Economic Growth and Carbon Emissions:
The Road to 'Hothouse Earth' is Paved with Good Intentions

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Abstract

All IPCC (2018) pathways to restrict future global warming to 1.5°C (and well below an already dangerous 2°C) involve radical cuts in global carbon emissions. Such de-carbonization, while being technically feasible, may impose a 'limit' or 'planetary boundary' to growth, depending on whether or not human society can decouple economic growth from carbon emissions. Decoupling is regarded viable in global and national policy discourses on the Paris Agreement—and claimed to be already happening in real time: witness the recent declines in territorial CO_2 emissions in a group of more than 20 economies. However, some scholars argue that radical de-carbonization will not be possible while increasing the size of the economy. This paper contributes to this debate as well as to the larger literature on climate change and sustainability. First, we develop a prognosis of climate-constrained global growth for 2014-2050 using the Kaya sum rule. Second, we use the Carbon-Kuznets-Curve (CKC) framework to empirically assess the effect of economic growth on CO_2 emissions using measures of both territorial (production-based) emissions and consumption-based (trade-adjusted) emissions. We run panel data regressions using OECD ICIO CO_2 emissions data for 61 countries during 1995-2011; to check the robustness of our findings we construct and use panel samples sourced from alternative databases (Eora; Exio; and WIOD). 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 (within our sample). We draw out the implications of these findings for climate policy and binding emission reduction obligations.

Keywords: Carbon Kuznets Curve; Climate change; Economic growth; Production-based CO_2 emissions, Consumption-based CO_2 emissions; Decoupling; Kaya Identity; Paris Agreement.

JEL codes: F64; Q54; Q55; Q56

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COP21: as the optimism starts to wane

If the Paris climate agreement of December 2015—the so-called COP21[1]—provided cause for optimism that, after years of fruitless diplomatic squabbling, coordinated global action to avoid dangerous climate change and ensure manageable warming of less than 2°C, would finally happen, post-Paris publications by climate scientists are nothing short of sounding the alarm bells. The most prominent example, perhaps, is the recent *PNAS* publication by a team of interdisciplinary Earth systems scientists (Steffen *et al*. 2018), which concludes that the problem of climate change may be far worse than we already thought. The authors warn that even if global emissions are drastically reduced in line with the 66% 'below 2°C' goal of COP21, a series of self-reinforcing bio-geophysical feedbacks and tipping cascades (from melting sea ice to deforestation), could still lock the planet into a cycle of continued warming and a pathway to final destination 'Hothouse Earth'. The *Intergovernmental Panel on Climate Change*, in a specifically commissioned post-Paris report published on October 6, 2018, concurs: allowing warming to reach 2°C would create risks that any reasonable person—not Donald Trump—would regard as deeply dangerous (IPCC 2018).[2] To avoid those risks, humanity will have to reduce emissions of greenhouse gases (GHGs) to net *zero* already by 2050.

What makes both the 'Hothouse Earth' paper and the recent IPCC report remarkable, is that their authors argue that runaway climate change is still preventable: technical (engineering) solutions (including quick fixes and negative-emissions technologies) to bring about deep de-carbonization are available and are beginning to work (*e.g.* see Table S5, Steffen *et al*. 2018; see also: Millar *et al.* 2017; Fankhauser and Jotzo 2017; Geels *et al.* 2017). But available solutions happen to go against the economic logic and the corresponding value system that have dominated the world economy for the last half decade—a logic to scale back (environmental) regulations, pamper the oligopolies of big fossil-fuel corporations, power companies and the automotive industry, give free reign to financial markets and

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[1] COP stands for 'Conference of the Parties', referring to the countries which have signed up to the 1992 United Nations Framework Convention on Climate Change (UNFCC). The COP in Paris is the 21st conference; the E.U. and 195 countries were the participants.

[2] One of the IPCC's (2018) starkest statements is that "limiting global warming to 1.5°C, compared with 2°C, could reduce the number of people both exposed to climate-related risks and susceptible to poverty by up to several hundred million by 2050."

prioritize short-run shareholder returns (Speth 2008; Klein 2014; Malm 2016; Storm 2017). Hence, as Steffen *et al.* (2018) write, the biggest barrier to averting going down the path to 'Hothouse Earth' is the present dominant socioeconomic system, based as it is on high-carbon economic growth and exploitative resource use (Speth 2008; Malm 2016; McNeill and Engelke 2016). Attempts to modify this system have met with some success locally, but very little success globally in reducing GHG emissions. There exists a big gap between the political rhetoric on climate action as in the 'voluntarist'[3] COP21 and the reality of growing GHG emissions. We will only be able to phase out greenhouse gas emissions before mid-century if we shift our societies and economies to a 'wartime footing', suggested Will Steffen, one of the authors of the 'Hothouse Earth' paper in an interview (Aronoff 2018). His analogy of massive mobilization in the face of an existential threat suggests directional thrust by state actors, smacks of planning and public interventionism, and goes against the market-oriented belief system of most economists (Storm 2017). "Economists like to set corrective prices and then be done with it," writes Jeffrey Sachs (2008), adding that "this hands-off approach will not work in the case of a major overhaul of energy technology." Climate stabilization requires a fundamental disruption of hydrocarbon energy, production and transportation infrastructures, a massive upsetting of vested interests in fossil-fuel energy and industry, and large-scale public investment—and all this should be done sooner than later.

