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Carbon Emissions and Economic Growth: Production-based versus Consumption-based Evidence on Decoupling

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ABSTRACT

We assess the Carbon-Kuznets-Curve hypothesis using internationally consistent and comparable production-based versus consumption-based CO_2 emissions data for 40 countries (and 35 industries) during 1995-2007 from the World Input Output Database (WIOD). The estimates for per capita CO_2 emissions are truly comprehensive as these include all carbon emissions embodied in international trade and global commodity chains. Even if we find evidence suggesting a decoupling of production-based CO_2 emissions and growth, consumption-based CO_2 emissions are monotonically increasing with per capita GDP. We draw out the implications of these findings for climate policy and binding emission reduction obligations.

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1. Introduction

Most scientists consider it extremely likely that the Earth's climate will become warmer if atmospheric concentrations of carbon dioxide (CO_2) continue to increase because of emissions by human (economic) activity.[1] In its fifth assessment report, the Intergovernmental Panel on Climate Change (IPCC 2014) predicts that in a business-as-usual scenario the mean global surface temperature will increase by 4°C or more above pre-industrial levels by the end of 21st century (Collins *et al*. 2013)—with a non-negligible risk of far higher dangerous warming (Wagner and Weitzman 2015). To avoid the risk of dangerous and irreversible climate change, the consensus view is that the global average temperature should not rise above pre-industrial temperatures by more than 2°C (Edenhofer *et al.* 2013). This consensus view which has recently been endorsed by 195 nations at the 21st session of the Conference of Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCC) in Paris in December 2015, implies that anthropogenic greenhouse gas (GHG) emissions have to be reduced by 41 to 72 percent in 2050 compared to emissions levels in 2010, and by as much as 78 to 118 percent in 2100 (IPCC 2014; COP21). These major emission reductions over the coming decades will need a dramatic decarbonization of our energy systems as well as a historically unprecedented ramping up of energy efficiency, the more so the higher is the rate of global economic growth (Grubb 2014, p. 14). This points to a major global challenge: is it possible to decarbonize and halve emissions by mid-century so as to keep below the 2°C limit while maintaining global economic growth (Martinez Alier 2009, 2015; Grubb 2014; Spash 2015)?

The issue of whether economic growth can be delinked from GHG emissions is usually framed in terms of the Carbon Kuznets Curve (CKC)—the inverted U-shaped relationship between per capita income and GHG emissions per capita (Dinda 2004; Müller-Fürstenberger & Wagner 2007; Kaika & Zervas, 2013a, 2013b). The CKC hypothesis holds that GHG emissions per person do initially increase with rising per capita income (due to industrialization), then peak and decline after a threshold level of per capita GDP, as countries become more energy efficient, more technologically sophisticated and more inclined to and able to reduce emissions by corresponding legislation. The large empirical and methodological literature on the CKC does

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[1] Ribes *et al.* (2016) provide a novel corroboration of the IPCC's (2014) conclusion that it "is extremely likely [*95 percent confidence*] more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together …"

not provide unambiguous and robust evidence of a CKC peaking for carbon dioxide (see Kaika & Zervas (2013a, 2013b) for a recent review), if only because of well documented but yet unresolved econometric problems concerning the appropriateness of model specification and estimation strategies (Wagner 2008).

We will leave these econometric issues aside however and instead focus on the fact that the overwhelming majority of empirical CKC studies use domestic production-based CO_2 emissions data to test the Kuznets hypothesis—and hence overlook the emissions embodied in international trade and in global commodity chains. Based on IPCC (2007) guidelines, GHG emissions are counted as the *national* emissions coming from domestic production. This geographical definition hides the GHG emissions embodied in international trade and obscures the empirical fact that domestic production-based GHG emissions in (for example) the EU have come down, but consumption-based emissions associated with EU standards of livings have actually increased (Peters and Hertwich 2008; Boitier 2012). Rich countries including the EU-27 and the U.S.A. with high average consumption levels are known to be *net carbon importers* as the CO_2 emissions embodied in their exports are lower than the emissions embodied in their imports (Nakano *et al*. 2009; Boitier 2012; Agrawala *et al.* 2014). *Vice versa*, most developing (and industrializing) countries are net carbon exporters. What this implies is that, because of cross-border carbon leakages, consumption-based CO_2 emissions are higher than production-based emissions in the OECD countries, but lower in the developing countries (Aichele & Felbermayr 2012). This indicates that while there may well be a Kuznets-like delinking between economic growth and per capita production-based GHG emissions, it is as yet unclear whether such delinking is also occurring in terms of *consumption-based* GHG emissions. If not, the notion of "carbon decoupling" has to be rethought—in terms of a delinking between growth and consumption-based GHG emissions. After all, it is no great achievement to reduce domestic per capita carbon emissions by outsourcing carbon-intensive activities to other countries and by being a net importer of GHG, while raising consumption and living standards. This also does not constitute a viable global strategy of meeting the GHG emission reduction obligations implied by COP21. Hence, this paper assesses the CKC hypothesis using internationally comparable and consistent production-based versus consumption-based CO_2 emissions data for 40 countries (and 35 industries) for 1995-2007 from the World Input Output Database (WIOD). We argue that the notion of a decoupling of economic growth and carbon emissions is meaningful (for climate change mitigation) only when we define it in terms of consumption-based CO_2 emissions (and not production-based emissions). The rest of the paper is organized as follows. Section 2 reviews the literature on the CKC. Section 3 provides salient features of the WIOD data used and outlines the Fixed Effects Model used in the regression analysis. Section 4 compares the estimation results of the production-based and the consumption-based CKC. Section 5 draws out the policy implications and concludes.

2. The CKC: a review of the empirical literature

The Carbon Kuznets Curve (CKC) hypothesis postulates an inverted U-shaped relationship between CO_2 emissions and per capita income (as is shown in Figure 1): emissions per person increase up to a certain threshold level as per capita income goes up, after which they start to decrease (Dinda 2004; Müller-Fürstenberger & Wagner 2007; Kaika & Zervas, 2013a, 2013b). Typically, most of the CKC studies use the following general reduced-form model in which GHG emissions per person is a polynomial cubic function (of degree three) of per capita income:

$$(1) \quad y_{it} = \alpha_i + \beta_1 x_{it} + \beta_2 x^2_{it} + \beta_3 x^3_{it} + \beta_4 z_{it} + e_{it}$$

where $i = 1, \ldots, n$ countries, and $t = 1, \ldots, T$ years. We note that equation (1) is a reduced-form equation (Kaika & Zervas, 2013a). Most studies do not explicitly specify the underlying structural equations of the system that lead to (1). The structural causes underlying the CKC have been widely debated however. While a detailed review of this literature is beyond the scope of our paper, the debate on the driving forces of the CKC pattern has focused on changes in income distribution during the process of per capita income growth (Torras and Boyce 1998; Scruggs 1998; Magnani 2000; Gangadhran & Valenzuela 2001; Bimonte 2002), the income elasticity of demand for environmental quality (Dinda 2004; Kaika & Zervas 2013a), structural and technological change from a specialization in primary activities to secondary activities and further to the more environmentally friendly tertiary sector (de Bruyn, van den Bergh & Opschoor 1998; Dinda 2004), the diffusion of more carbon efficient technology through international trade and FDI (Muradian & Martinez-Alier 2001; Stavins *et al.* 2014), and changes in institutions and governance during the process of economic development (Dasgupta, Laplante, Wang & Wheeler 2002; Dutt 2009). However, most of the empirical evidence depends only on the reduced-form equation (1) and not on the underlying (larger) structural model (Dinda 2004).

