Unit: kg oil equivalent per PPP GDP.	OECD/ IEA/WB, IMF
Trade Balance	.88	.16	.02	1.86	.32	.09	2.43	852	174	Trade balance the ratio of exports to imports of goods and services as shares of GDP.	WB
Industry, value added	28.29	3.31	13.05	55.82	11.62	7.15	79.76	826	174	Industry corresponds to the International Standard Industrial Classification (ISIC) divisions 10-45. The origin of value added is determined by the ISIC, revision 3. Unit: % of GDP.	WB
Services, value added	56.35	3.76	37.57	76.33	13.68	19.03	81.98	822	173	Services correspond to ISIC divisions 50-99. The industrial origin of value added is determined by the ISIC, revision 3. Unit: % of GDP.	WB

Notes: EDGAR = Emission Database for Global Atmospheric Research, GCA = Global Carbon Atlas, IEA = International Energy Agency, IMF = International Monetary Fund, OECD = Organization for Economic Co-operation and Development, WB = World Bank; All variables in the models are included in the units reported above.

Table A2
Countries included in the analyses.

Albania*	Costa Rica*	India*	Morocco*	Slovak Republic*
Argentina*	Cote d'Ivoire*	Indonesia*	Mozambique*	Slovenia*
Armenia*	Croatia*	Iran, Islamic Rep.*	Namibia*	South Africa*
Australia*	Cyprus*	Ireland*	Nepal*	South Korea*
Austria*	Czech Republic*	Israel	Netherlands*	Spain*
Azerbaijan*	Denmark*	Italy*	New Zealand*	Sri Lanka
Bahrain	Dominican Rep.*	Jamaica*	Nicaragua*	Sweden*
Bangladesh*	Ecuador*	Japan*	Nigeria*	Switzerland*
Belarus*	Egypt, Arab Rep.*	Jordan*	Norway*	Tanzania*
Belgium*	El Salvador*	Kazakhstan*	Pakistan*	Thailand*
Benin*	Estonia*	Kenya*	Panama*	Togo*
Bolivia*	Ethiopia	Kyrgyz Republic*	Paraguay*	Tunisia*
Botswana*	Finland*	Lao PDR	Peru*	Turkey*
Brazil*	France*	Latvia*	Philippines*	Uganda
Bulgaria*	Georgia*	Lithuania*	Poland*	Ukraine*
Burkina Faso	Germany*	Madagascar	Portugal*	United Kingdom*
Cambodia*	Ghana*	Malawi	Romania*	United States*
Cameroon*	Greece*	Malaysia*	Russia*	Uruguay*
Canada*	Guatemala*	Malta*	Rwanda	Venezuela, RB*
Chile*	Guinea	Mauritius*	Saudi Arabia*	Vietnam*
China*	Honduras*	Mexico*	Senegal*	Zambia*
Colombia*	Hungary*	Mongolia*	Singapore*	Zimbabwe*

Notes: We only took countries into consideration that are full members of the United Nations. Models 1 and 2 of Fig. 2 contain all 110 countries. Model 3 of Fig. 2 is based on 99 countries indicated by '*'.

Table A3
Regressions of the ratio of CBA to PBA of CO_2 Emissions per capita.

Model	(1) RE	(2) FE	(3) FE
OECD Membership	−0.02		
	(0.07)		
GDP p.c.		−0.02	−0.02
		(0.01)	(0.01)
GDP p.c. squared		0.00	0.00
		(0.00)	(0.00)
Energy Intensity			−0.99*
			(0.28)
Trade Balance (Exports/Imports)			−0.21*
			(0.06)
Industry			0.02
			(0.01)
Services			0.01
			(0.01)
2001	0.03	0.05*	0.01
	(0.03)	(0.02)	(0.03)
2004	0.06	0.11*	0.04
	(0.03)	(0.03)	(0.04)
2007	0.14**	0.22*	0.12
	(0.04)	(0.05)	(0.07)
2011	0.18***	0.28**	0.16*
	(0.04)	(0.05)	(0.06)
n x T	550	549	488
n	110	110	99
adj. R^2 within	0.0855	0.0912	0.1276
theta	.71		

Notes: * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$. Unstandardized regression coefficients with standard errors in brackets. All models contain dummy variables for each year in order to control for overall time-trends. All standard errors are clustered by country and year, and therefore robust with respect to heteroscedasticity and autocorrelation. Robustness checks comprise FE panel regressions with country-specific constants and slopes (FEIS) (Brüderl and Ludwig, 2015), and penalized splines FE models (Ruppert et al., 2003) to test all parameters for linearity. Furthermore, we ran 110 regressions dropping one country each time to test for statistical outliers. In addition, the robustness of standard errors was checked using non-parametric bootstrapping. Moreover, we tested for the influence of omitted variables using the method suggested by Frank (2000). None of these checks had any substantial influence on the estimates. Table A1 in Appendix A describes all variables and Table A2 lists all countries included in the models. All models as well as all the robustness checks were conducted using the statistical software package STATA 14.2.

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