The unmistakably alarmist tone of the 'Hothouse Earth' article stands in contrast to more upbeat reports that there has been a delinking between economic growth and carbon emissions in recent times, at least in the world's richest countries and possibly even more globally. The view that decoupling is not only possible, but already happening in real time, is a popular position in global and national policy discourses on COP21. To illustrate, in a widely read *Science* article titled 'The irreversible momentum of clean energy', erstwhile U.S. President Barack Obama (2017), argues that the U.S. economy could continue growing

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3 Consider *Article 2* of COP21: "The Agreement … *aims* to strengthen the global response to the threat of climate change by …. holding the increase in the global average temperature well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C …" The crucial word here is 'aims'. There is no international legal apparatus to enforce the Paris pledges. These pledges incidentally do not cover emissions from global aviation and shipping which in a business-as-usual scenario are together expected to contribute almost 40% of global CO_2 emissions by 2050. Even if countries meet their Paris pledges, global emissions are likely to exceed the emissions in the RCP2.6 scenario of the IPCC Fifth Assessment Report in which warming is likely kept within 2°C. It is difficult to agree with President Obama's optimism that COP21 is the 'turning point for the world'.

without increasing CO_2 emissions thanks to the rollout of renewable energy technologies. Drawing on evidence from the report of his *Council of Economic Advisers* (2017), Obama claims that during the course of his presidency the American economy grew by more than 10% despite a 9.5% fall in CO_2 emissions from the energy sector. "…this "decoupling" of energy sector emissions and economic growth,' writes Obama with his usual eloquence, "should put to rest the argument that combating climate change requires accepting lower growth or a lower standard of living."

Others have highlighted similar trends, including the *International Energy Agency* (IEA), which argues—albeit on the basis of just three years of data 2014-2016—that global carbon emissions (which remained stable) have decoupled from economic growth (IEA 2016). Likewise, the *World Resources Institute*, a climate think-tank based in Washington D.C., reports that as many as 21 countries (mostly belonging to the OECD) managed to reduce their (territory-based) carbon emissions while growing their GDP in the period 2000 to 2014 (Aden 2016); these 21 countries should be role models for the rest of the world. This conclusion is echoed by Grubb *et al.* (2016) who write that "…if there is one conclusion to be drawn from a more country-specific look at the data, it is that both structural change and policies have already started to have a major impact in many industrialized countries …" The latest report by the *Global Commission on the Economy and Climate* (2018) speaks about a 'new era of economic growth' which is sustainable, zero-carbon and inclusive and driven by rapid technological progress, sustainable infrastructure investment and drastically increased energy efficiency and radically reduced carbon intensity. A high-profile predictive analysis for Australia, published in *Nature* and supported by *Commonwealth Science and Industrial Research Organisation* (CSIRO), concludes that the country could achieve "strong economic growth to 2050 …. in scenarios where environmental pressures fall or are stable" (Hatfield-Dods *et al.* 2015).[4] And *International Monetary Fund* economists Cohen, Tovar Jalles, Loungani and Marto (2018), using trend/cycle decomposition techniques, find some evidence of decoupling for the period 1990-2014, particularly in European countries and especially when emissions measures are production-based. The essence of the decoupling thesis is captured well by the title of the OECD (2017) report 'Investing in Climate, Investing in Growth'. The OECD report, prepared in the context of the German G20 Presidency, argues

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[4] According to Hatfield-Dods *et al.* (2015), real GDP in Australia can grow at a rate of 2.41% yr^{-1} during 2015-2050 while emissions are reduced. For a critique, see Ward *et al.* (2016).

that the G20 countries can achieve 'strong' and 'inclusive' economic growth at the same time as reorienting their economies towards development pathways featuring substantially lower GHG emissions. The optimism shows in the fact that IEA 66% 'below 2°C'pathways highlighted in the report are predicated on steady state rates of potential output growth during 2014-2050 of 2% for the U.S.A., 1% for the E.U. and ½ % for Japan (OECD 2017, p. 171).

It should be clear by now that the road to 'Hothouse Earth' is paved with good intentions, as we argue in the remainder of this paper. We first assess the viability of a long-run decoupling of economic growth and carbon emissions using the easily understood Kaya identity (in the next section). Using the Kaya sum rule we decompose global CO_2 emission growth in terms of its primary drivers using historical data for the period 1971-2015, and we then develop a long-term prognosis of the rate of global per capita income growth for the period 2014-2050 that is consistent with the COP21 carbon emission pledges and based on official IEA-OECD assumptions concerning future energy and carbon efficiency changes consistent with the Paris pledges. Based on these assumptions, we conclude that realizing the radical carbon emission reductions demanded by COP21 and IPCC (2018) does compromise economic growth: 'green' growth predicated on carbon decoupling, is impossible if we rule out (as is done by the IEA and OECD) truly game-changing technological progress and revolutionary social change.