Figure 1

The Carbon Kuznets Curve (CKC)

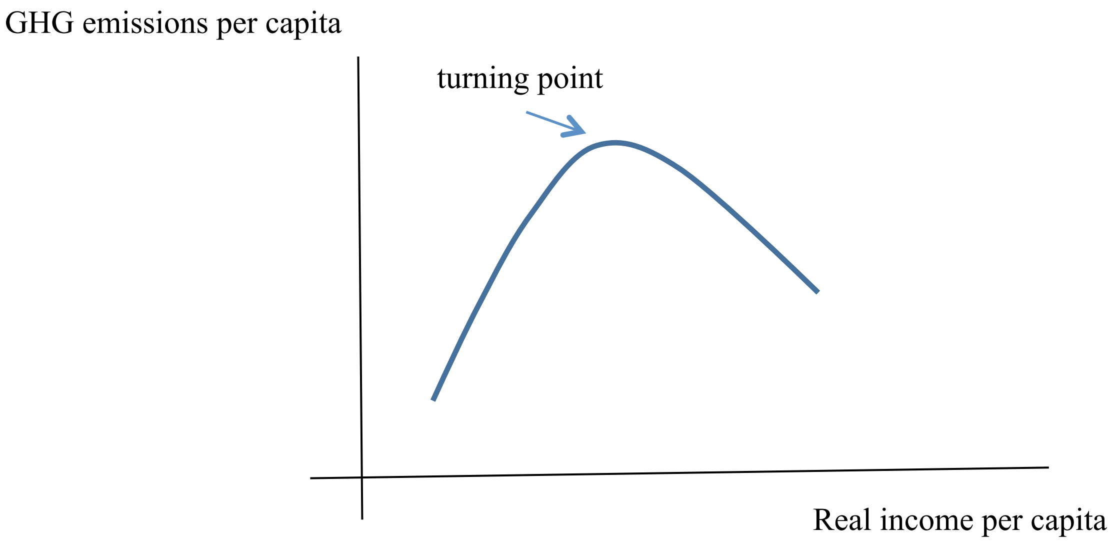

Table 1

Possible Relationships between Economic Growth and GHG Emissions

	Values of coefficients βi	**Relationship between income per capita (x) and GHG emissions per capita (y)**
1	$\beta_1 = \beta_2 = \beta_3 = 0$	No relationship
2	$\beta_1 > 0$ and $\beta_2 = \beta_3 = 0$	A monotonically increasing or linear relationship
3	$\beta_1 < 0$ and $\beta_2 = \beta_3 = 0$	A monotonically decreasing relationship
4	$\beta_1 > 0, \beta_2 < 0$ and $\beta_3 = 0$	An inverted-U-shaped relationship (CKC)
5	$\beta_1 < 0, \beta_2 > 0$ and $\beta_3 = 0$	A U-shaped relationship
6	$\beta_1 > 0, \beta_2 < 0$ and $\beta_3 > 0$	An N-shaped relationship
7	$\beta_1 < 0, \beta_2 > 0$ and $\beta_3 < 0$	An inverted-N-shaped relationship

In equation (1), y is the dependent variable indicating GHG emissions per person, x is the independent variable (which is per capita income in real terms), z represents control variables that might influence y, α is the constant term or country-specific intercept, βi are the estimated coefficients of the k explanatory variables and e represents the error term. The final choice of the functional form (whether or not to include higher order terms and natural logarithms) depends on the model that best fits the data available and has a higher explanatory power within the data range (Lieb 2003). Depending on the values of βi and their combinations, equation (1) can take several relevant forms which are given in Table 1 (Kijima, Nishide & Ohyama 2010). It can be seen that the CKC is only one of various possible numerical outcomes for equation (1), namely outcome 4 in Table 1, which occurs when we find that $\beta_1>0$, $\beta_2<0$ and $\beta_3 = 0$. Using (1), the turning point or threshold level of per capita income can be calculated as (assuming $\frac{dy_i}{dx_i} = 0$):

$$\text{(2)} \qquad \mathbf{x^*}=-\frac{\boldsymbol{\beta 1}}{\boldsymbol{2\beta 2}}, \text{ or in logarithmic version } \quad \mathbf{x^*}= \boldsymbol{e}^{-\frac{\boldsymbol{\beta 1}}{\boldsymbol{2\beta 2}}}$$

The (mechanistic) assumption underlying the CKC curve is that developing countries (which have low per capita incomes and are usually found on the rising slope of the curve) will follow the same development trajectory as the one followed by the developed countries (which feature higher per capita GDP and are found on the downward-sloping side of the curve). It is possible of course that due to some new technological breakthrough developing countries may be able to leapfrog to higher levels of per capita income (Grossman & Krueger 1995). At the same time, however, in our finite world, the poor countries of today will be unable to find further countries from which to import carbon-intensive products as they themselves grow richer. Thus these countries would face the difficult task of *abating* pollution activities rather than outsourcing them to other countries (Arrow *et al.* 1995; Stern *et al.* 1996). Therefore, today's developing (and industrializing) countries may not be able to follow in the steps of the developed countries.

There is a voluminous econometric literature estimating the CKC equation (1), which goes back to the 1990s and reports mixed (inconclusive) results.[2] Table 2 summarizes twenty recent (post-2006) empirical studies on the CKC. It highlights authors' names, year of publication of article, sample used and econometric method employed for analysis, outcomes/relationships between CO_2 emissions and economic growth and other explanatory variables incorporated in the study or descriptions added to explain the observed relationship between carbon emissions and economic growth. While a detailed review of each separate study is not possible here, a few general observations are in order. First, most studies use panel data analysis, mainly because of a lack of time-series data for a long enough period of time for individual countries. Second, outcomes are clearly sensitive to the exact sample of countries used as well as the time period chosen for investigation. It is fair to conclude, finally, that there is no unambiguous and robust evidence in support of the CKC—notwithstanding the fact that eleven out of 20 studies report findings (partly) in support of the CKC.

What all the studies reported in Table 2 share in common (and perhaps surprisingly so) is that they rely on (domestic) production-based emissions data to test the CKC hypothesis. Doing so has two drawbacks. The first drawback of using production-based emission data is that it ignores non-trivial emissions associated with international transportation and international trade (Peters & Hertwich, 2008). CO_2 Emissions from the production of traded goods and services have increased from 4.3 $GtCO_2$ in 1990 (20% of global CO_2 emissions) to 7.8 $GtCO_2$ in 2008 (26% of global CO_2 emissions) (see Peters, Minx, Weber & Edenhofer, 2011). This shows that international trade cannot be ignored while determining the underlying driving forces behind global, regional and national emissions. However, attributing emissions from international transportation to countries is controversial and as of now there is no transparent and agreed-upon method to allocate these emissions to (trading) countries (Peters *et al*. 2011; Boitier 2012).

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[2] The older (pre-2006) literature includes Shafik & Bandyopadhyay (1992), Holtz-Eakin & Selden (1995), Roberts &Grimes (1997), Schmalensee *et al.* (1998), De Bruyn *et al.* (1998), Agras & Chapman (1999), Galeotti & Lanza (1999), Borghesi (2000), Perrings & Ansuategi (2000), Panayotou *et al.*(2000), Pauli (2003) and Aldy (2005).

Table 2
Empirical CKC Studies (2006-2015)

	Authors (year)	Sample and Method	Time Period	Results	Other Significant Variables
1	Azomahou, Laisney and Van Phu (2006)	100 countries Panel data	1960-1996	↗	
2	Richmond and Kaufmann (2006)	36 countries Panel data	1973-1997	↗	Fuel mix/ limited support of a turning point in OECD countries
3	Lantz and Feng (2006)	Canada (Five regions) Panel data	1970-2000	No significant relationship	∩ Population ∪ Technology
4	Kunnas and Myllyntaus (2007)	Finland Time series	1800-2003	↗	
5	Coondoo and Dinda (2008)	88 countries Panel Data	1960-1990	↗; ∩ for Europe	Inter-country income inequality
6	Lee, Chiu and Sun (2009)	89 countries Panel data	1960-2000	N for the panel ∩ in middle income, American and European countries	PHH
7	Aslanidis and Iranzo (2009)	77 non-OECD countries Panel data	1971-1997	↗	
8	Dutt (2009)	124 countries Panel data	1960-2002	↗ 1960-1980 ∩ 1984-2002	Governance; Political institutions; Socio-economic conditions; Education
9	Jalil and Mahmud (2009)	China Time series	1971-2005	∩	Energy consumption
10	Narayan and Narayan (2010)	43 developing countries Panel data and Time series	1980-2004	∩ in 15 countries (time series) ∩ in Middle Eastern and South Asia (panels_	
11	Acaravci and Ozturk (2010)	19 European countries Time series	1960-2005	∩ in 2 countries	Energy consumption

12	Iwata, Okada and Samreth (2011)	28 countries (17 OECD, 11 non-OECD) Panel data	1960-2003	↗	Nuclear power
13	Jaunky (2011)	36 high income countries Panel data and Time series	1980-2005	↗ for whole panel ∩ in 5 countries (time series)	
14	Nasir and Rehman (2011)	Pakistan Time series	1972-2008	∩	Energy consumption; Trade
15	Fosten, Morley and Taylor (2012)	UK Time series	1830-2003	∩	Technological change
16	Shahbaz, Ozturk, Afza and Ali (2013)	Turkey Time series	1970-2010	∩	Energy intensity Globalization
17	López-Menéndez, Perez and Moreno (2014)	27 European countries Panel data	1996-2010	N for the Panel ∩ 4 countries ∪ 3 countries ↗11 countries ↘ 9 countries	Renewable energy sources
18	Farhani, Mrizak and Chaibi (2014)	10 MENA countries Panel data	1990-2010	∩	Energy consumption; Trade; Manufacturing. added value HDI
19	Apergis and Ozturk (2015)	14 Asian countries Panel data	1990-2011	∩	Population density; Land; Industry share in GDP; Quality of institutions
20	Robalino-Lópezet *et al.* (2015)	Venezuela Time series	1980-2025	↗	CO_2 Projections for coming years

Source: Adapted from (Kaika & Zervas, 2013a)

The second drawback of using production-based CO_2 emissions is that this ignores the fact that the reduction in per capita carbon emissions in (especially) the rich countries committed to the Kyoto Protocol (the so-called Annex I Parties) has been (at least partly) offset by an increase in emissions in the (industrializing and exporting) developing countries which are not committed to any binding emission targets (the non-Annex I Parties), as has been shown by Aichele & Felbermayr (2012) and Blanco *et al.* (2014). Specifically, due to the dramatic internationalization of trade in global production chains, the Annex I countries have been able to reduce their national production-based carbon emissions by importing carbon-intensive industrial products from abroad. Hence, for most countries production-based and consumption-based emissions are found to differ considerably (for evidence, see Peters 2008; Davis & Caldeira 2010; Ahmad & Wyckoff 2003; Peters, Minx, Weber & Edenhofer 2011). We define how we measure production-based and consumption-based GHG emissions below, but we can already observe here that net carbon imports (and exports) have grown substantially in recent years. To illustrate, in 1990, the territorial production-based emissions of the Annex I Parties to the Kyoto Protocol amounted to 14.2 $GtCO_2$; their consumption-based emissions were higher (14.6 $GtCO_2$) which implies these rich countries had a carbon import surplus of 0.4 $GtCO_2$ (or 2.8% of their production-based emissions). In 2008, production-based emissions of the Annex I Parties had declined to 13.9 $GtCO_2$, but their consumption-based emissions had increased to 15.5 $GtCO_2$; net carbon imports amounted to 1.6 $GtCO_2$ (or 11.5% of production-based emissions). Trends were the reverse in the non-Annex I Parties which are net carbon exporters. Their production-based emissions increased from 7.7 $GtCO_2$ in 1990 to 16.4 $GtCO_2$ in 2008, while their consumption-based emissions rose from 7.3 $GtCO_2$ to 14.8 $GtCO_2$ over the same period. In 2008, the non-Annex I countries were exporting about 10% of their production-based emissions to the Annex I countries (Peters *et al.* 2011). In general, the increasing carbon-import surplus in the OECD countries has been made possible by an increasing carbon-export surplus in developing countries (Boitier 2012; Agrawala *et al*. 2014; Nakano *et al.* 2009). In light of the above, it is vitally important to statistically test for any decoupling between CO_2 emissions and economic growth using both consumption-based and production-based emission data.