In the next section we present the results of a systematic econometric analysis of the (historical) relationship between economic growth and carbon dioxide emissions. We use the Carbon-Kuznets-Curve (CKC) framework and run panel data regressions using OECD Inter-Country Input-Output (ICIO) CO_2 emissions data for 61 countries during 1995-2011; to check the robustness of our findings, we construct and use three other panel samples sourced from alternative databases (Eora; Exio; and WIOD).[5] We present a variety of models, and pay particular attention to the difference between production-based (territorial) emissions and consumption-based emissions, which include the impact of international trade. We find that over this period there is some evidence of decoupling between economic growth and territorial emissions, but no evidence of decoupling for consumption-based emissions.

In the final section which wraps up our analysis and highlights policy and wider implications, we explain why we think Will Steffen (Aronoff 2018) and Hans Joachim

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[5] We agree with Grubb *et al.* (2016) that using multi-model results is necessary when drawing conclusions about PB and CB carbon emissions.

Schellnhuber (Watts 2018) are right to call for large-scale climate mobilization. Yes, it is possible to reduce CO_2 emissions without disastrous economic consequences, but not at the speed and scale required by COP21 and IPCC (2018). Without a concerted (global) policy shift to deep de-carbonization (Fankhauser and Jotzo 2017; Geels *et al.* 2017), a rapid transition to renewable energy sources (Peters *et al.* 2017), structural change in production, consumption and transportation (Steffen *et al*. 2018), and a transformation of finance (Malm 2016; Mazzucato and Semieniuk 2018), the decoupling will not even come close to what is needed (*e.g.* Storm 2017). The key insight is that marginal, incremental, improvements in energy and carbon efficiency cannot do the job and that what is needed is a structural transformation—and establishment economics lacks the instruments and approaches to analyze exactly this (Storm 2015; Wade 2018).

Can economies grow as carbon emissions fall?

All economic activity requires energy; to the extent this energy comes from fossil fuels, the energy use results in emissions of CO_2.[6] This linkage implies that deep emissions reduction will constrain economic growth, unless there is decoupling—meaning that drastic emission reductions are possible with little or no effect on growth. An instructive device for analyzing the linkage (or decoupling) of growth and CO_2 emissions is the well-known Kaya identity (Kaya and Yokoburi 1997), which decomposes global CO_2 emissions (in million tonnes), denoted by *C*, into measurable 'drivers' directly relevant to climate and energy policy:

$$(1) \qquad C = P \times \frac{Y}{P} \times \frac{C}{E} \times \frac{E}{Y} = P \times y \times c \times e$$

where *P* = world population (billions of persons), *Y* = world GDP (in 2005 U.S. dollars), *E* = total primary energy supply or TPES (in PJ), *y* = global per capita income (in 2005 U.S. dollars), *c* = *C/E* = carbon intensity of primary energy supply, or CO_2 emissions per TPES, and *e* = *E/Y* = energy intensity of GDP. Carbon emissions rise when world population

6 See Malm (2016) and McNeill and Engelke (2016). Recent long-run analyses of the economic growth and energy intensity come to conflicting findings. Using a dataset of 99 countries (1970-201), Csereklyei, Rubio-Varas and Stern (2016) find that energy intensity declines less than proportionately with growth, but Semieniuk (2018) who uses data for 180 countries (1950-2014) concludes that energy intensity is constant with growth. No one observes an absolute decoupling of growth and energy use.

increases and/or when per capita income rises. Emissions decline when energy intensity declines, for example, when higher energy prices cause firms to make energy efficiency investments that reduce the amount of energy needed to produce product. Carbon intensity declines when the share of renewable energy sources in electricity generation increases and the share of fossil-fuel energy goes down. Totally differentiating equation (1), and rearranging, gives the Kaya sum rule (for compound average annual growth rates) as:

$$(2) \qquad \hat{C} = \hat{P} + \hat{y} + \hat{c} + \hat{e}$$

Global carbon emissions growth is driven by population growth $\hat{P}$, per capita income growth $\hat{y}$, the growth of carbon intensity of energy $\hat{c}$, and the growth of energy intensity of GDP $\hat{e}$. In Table 1 appear the results of a decomposition of global CO_2 emissions for the period 1971-2015 and our projection for the period 2014-2050, which satisfy (2). We focus on CO_2 emissions from the energy system which represent 70% of global GHG emissions in 2010.[7]

Let us first consider actual (historical) changes during 1971-2015 when global CO_2 emissions increased by 1.93% yr^{-1}. Growth in population (at 1.53% yr^{-1}) and in per capita real GDP (at 1.91% yr^{-1}) exerted upward pressure on CO_2 emissions, which was only partially offset by downward pressure from higher energy efficiency (energy intensity declined by 1.35% yr^{-1}) and lower carbon intensity (which declined by 0.15% yr^{-1}).[8] These downward trends in energy and carbon intensity are still insufficient to delink economic growth and carbon emissions—and they are not close to what is needed to achieve the longer-term Paris pledges or the recommendation of IPCC (2018) to have net-zero emissions already by 2050. Table 1 signals some improvement over time however, as energy intensity has begun to decline appreciably faster post 1990, recording a decline of 1.59% yr^{-1} during 1990-2015 as compared to 1.08% during 1971-1990. There is no similar sign of declining carbon intensity—our data show that carbon intensity has started to decline only from 2012 onwards and at a modest pace of -0.28% yr^{-1}.