3. Data and Econometric Model

The data on production-based and consumption-based CO_2 emissions by country are from the World Input Output Database (WIOD), which provides consistent annualized inter-country input-output accounts covering the period 1995-2009 for 40 countries (27 EU member states and 13 non-European countries). The WIOD data are broken down across 36 different sectors (35 industries and one household sector) and 26 energy commodities plus one entry for non-energy related CO_2 emissions to complete the emission matrix (see Timmer *et al.* 2015). For the countries covered, the database uses economic linkages between industries, which are portrayed by a set of harmonized supply and use tables (SUTs), together with data on international trade in goods and services to integrate them into sets of inter-country input output tables (IOTs). These input output tables are then used to develop environmental accounts including for GHG emissions. The main source of information for WIOD's energy accounts is the energy balances from the IEA (2011a), which have been made compatible with WIOD's inter-country input-output tables (see Timmer *et al.* 2015 for details) The WIOD data notably do account for emissions arising from international aviation, fishing vessels and marine bunkers. The WIOD database uses standard production-based CO_2 emission factors provided by the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2014a), complemented by country-specific production-based emission factors provided in national CO_2 emission reports by the UNFCCC. Boitier (2012) has calculated annual production-based and consumption-based CO_2 emissions for 40 countries during 1995-2009 using the WIOD database. We use his estimations to calculate CO_2 emissions per capita (using population data from the World Bank database). GDP per capita is given in constant 2011 international dollars (measured in Purchasing Power Parity terms). Because the data from World Bank do not cover Taiwan, Taiwan was dropped from the panel of countries. We further excluded the crisis years 2008 and 2009 from the sample, because emissions behavior and economic growth are out of line with the earlier period 1995-2007. Our panel, which has observations for 39 countries during 1995-2007 (n = 507), covers 79.7% of the world's anthropogenic production-based CO_2 emissions and 80.7% of consumption-based CO_2 emissions in 2007.

Boitier (2012) follows standard Leontief input-output model (IOM) methodology to calculate emissions intensities. The IOM can be represented by:

$$(3) \qquad x = \mathbf{A}\,x + f$$

where $x = (x_1, \ldots x_M, \ldots x_N)$ is the vector of total output in country $m = 1, \ldots N$; $f = (f_{1M}, \ldots f_{VM}, \ldots f_{NM})$ is the vector of total final demand in country m addressed to country v, $m = 1, \ldots N$; and $\mathbf{A}$ is the inter-industry matrix of which the representative element A_{MV} stands for intermediate inputs supplied by country m to country v (measured per unit of output of country v). The solution to equation (3) is given by:

$$(4) \qquad x = (1 - \mathbf{A})^{-1} f = \mathbf{R}\, f$$

where $\mathbf{R} = (1 - \mathbf{A})^{-1}$ is the (multi-country) Leontief inverse. The column sum $\sum_{\mathrm{M}=1}^{N} \mathrm{R}_{\mathrm{MV}}$ gives the total (direct and indirect) increase in production in all industries in all 39 countries due to a unitary increase in all elements of final demand in country v. This is known as the backward production linkage of f_V. If we next define e_{M} as an element of the row vector ($\mathbf{e}'$) of GHG emissions by country m (measured per unit of output in country m), we can calculate a matrix of embodied emissions $\mathbf{E} = \mathbf{e}'\,\mathbf{R}\, f$ of which the diagonal elements E_{MM} are the (direct and indirect) domestic GHG emissions in country m, the column sum of the off-diagonal elements $\sum_{\substack{\mathrm{V}=1 \\ \mathrm{M}\neq\mathrm{V}}}^{N} \mathrm{E}_{\mathrm{MV}}$ stands for the (direct and indirect) emissions embodied in the intermediate imports of country m, and the row sum of the off-diagonal elements $\sum_{\substack{\mathrm{M}=1 \\ \mathrm{M}\neq\mathrm{V}}}^{N} \mathrm{E}_{\mathrm{MV}}$ stands for the (direct and indirect) emissions embodied in the exports of country m (Boitier 2012). Using these definitions, national production-based GHG emissions of country m are computed as:

$$(5) \qquad \mathrm{E}^{\mathrm{prod}} = \mathrm{E}_{\mathrm{MM}} + \sum_{\substack{\mathrm{M}=1 \\ \mathrm{M}\neq\mathrm{V}}}^{N} \mathrm{E}_{\mathrm{MV}} + \mathrm{E}^{\mathrm{H}}$$

where E^{H} are national emissions directly originating from households' consumption. We must emphasize that $\mathrm{E}^{\mathrm{prod}}$ is a truly comprehensive measure of production-based GHG emissions, because it includes all direct and indirect emissions associated with the production and export of goods and services by country *v*. Likewise, national consumption-based GHG emissions of country *m* are estimated as:

$$(6) \qquad \mathrm{E}^{\mathrm{cons}} = \mathrm{E}_{\mathrm{MM}} + \sum_{\substack{\mathrm{V}=1 \\ \mathrm{M}\neq\mathrm{V}}}^{N} \mathrm{E}_{\mathrm{MV}} + \mathrm{E}^{\mathrm{H}}$$

$\mathrm{E}^{\mathrm{cons}}$ comprehensively measures all the direct and indirect GHG emissions occurring throughout global commodity chains of consumption spending in country *v*. To illustrate, if German consumers buy goods produced in France and if the French producers of these goods use intermediate inputs produced in the U.S.A., Brazil and China, and if Chinese producers of these intermediate goods source components in Japan and South Korea, then the estimate of $\mathrm{E}^{\mathrm{cons}}$ includes all carbon emissions associated with producing those goods in France, the U.S.A., Brazil, China, Japan and South Korea, as well as all emissions occurring in the actual transportation of components, intermediates and the goods themselves between the various countries in this hypothetical global production chain (Timmer *et al*. 2015).

In Figure 2 appears the difference ($\mathrm{E}^{\mathrm{cons}} - \mathrm{E}^{\mathrm{prod}}$) or *net* GHG imports ($\sum_{\substack{\mathrm{V}=1 \\ \mathrm{M}\neq\mathrm{V}}}^{N} \mathrm{E}_{\mathrm{MV}} - \sum_{\substack{\mathrm{M}=1 \\ \mathrm{M}\neq\mathrm{V}}}^{N} \mathrm{E}_{\mathrm{MV}}$) for 5 aggregated regions: the EU-27, the USA, the OECD countries, the BRICs, and the rest of the world (RoW) for the period 1995-2007. It can be seen that the EU-27, the USA and the OECD countries are carbon importers (as emissions from production are lower than total emissions from consumption), while the developing countries (including the BRICs) are carbon exporters. The gap between CO_2 consumed and CO_2 produced has widened continuously and rapidly during 1995-2007. Net carbon *imports* into the EU-27 doubled from 11% of production-based emissions in 1995 to 22% in 2007, while for the U.S. net carbon imports increased from 6% of production-based emissions in 1995 to 16.3 % in 2007. (For all OECD countries, some of which are net carbon exporters, *e.g*. Canada, net carbon imports increased from 7% of production-based emissions in 1995 to 13.6% in 2007.) The rich countries are mostly importing carbon from Brazil, Russia, India and China: net carbon *exports* by the BRICs increased from 17% of their production-based emissions in 1995 to more than 20% in 2007 (Boitier 2012).

Figure 2

GHG emissions imports in five regions in the world (1995-2007)

Source: Based on Boitier (2012), Table 1. Boitier's results for the U.S.A. are available at: http://www.erasme-team.eu/modele-economique-econometrie-publications-et-rapports-vpub2.html

Figure 3

Scatter Plot between CO$_2$ Emissions and GDP Per Capita

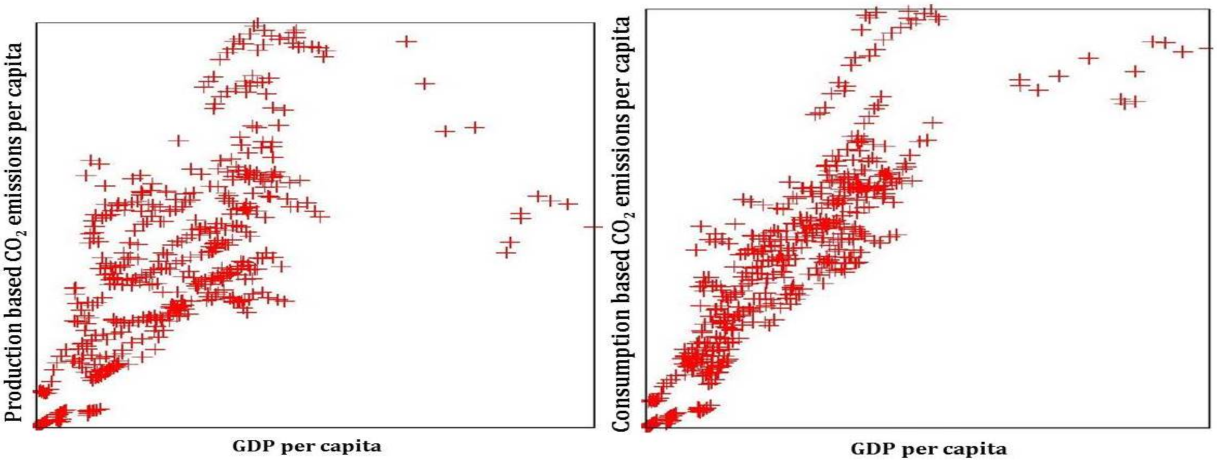

Figure 3 presents the scatter plots between CO_2 emissions per capita and GDP per capita. In the left-hand panel appear production-based CO_2 emissions (calculated using equation (5)) and the data points visually suggest a non-linear (inverted U-shaped) association between emissions and GDP per person (which is suggestive of decoupling). In contrast, in the right-hand panel in which we have plotted consumption-based CO_2 emissions (based on equation (6)), the correlation appears to be a linear one. The nature and the statistical significance of the relationship between emissions and income per capita will be tested in the next section. Table 3 provides the descriptive statistics of our data panel. It can be seen that the distribution of GDP per capita is skewed towards the right, as median income ($25,885) is lower than average income per capita ($26,357); we observe that 95% of the countries in the sample have per capita income lower than $45,983. We note that the mean level of production-based and consumption-based CO_2 emissions for the world as a whole must be identical (because global production- and consumption-based emissions must be equal after all); in our sample of 39 countries, however, average per capita consumption-based emissions exceed average production-based carbon emissions per person.

Table 3
Descriptive Statistics

Variable	Mean	Median	Minimum	Maximum	Std. dev.	5% Perc.	95% Perc.
GDP Per Capita	26356.9	25884.9	2069.2	96245.5	14942.8	5463.12	45983.2
Production-based CO_2 Emissions Per Capita	8.724	8.291	0.844	19.887	4.50	1.57	18.41
Consumption-based CO_2 Emissions Per Capita	9.519	9.677	0.770	22.114	4.91	1.50	18.84

We used linear, quadratic as well as cubic functional forms to study the relationship between growth and (per capita) emissions to see which specification better explains the variance in CO_2 emissions (Galeotti and Lanza 1999). Our prime objective is to observe the relationship between income per capita and CO_2 emissions per person, while controlling for the unobserved heterogeneity across countries and for time-specific effects. We rejected the Pooled Ordinary

Least Squares (OLS) model for our full sample, because country- and time-specific effects are non-zero (Borghesi 2000). The Pooled OLS model also assumes that the variance of country-specific errors is zero, *i.e.* the error term is independently and identically distributed in the panel. However, this condition is unlikely to be met in a panel context. If (unobservable) country-specific characteristics are correlated with real per capita income (our explanatory variable), the Fixed Effects model is consistent and efficient (Dutt 2009) and should be preferred to the Random Effects model. For all specifications, the Random Effects model is rejected in favour of the Fixed Effects model based on the Hausman specification test. We also rejected the Generalized Least Squares method model based on the Breusch-Pagan LM test. Accordingly, given the nature of the data in our full sample of 39 countries, the Fixed Effects model (which works under the condition of strict exogeneity) is found to be consistent and efficient. In the case of cubic functional form our Fixed Effect regression model can be written as:

$$(7) \qquad \mathbf{(CO_2\ pc)_{it}} = \beta_o + \beta_1(GDPpc)_{it} + \beta_2(GDPpc)^2_{it} + \beta_3(GDPpc)^3_{it} + u_i + \gamma_t + \varepsilon_{it}$$

where i =1,……, N and t =1,………, T. u_i denotes country specific effects, γ_t offers time specific effects and ε_{it} is the error term. "pc" stands for per capita. We report Hubert-White heteroskedasticity and auto-correlation adjusted (HAC) robust standard errors and note that the computed R^2 represents the 'with-in variance'[3]. The overall R^2 of the model with Fixed Effects is usually high, because the addition of country-specific effects increases the coefficient of determination considerably. We do not report the estimation results for the country- and time-related control variables introduced in the model. The 39 countries included in our panel are listed in Appendix I.[4]

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[3] With-in variance measures the variation with in one country over time.