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7 The drivers are different for non-CO_2 GHGs, such as those from agriculture, and CO_2 emissions not derived from energy use (such as cement and deforestation).

8 For similar decomposition results for global emissions, see Peters *et al.* (2017). Csereklyei *et al.* (2016) find that world energy intensity declined by 1.1% per annum during 1971-2010, which is consistent with what we report in Table 1.

Table 1

A Kaya identity decomposition of global CO_2 emissions, 1971-2015 and 2014-2050

(average annual growth rates %)

	actual change			projections: 85% reduction in CO2 emissions	projections: 90% reduction in CO2 emissions
	1971-1990	1991-2015	1971-2015	2014-2050	2014-2050
global CO_2 emissions	2.05	1.89	1.93	−5.13	−6.20
world population	1.80	1.31	1.53	0.79	0.79
real GDP per capita	1.75	2.14	1.91	0.45	−0.62
energy intensity (TPES/GDP)	−1.08	−1.59	−1.35	−2.69	−2.69
carbon intensity (CO_2/TPES)	−0.40	0.06	−0.15	−3.68	−3.68

Sources: Data for 1971-2015 are from IEA (2017) *CO2 Emissions from Fuel Combustion*. The CO_2 intensity (CO_2/TPES) and energy intensity (TPES/GDP) in 2050 are from OECD (2017), Table 2.18, and refer to the G20 countries. Projected growth of world population is from UN DESA (2015), "World Population Prospects: The 2015 Revision".

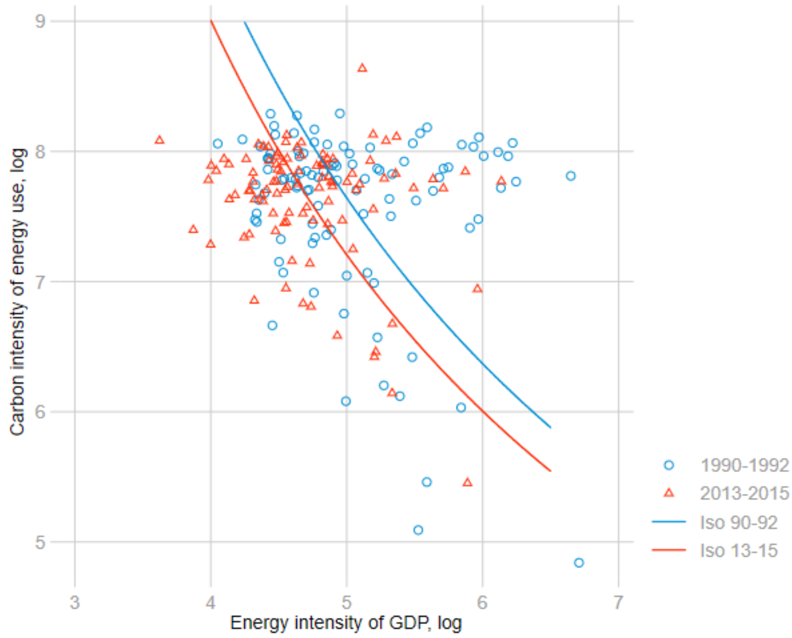
Notes: Average annual growth rate are compound average annual growth rates. Calculations are based on the IEA (2017) and IEA 66% 2°C scenario projections. The projected changes for the period 2014-2050 are consistent with the IEA 66% 2°C scenario projections; the average annual reduction in global CO_2 emissions is consistent with the target to reduce emissions in 2050 by 85% below 1990 levels accepted in the 2050 Low Carbon Economy Roadmap adopted by the E.U. and the COP21. The projected average annual growth rate of per capita real GDP (2014-2050) has been estimated as a residual (using the Kaya identity (3)), as explained in the text.