[4] The panel is sub-divided into Annex I and non-Annex I countries. Annex I countries are developed countries which are less vulnerable to the adverse effects of climate change, whereas non-Annex I countries are mostly developing countries which are more vulnerable to the adverse impacts of climate change and also rely more heavily on fossil fuel production and commerce. The estimation results for each of these groups separately are available upon request from the authors.

4. Estimation Results

Table 4 presents the estimated results for the linear, quadratic and cubic model, using production-based CO_2 emissions per capita. The goodness of fit of the linear model, as given by the coefficient of determination R^2, is not very high and GDP per capita is not found to be a statistically significant determinant of production-based CO_2 emissions per capita. We can hence reject the hypothesis that there is a monotonically increasing relationship between per capita income and per person production-based carbon emissions. Using the quadratic functional form, all the coefficients are found to be statistically significantly different from zero and they also have the expected sign; the value of R^2 of 0.39 indicates that GDP is a major explanatory factor in determining production-based CO_2 emissions. In the third case of the cubic functional form, β_3 is found to be zero and the other coefficients (β_1 and β_2) are statistically insignificant. Hence, the quadratic functional form provides the best fit for the relation between production-based CO_2 emissions per capita and GDP per capita, which suggests an inverted-U shaped pattern.

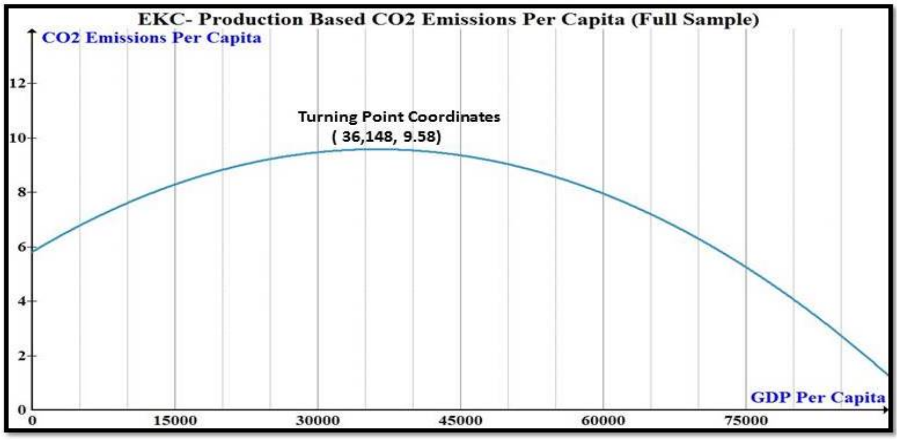
Using Equation (2), we can calculate the threshold level of income at which production-based carbon emissions start to decouple from per capita income growth at \$36,148 (see Figure 4 for an illustration). This turning point lies within the sample range of GDP (see Table 4), but it is well above the sample average (of \$26,356 in Table 3). This indicates that overall production-based emissions will continue to increase until the sample average per capita income has reached the threshold.

Table 4
Estimated Results:
Production-based CO_2 Emissions Per Capita and GDP per Capita

Production-based CO_2 Emissions per Capita	**Coefficient Linear Functional Form**	**Coefficient Quadratic Functional Form**	**Coefficient Cubic Functional Form**
Constant term	11.3508*** (2.8347)	5.8091*** (1.16534)	7.01527*** (1.06731)
GDP	−0.000127012 (0.000122776)	0.000208474*** (5.69269e-05)	7.33742e-05 (9.71152e-05)
GDP^2	-	−2.87729e-09*** (3.58711e-010)	7.30173e-010 (4.11913e-09)
GDP^3	-	-	0 (NA)
Turning Point($)	-	36,148	-
R^2	0.15088	0.389914	0.410302
Number of Obs	507	507	507

Notes: Standard errors are robust *i.e.* heteroskedasticity and autocorrelation consistent (HAC), and are shown in parenthesis. Based on the Hausman specification test we rejected the use of the Random Effects model and the *F*-test rejects the use of the Pooled OLS model. Coefficients are significant at ***P<0.01, **P<0.05, *P<0.10.

Figure 4
Relation between Production-based CO_2 Emissions per Capita and GDP per Capita



Note: based on results for the quadratic functional form reported in Table 4.

Table 5 presents the estimated results using consumption-based CO_2 emissions per person. Unlike in our regressions using production-based emissions, we now find in the linear model that real GDP per capita has a statistically significant impact (at less than 5%) on per capita consumption-based emissions. The value of R^2 for the linear model is high (0.51), which shows that GDP per capita is a major factor in determining consumption-based CO_2 emissions indeed. However, we also find that the coefficients of the quadratic functional form are statistically significant (and having the expected sign), while coefficient β_3 is found to be zero in the case of the cubic functional form (as in Table 5). The results for the quadratic functional form suggest that there is an inverted U-shaped CKC, as is illustrated in Figure 5. When we calculate the threshold level of per capita income (using equation (2)), we obtain a high level of real income per person of $113,709. This level of income is outside the per capita income range of the whole sample (as maximum GDP per capita in the sample is $96,246; see Table 3). This implies that statistically (*i.e.* within the sample range) the relationship between per capita income and per capita carbon emissions is monotonically increasing and the consumption-related CO_2 emissions per capita do not decouple from economic growth within sample range. Even if we would entertain the possibility that there will be a decoupling of growth and emissions at the very high per-capita income level of $113,709 (as suggested by our findings), it should be immediately clear that waiting for this to happen is both unrealistic and extremely risky. By the time average income reaches that turning point, the world will have crossed major climate thresholds and global warming would have become unstoppable and its consequences irreversible and catastrophic (Wagner and Weitzman 2015). We cannot therefore reject the hypothesis that there is a monotonically increasing relationship between per capita income and per person consumption-based carbon emissions. Table 6 summarizes and compares our econometric findings for production-based and consumption-based carbon emissions per capita.

Table 5

Estimated Results:

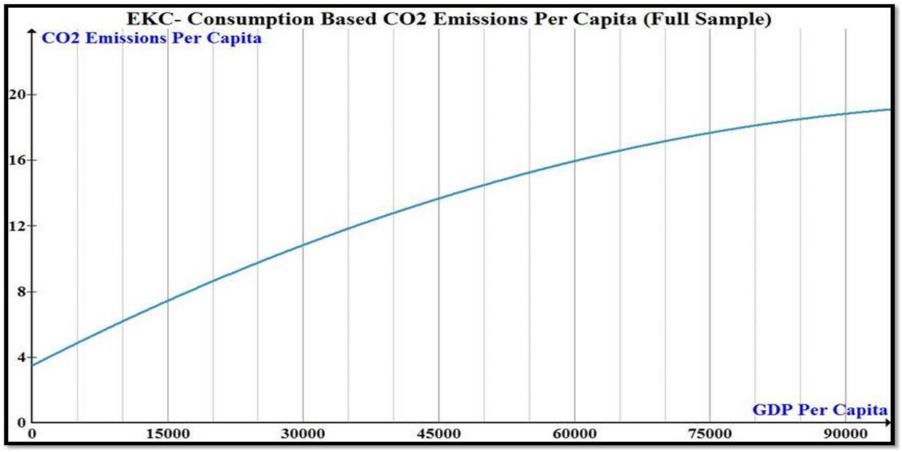
Consumption-based CO_2 Emissions Per Capita and GDP per Capita

Consumption-based CO_2 Emissions per Capita	Coefficient Linear Functional Form	Coefficient Quadratic Functional Form	Coefficient Cubic Functional Form
Const	5.86331*** (1.28026)	3.47425*** (0.707499)	4.24609*** (0.720909)
GDP	0.000137762** (5.56448e-05)	0.000282391*** (3.60992e-05)	0.00019594*** (7.03484e-05)
GDP^2	-	−1.24041e-09*** (2.18302e-010)	1.06803e-09 (3.31948e-09)
GDP^3	-	-	0 (NA)
Turning Point($)	-	113,709	-
R^2	0.512735	0.554412	0.562245
Number of Obs	507	507	507

Notes: Standard errors are robust *i.e.* heteroskedasticity and autocorrelation consistent (HAC), and are shown in parenthesis. Based on the Hausman specification test the use of Random Effects model was rejected and the *F*-test rejects the use of the Pooled OLS model. Coefficients are significant at ***P<0.01, **P<0.05, *P<0.10.

Figure 5

Relation between Consumption-based CO_2 Emissions per Capita and GDP per Capita



Note: based on results for the quadratic functional form reported in Table 5.

Table 6
Comparison of Production and Consumption Based Results

Production-based CO_2 Emissions per Capita	**Consumption-based CO_2 Emissions per Capita**
∩ -an EKC pattern with turning point at $36,148.	↗-monotonically increasing for the sample. Turning point outside sample range $113,709.

The predicted turning point for *production-based GHG emissions* has to be seen in the context of the intentions expressed at the COP21 in Paris to keep global warming below 2^{o}C by the end of this century with an estimated likelihood greater than 66% (Rogelj. *et al.* 2012; Baer *et al.* 2013). This means (as we noted above) that global annual CO_2 emissions need to be reduced by at least 50% by 2050 (Rogelj *et al.* 2011; Rogelj *et al.* 2012) and cumulative greenhouse gas emissions up to 2050 have to be kept within the global "carbon budget"—the total allowable carbon emissions for a >66% chance to keep global average temperature below 2°C. The 2^{o}C global carbon budget thus defined has been estimated to amount to 1,330 $GtCO_2e$ for the period 2012-2050 and 1,860 $GtCO_2e$ for 2012-2100 (Baer *et al.* 2013). Global GHG emissions in 2012 were 50 $GtCO_2e$ (IPCC 2014a) and (corresponding to a global per capita income level of $26,357), carbon emissions per person were about 7 tCO_2e, while world population in 2012 was 7 billion persons (den Elzen *et al.* 2013). Meeting the 2^{o}C target would mean that we have to cut global emissions by 25 $GtCO_2e$ or by about 3.5 tons *per person* by 2050.

Let us suppose we don't want to give up (as yet) on global economic growth and we allow global real per capita GDP to increase from a starting level of $ 26,357 (our sample average) in 2012 up to the production-based CKC turning point of $ 36,148 in 2050; this implies a rather modest annual average growth rate of real GDP per person of 0.8% during 2012-2050. Using the estimated production-based CKC of Table 4, continuous per capita income growth of 0.8% per annum raises the level of per capita CO_2 emissions to 7.2 tCO_2 per capita in 2050 (see Table 7). We assume (following official U.N. estimates) that world population increases from 7 billion in 2012 to 9.7 billion in 2050. This in turn would imply that global GHG emissions in 2050 are 70.3 $GtCO_2e$, which is 40% higher than the actual level of emissions in 2012 (of

50GtCO$_2$e) and roughly 80% above the level needed (of 25GtCO$_2$e) to have a 66% probability of meeting the 2°C target of COP21. Annual emissions hence continue to increase before decoupling starts and this means the atmospheric concentration of CO$_2$ will continue to inexorably rise as well. The cumulative 2012-2050 increase in the atmospheric stock of carbon amounts to 2317GtCO$_2$e, which exceeds the global carbon budget for 2012-2050 by more than 74% and—importantly—more than exhausts the total 2°C global carbon budget up to 2100 (Table 7). This scenario with global emissions increasing to 70.3GtCO$_2$e roughly corresponds to one of the emission pathways developed by Rogelj *et al.* (2011), in which carbon emissions exceed 70GtCO$_2$e in 2050 and peak only around 2080, and which results (with a likely probability > 66%) in a global mean temperature increase of 3.5°C by 2100; significantly, along this pathway, the probability of attaining the 2°C warming target would be much less than 33% (Baer *et al.* 2013).

While this particular pathway is evidently inconsistent with the aim of COP21, it is clearly not the only conceivable scenario. However, further slowing down per capita real GDP growth (below the rate of 0.8% per year assumed here) will postpone reaching the CKC turning point and hence not help to bring down per capita carbon emissions in time. It is true that significantly speeding up per capita income growth so as to reach the CKC turning point much earlier than in 2050 (say, already in 2025) will help to reduce additional cumulative emissions (mainly because of a still smaller global population), but this scenario is economically unrealistic and still incompatible with the 2°C global warming target.[5] Accordingly, the emission gap between the pathway needed to stay below 2°C warming (*i.e.* annual global emissions of 25GtCO$_2$e by 2050) and the projected CKC pathway in Table 7 is an unambiguous signal that waiting for the production-based CKC turning point conflicts with the ambitions of COP21—and the "grow and wait for the turning point" pathway is a sure recipe for climate disaster.

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[5] If we assume global per capita real income growth to equal 2.5% per year (which we deem unlikely), the CKC turning point will be reached in 2025. Per person carbon emissions will peak at 7.2 tCO$_2$e and then decline. With a global population of 7.9 billion people in 2025, global emissions will be 56.9GtCO$_2$e (14% higher than in 2012) and the global 2°C carbon budget will have gone down by more than half (745GtCO$_2$e). With continued global population and a remaining carbon budget for 2025-2050 of only 585GtCO$_2$e, there has to be a historically unprecedented decoupling between economic growth and emissions to give humanity a fair chance to keep warming below 2°C.