Global average changes are the net outcomes of underlying regional (and country-level) changes. In Table 2 appear the Kaya decomposition results for the OECD countries and the non-OECD countries, as well as separately for the U.S.A., the E.U.-28, China, India and Indonesia, for the period 1971-2015. Country trajectories differ, but there are four general developments which are of critical importance to changes in emission trajectories. First, population growth has been lower during 1991-2015 compared to 1971-1990, leading to lower CO_2 emissions growth; this declining trend will continue during the rest of this century. Second, all countries experienced negative energy intensity growth—in the OECD countries during 1991-2015, the improved energy efficiency more than offset the upward pressure on carbon emissions coming from per capita income growth. Third, the E.U.-28 and the U.S.A. exhibit negative carbon intensity growth, but somewhat worryingly, the rate of de-carbonization in the OECD has been slowing down during 1991-2015 compared to the years

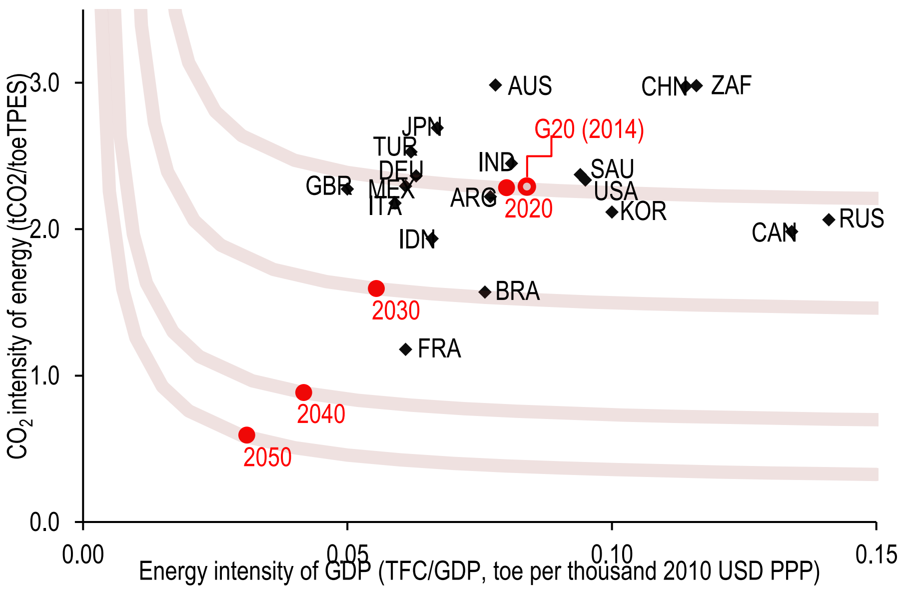
1971-1990. The E.U. carbon intensity decline recorded during 1991-2015 is dominated by the growing share of (zero-carbon) renewables in total energy use, particularly due to Germany's *Energiewende* (cf. Peters *et al.* 2017, p. 120). The non-OECD countries as a whole experienced almost unchanged carbon intensity growth during 1971-2015, but China, India and Indonesia have managed to substantially lower their (still positive) carbon intensity growth rates. For instance, China brought down carbon intensity growth from 0.94% yr^{-1} during 1971-1990 to 0.69% yr^{-1} during 1991-2015, mostly because it reduced the share of fossil fuels in total energy use, and especially of coal (Grubb *et al.* 2015; Peters *et al.* 2017, p. 119; Guan *et al*. 2018). Finally, neither in the OECD nor in the non-OECD countries are the negative energy intensity growth and the declining carbon intensity growth substantial enough to ensure a decoupling of growth of CO_2 emissions and growth of real GDP. So far the world has achieved only *relative* decoupling but no absolute decline in carbon emissions.

Panel (A) of Figure 1 displays the energy (to GDP) intensities and carbon (to energy use) intensities in 1990-92 and 2013-15 of the 100 countries with the highest average CO_2 emissions in 2013-2015 (see also Grubb 2014; OECD 2017; Fankhauser and Jotzo 2017). The figure shows wide cross-country variations along both dimensions. Global *mean* energy intensity in 1990-92 is 188 kg of oil equivalent per $1,000 GDP (constant 2011 PPP), with a standard deviation of 140 kg; average energy intensity in 2013-15 is lower: 127 kg of oil equivalent per $1,000 GDP (constant 2011 PPP), with a standard deviation of 74 kg. Global mean energy intensity has hence declined at a rate of 1.69% yr^{-1} during 1990-92 and 2013-15 (which is comparable to what we found, using IEA (2017) data, in Table 1); the decline in the standard deviation suggests some convergence to the global mean. Global *mean* carbon intensity in 1990-92 is 2.28 $kgCO_2$ per kg of oil equivalent, with a standard deviation of 0.9; the world's mean carbon intensity in 2013-15 is 2.25 $kgCO_2$ per kg of oil equivalent, with a standard deviation of 0.8. Global mean carbon intensity declined at a rate of only 0.06% yr^{-1} during 1990-92 and 2013-15 (see Table 1). For the majority of low- and middle-income countries, which have been increasing the role of coal in electricity supply and of oil in transportation, carbon intensity of energy increased over the period (e.g. Fankhauser and Jotzo 2017, Fig. 2; Peters *et al.* 2017).