Table 7

The "grow and wait for the turning point" pathway:

Production-based CKC estimates 2012-2050

	Average real global GDP per capita (in constant 2011 PPP$)	Annual per capita CO_2 emissions	World population (billions of persons)	Annual global CO_2 emissions ($GtCO_2e$)
2012	26,357	7.0	7.0	50.0
2050	36,148	7.2	9.7	70.3
Average annual growth rate	0.8%	0.1%	0.8%	0.9%
Cumulative emissions (in $GtCO_2e$) 2012-2050				2,317
Global carbon budget: 2012-2050 (in $GtCO_2e$) 2012-2100 (in $GtCO_2e$)				 1,330 1,860

Source: Authors' estimation based on Tables 3 and 4. The growth rate of world population (2012-2050) is based on estimates by the United Nations Department of Economic and Social Affairs (UN-DESA); see: http://www.un.org/en/development/desa/news/population/2015-report.html. Data on the global carbon budget are from Baer *et al*. 2013.

5. Conclusions and Policy Implications

We estimated the relationship between CO_2 emissions and economic growth using input-output-based production- and consumption-related CO_2 emission inventories from WIOD's environmental accounts for 39 different countries for a period of 13 years (1995-2007). Our CO_2 emissions data include emissions embodied in international trade and along internationally fragmented commodity chains—and hence represent the most comprehensive accounting of both production- and consumption-based GHG emissions to date. While there is econometric evidence in support of a CKC pattern for production-based CO_2 emissions, the estimated per-capita income turning point implies a level of annual global GHG emissions of 70.3$GtCO_2e$, which is 40% higher than the 2012 level and not compatible with the COP21 emissions reduction pathway consistent with keeping global warming below 2°C. The production-based inverted U-shaped CKC is, in other words, not a relevant framework for climate change mitigation. In addition, we do not find any support for a decoupling between living standards and per capita consumption levels on the one hand and GHG emissions per person on the other hand. This means that the Annex-I countries (which are mostly the rich OECD countries) have managed to some extent to delink their production systems from GHG emissions by relocating and outsourcing carbon-intensive production activities to the non-Annex I countries—as is indicated in the growing carbon-import surplus of the former and the growing carbon-export surplus of the latter group of countries (Figure 2). The generally used production-based GHG emissions data ignore the highly fragmented nature of global production chains (and networks) and are unable to reveal the ultimate driver of increasing CO_2 emissions: consumption growth (or "affluenza") in the rich economies. What appears (at first sight) to be the result of structural change in the economy is in reality just a relocation of carbon-intensive production to other regions—or carbon leakage. In terms of consumption patterns, we find no noticeable structural change as (direct and indirect) consumption-based GHG emissions continue to rise with higher per capita GDP.

These results should be sobering as they strongly indicate that there is no such thing as an automatic decoupling between economic growth and GHG emissions. It means we have to give up on the notion of the CKC (see also Storm 2009; Lohmann 2009). To keep warming below 2°C de-carbonization has to be drastic and it has to be organized by deliberate (policy) interventions and conscious change in consumption and production patterns. Grubb (2014), Mazzucato and Perez (2014) and the Global Apollo Programme (2014) formulate potentially feasible innovation agendas to bring about the needed transformative change, away from fossil fuels and toward renewable energy systems, which all rely on some form of "entrepreneurial state intervention". The rich Annex-I countries which are in the forefront of technological innovation, are in the position to take the lead and also encourage the developing non-Annex-I countries to participate by investing heavily in the development of new energy technologies that are clean, efficient, and are also affordable for the developing countries. Without such change, the business-as-usual scenario looks bleak, as GHG emissions will continue to increase with economic growth and world population growth (Figure 5) and there is hardly any time or global carbon budget left. Recent projections, based on new modeling using long-term average projections of economic growth, population growth and energy use per person, by Wagner, Ross, Foster and Hankamer (2016), point to a 2^{o}C rise in global mean temperatures already by 2030. Their results suggest that we may be much closer than we realized to breaching the 2^{o}C limit and have already used up all of our room for maneuver (see Pfeiffer *et al.* 2016 for a similar warning). This carries considerable risk, as warming becomes self-reinforcing and dangerous beyond the 2^{o}C limit, and it is the precise outcome COP21 wishes to avoid—but quite in line with our findings.

There is therefore no escape from deep reforms of the global economy which speed up the process of de-carbonization (Grubb 2014) as well as lower carbon-intensive consumption (Global Apollo Programme 2014)—and perhaps even restrict economic growth itself (Martinez Alier 2009, 2015; von Arnim and Rada 2011; Spash 2015). The active participation of and commitment by both the (carbon-importing) developed countries and the (carbon-exporting) developing countries is critical—it is in this respect that the COP21 agreement between 195 countries is a source of some hope. However, to make the agreement work, global action to reduce GHG emissions and to share the burden of adjusting to a low- or zero-carbon economy should be fair (Baer *et al.* 2009) and ideally be based on an assessment of capacity (a country's ability to pay) and historical responsibility (a country's cumulative contribution to the problem of excess GHG concentrations in the atmosphere). As a starting point, this requires comprehensively accounting for the *total* (direct and indirect) carbon pollution over global commodity chains as a whole and distinguishing between a country's production-based and consumption-based CO_2 emissions to enable the working out of a "fair" sharing of the responsibility between the various actors operating in the global commodity chain (on this, see Rodriguez *et al*. 2006; Lenzen *et a*l. 2007; Marques *et al.* 2008; Andrew and Forgie 2008). Our analysis must hence not just be read as a falsification of the Carbon Kuznets Hypothesis (which we think is important in and of itself), but more broadly as pointing out the urgent need to come to a global agreement on shared producer and consumer responsibility on CO_2 emissions (see Lenzen *et al*. 2007; Grubb 2014).

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Appendix List of Annex I and Non-Annex I Countries

Annex I Countries	**Country Code**	**Non-Annex I Countries**	**Country Code**
Australia	AUS	**Brazil**	BRA
Austria	AUT	**China**	CHN
Belgium	BEL	**Cyprus**	CYP
Bulgaria	BGR	**Indonesia**	IDN
Canada	CAN	**India**	IND
Czech Republic	CZE	**South Korea**	KOR
Germany	DEU	**Mexico**	MEX
Denmark	DNK	**Malta**	MLT
Spain	ESP		
Estonia	EST		
Finland	FIN		
France	FRA		
United Kingdom	GBR		
Greece	GRC		
Hungary	HUN		
Ireland	IRL		
Italy	ITA		
Japan	JPN		
Lithuania	LTU		
Luxembourg	LUX		
Latvia	LVA		
Netherlands	NLD		
Poland	POL		
Portugal	PRT		
Romania	ROM		
Russian Federation	RUS		
Slovakia	SVK		
Slovenia	SVN		
Sweden	SWE		
Turkey	TUR		
United States	USA		