Figure 1
Energy intensity (e) and carbon intensity of energy (c)
Panel (A)
100 countries, 1990-1992 versus 2013-2015



Panel (B)
The G20 economies, 2014 and their path to 2050



Sources:	Panel (A): Data are from *World Development Indicators*, https://data.worldbank.org/indicator. Panel (B): Table 2.18, OECD (2017).
Notes:	Panel (A): energy intensity of GDP = energy use in kg of oil equivalent per $1,000 GDP (constant 2011 PPP); CO_2 intensity of energy = kg per kg of oil equivalent energy use. Global mean CO_2 intensity of GDP in 1990-1992 is 429 kg/$1,000 (constant 2011 PPP); it equals 286 kg/$1,000 (constant 2011 PPP) in 2013-15. The sample consists of the 100 countries with the highest average CO_2 emissions in 2013-2015.

Table 2

A Kaya Identity decomposition of CO2 emissions, 1971-2015

(average annual growth rates %)

		1971–1990	1991–2015	1971–2015
OECD	CO_2 emissions	0.87	0.25	0.52
	Population	0.94	0.69	0.80
	GDP per capita	2.33	1.48	1.82
	energy intensity (TPES/GDP)	–1.66	–1.58	–1.58
	carbon intensity (CO_2/TPES)	–0.69	–0.32	–0.49
U.S.A.	CO_2 emissions	0.60	0.20	0.35
	Population	0.98	1.00	1.00
	GDP per capita	2.24	1.54	1.78
	energy intensity (TPES/GDP)	–2.19	–1.98	–2.01
	carbon intensity (CO_2/TPES)	–0.39	–0.32	–0.38
E.U.-28	CO_2 emissions		–0.92	
	Population		0.26	
	GDP per capita		1.45	
	energy intensity (TPES/GDP)		–1.84	
	carbon intensity (CO_2/TPES)		–0.77	
Non–OECD	CO_2 emissions	4.17	3.28	3.61
	Population	2.05	1.45	1.72
	GDP per capita	2.00	3.48	2.74
	energy intensity (TPES/GDP)	–0.27	–2.00	–1.23
	carbon intensity (CO_2/TPES)	0.35	0.38	0.37
China	CO_2 emissions	5.29	6.09	5.73
	Population	1.59	0.73	1.12
	GDP per capita	6.09	9.19	7.81
	energy intensity (TPES/GDP)	–3.22	–4.20	–3.94
	carbon intensity (CO_2/TPES)	0.94	0.69	0.96
India	CO_2 emissions	5.82	5.50	5.69
	Population	2.29	1.63	1.92
	GDP per capita	2.08	5.05	3.62
	energy intensity (TPES/GDP)	–0.63	–2.43	–1.53
	carbon intensity (CO_2/TPES)	1.99	1.26	1.63
Indonesia	CO_2 emissions	9.19	4.76	6.73
	Population	2.29	1.40	1.79
	GDP per capita	4.04	3.21	3.61
	energy intensity (TPES/GDP)	–0.78	–1.30	–1.09
	carbon intensity (CO_2/TPES)	3.40	1.42	2.31

Sources: Data for 1971-2015 are from IEA (2017) *CO_2 Emissions from Fuel Combustion*.

Combining *e* and *c* gives a global average for the carbon intensity of GDP. The two isoquants display all combinations of *e* and *c* which result in the global *mean* carbon intensity of GDP (*c/y*) in 1990-92 and 2013-15. The isoquants can be interpreted as reflecting a technological frontier in terms of energy intensity and carbon intensity. The isoquant has shifted down (towards the origin) over time, mostly because of improvement in energy efficiency. But the downward shift is only limited, in line with the growth data in Tables 1 and 2—and not remotely what is required to meet the COP21 pledges or the targets set by the IPCC (2018).

Panel (B) of Figure 1 shows similar isoquants (or 'frontiers') at levels which are consistent with the IEA 66% 2°C scenario, with the data points indicating the G20 average projected by the IEA. The 2014 positions of the G20 countries are also plotted to indicate the cross-country variety in starting points. The lines provide clear directions how energy intensity and/or carbon intensity need to be reduced in order to meet the 66% below 2°C warming target. These projected reductions will require radical technological progress and an unprecedented transformation of productive, consumption and economic structures, as well as finance (Steffen *et al.* 2018). For the G20 countries as a group, projected energy intensity growth $\hat{e}$ between 2014 and 2050 is −2.69% yr^{-1} (which, we note, is considerably faster than the historical decline of −1.35% yr^{-1} during 1971-2015). Average carbon intensity growth $\hat{c}$ in the G20 is forecast to equal −3.68% yr^{-1} during 2014-2050, which (needless to say) implies very aggressive de-carbonization. This shows that the greatest potential for drastic cuts in emissions lies in the deep de-carbonization of energy systems (Geels *et al.* 2017), which is exactly what emission scenarios consistent with COP21 indicate (Peters *et al*. 2017). The future potential for deep de-carbonization is largest in the non-OECD countries, where 'low-hanging fruit' could be harvested by means of a rapid phasing out of coal, an equally rapid 'phasing in' of renewable energies, enhancing the biosphere and carbon sinks, and the large-scale deployment of CCS; particularly telling is the observation that most models cannot identify emission pathways consistent with the 66% 'below 2°C' goal without a large-scale ramp-up of (as yet unproven) CCS facilities (Peters 2017 *et al.*, p. 121).

It should be obvious that past and current trends in energy and carbon intensity are woefully inconsistent with future pathways that would stabilize the climate at temperature rises well below 2°C—continuing with business-as-usual will irreversibly put the Earth System onto a 'Hothouse Earth' pathway (Steffen *et al*. 2018). "The challenge that humanity faces," write Steffen *et al.* (2018, p. 3), "is to create a "Stabilized Earth" pathway that steers the Earth System away from its current trajectory toward the threshold beyond which is Hothouse Earth.” The key issue is what the deep emissions reductions will mean for economic growth. Can we stabilize the climate system while growing the economy? A tentative, but not unrealistic, growth projection for the period 2014-2050 which is consistent with COP21 is provided in the last two columns of Table 1.

Let us first provide a disclaimer. Whatever the (modelling) method, projections about future population growth, economic growth and energy and carbon intensities are highly sensitive to assumptions about technological progress (e.g. concerning CCS or energy storage technologies) as well as about economic and climate policies. Given the uncertainties involved, what do the models tell us about the impacts of climate change and climate policy? ‘Very little,’ is Robert Pindyck’s (2013, p. 860) honest answer, and we agree. Model analyses of climate policy “create a perception of knowledge and precision, but that perception is illusory and misleading” (*ibid.*) Hence, rather than employing a model, we use the Kaya growth identity (2), which holds by definition, to explore the scope for economic growth in climate-constrained world. We determine per capita real income growth as the residual:

(3) $\hat{y} = \hat{C} - \hat{P} - \hat{c} - \hat{e}$

We assume (in line with the *2050 Low Carbon Economy Roadmap* adopted by the E.U.) that global CO_2 emissions in 2050 have to be reduced by 85% relative to their 1990 level; this implies a reduction in global carbon emissions $\hat{C}$ by 5.13% yr^{-1}. World population growth $\hat{P}$ is assumed to equal 0.79% yr^{-1} during 2014-2050, based on United Nations projections. The projected decreases in energy and carbon intensity are taken from OECD (2017, Table 2.18): $\hat{e}$ = −2.69% yr^{-1} and $\hat{c}$ = −3.68% yr^{-1} (these numbers are consistent with Panel (B) of Fig. 1). The ambitious growth projections of $\hat{e}$ and $\hat{c}$ are in line with IEA-OECD 66% below 2°C scenarios, but still fall short of what would be required for a “Stabilized Earth” as recommended by IPCC (2018). Using these estimates for 2014-2050, we derive an estimate of the ‘climate-constrained’ annual growth rate of per capita real GDP that is consistent with a ‘66% below 2°C’ scenario (see Table 1):

(4) $\hat{y} = \hat{C} - \hat{P} - \hat{c} - \hat{e} = -5.13\% - 0.79\% + 3.68\% + 2.69\% = 0.45\%$

Based on our arguably optimistic assumptions, climate-constrained growth of global per capita income cannot exceed 0.45%yr^{-1} during the next three decades. If global carbon emissions are cut by 90% (rather than by 85%) relative to their 1990 level, warming-constrained growth turns negative (see the last column of Table 1). Climate-constrained growth is well below the historical income growth rate (1.93%yr^{-1}) during 1971-2015. It is also lower than the (exogenous) global per capita income growth rate of 2.65%yr^{-1} during 2014-2050, which the IEA assumes to occur in all its scenarios, including the *2D* and *B2D* ones.[9] If we assume, as the IEA does, that $\hat{y}$ equals 2.65%yr^{-1}, while keeping constant our numbers for $\hat{P}$, $\hat{e}$ and $\hat{c}$, then global CO_2 emissions would decline by only 2.93%yr^{-1} during 2014-2050; this would amount to a reduction in global carbon emissions by only 65% relative to their 1990 level and would lock the Earth System into a trajectory all the way down to 'Hothouse Earth'.[10]

The bottom line is that the climate constraint is binding: future global economic growth must be significantly lower than historical growth[11] if humanity wishes to keep the global average temperature increase to well below 2°C above pre-industrial levels—and this holds true under the optimistic assumption that we manage to bring about historically unprecedented reductions in carbon intensity and energy intensity. Decoupling has not occurred in *absolute* terms (for related evidence, see: Wiedman *et al.* 2012; Knight and Schor 2014; Mir and Storm 2016; Ward *et al.* 2016; McNeill and Engelke 2016; and Semieniuk 2018)—and we may be only deceiving ourselves if we do not face up to the fact that we have reached a fork in the road: either we continue to grow our economies the way we did in the past, but this means we have to prepare for global warming of 3-4°C *or more* by 2100 and run a big risk of ending up in 'Hothouse Earth'; or, alternatively, we do whatever it takes to force through the technological, structural and societal changes needed to reduce carbon emissions so as to stabilize warming at 1.5°C (Grubb 2014; Steffen *et al*. 2018) and just accept whatever consequences this has in terms of economic growth (Ward *et al.* 2016).

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9 See: IEA (n.d), *Energy Technology Perspectives*: Framework assumptions https://www.iea.org/etp/etpmodel/assumptions/ .

10 It is difficult to see how the IEA numbers add up to sufficient carbon emission reductions to contain human-induced climate change well within a 2°C rise within this century.

11 Our estimate of the rate of global climate-constrained growth points to a zero-sum conflict between the developmental ambitions of the (often fast-growing) non-OECD economies and economic growth in the rich OECD economies (Wade 2018). It follows that it is in the (enlightened) self-interest of the OECD countries to support the non-OECD countries in bringing about early de-carbonization, introducing clean technology and achieve significant improvements in their energy efficiency (Fankhauser and Jotzo 2017).

Is Obama right about decoupling?

The only way the world can meet the COP21 target is by a permanent absolute decoupling of growth and CO_2 emissions (de Bruyn and Opschoor 1997; Ward *et al*. 2016). As shown in Tables 1 and 2 (and Figure 1) absolute decoupling remains elusive both in the OECD and non-OECD countries (as a whole). But what about (recent) individual country experiences: is there a group of leading (high-income) countries, including the U.S., which are growing their GDP while at the same time reducing their aggregate carbon emissions? Can we indeed put to rest the argument that halting warming requires accepting lower growth, as Obama argues? We systematically investigate the hypothesis that a small group of (advanced) countries has crossed the turning point of the ubiquitous 'inverted U-shaped' Carbon-Kuznets Curve (CKC) (see Dinda 2004; Kaika & Zervas, 2013a, 2013b). The CKC hypothesis holds that CO_2 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 arguably 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[12] on the CKC does not provide unambiguous and robust evidence of a CKC peaking for carbon dioxide, if only because of well documented but yet unresolved econometric problems concerning the appropriateness of model specification and estimation strategies (e.g. Wagner 2008).

We will leave these econometric issues aside however and instead focus on the fact that the majority of empirical CKC studies use territorial or production-based CO_2 emissions data to test the CKC hypothesis (Mir and Storm 2016)—and hence overlook the emissions embodied in international trade and in global commodity chains (Peters *et al*. 2011). 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

[12] Recent reviews of this literature are Kaika and Zervas (2013a, 2013b), Knight and Schor (2014), Mir and Storm (2016) and Allard *et al.* (2018).

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 (e.g. Rosa and Dietz 2012; Knight and Schor 2014; Jorgenson 2014; Mir and Storm 2016). 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 (e.g. Rothman 1998; Bagliani *et al*. 2008).

Estimating the turning points of production-based and consumption-based CKCs

Method. To evaluate the CKC hypothesis we run standard panel data regressions of per-capita CO_2 emissions on per-capita income and per-capita income squared. The population model includes country-specific effects and time-specific effects:

$$(5) \qquad \ln co2 = \beta_1 \ln y + \beta_2 (\ln y)^2 + \alpha_t + a_i + u$$

The dependent variable, *co*2, is either production-based (PB) per-capita CO_2 emissions or consumption-based (CB) per-capita CO_2 emissions. *y* is "real" per-capita GDP, and *u* is the unobserved disturbance term. t = 1, 2, …,T indexes time periods, and i = 1, 2, …, n indexes countries. a_i is a time-specific effect, and α_i is a country-specific effect. The model restricts all countries to have a common turning point, while allowing the level of emissions at the turning point to differ across countries. Turning points *TP* are calculated as

$$(6) \qquad TP = \exp\left(-\frac{\hat{\beta}_1}{2\hat{\beta}_2}\right)$$

where the hat "^" from now on denotes an estimate of the corresponding population parameter.

The country-specific effect captures, for instance, a country's endowment with fossil fuels. This interpretation immediately suggests that a_i correlates with y; after all, a large resource endowment can be expected to increase a country's income. To address this type of endogeneity problem, we use the fixed-effect estimator (FE) and the first-difference estimator (FD). Under conventional assumptions, fixed-effects estimation (OLS on the within-transformed data) and first-difference estimation (OLS on the first-differenced data) both yield consistent estimates of β_1 and β_2 for $n \rightarrow \infty$. The cross-country panel is short (large n, small T). The time-specific effects are estimated by the inclusion of dummy variables in the regressor vector.

We do not deal with endogeneity problems other than the correlation between the country-specific effects and the income variable. The population parameters β_1 and β_2 have no causal interpretation, since the causal relationship between emissions and income is likely to run both ways. The coefficient estimates $\hat{\beta}_1$ and $\hat{\beta}_2$ capture associations in the statistical sense; they do not represent estimates of the causal effect of income on CO_2 emissions. Our intention is not to causally explain why and how growth leads to (higher and then lower) emissions, but is more modest. We try to falsify the existence of a (within-sample) turning point of the CKC—the presence of which would mean that the average rich country has managed to decouple growth and emissions in actual fact.

We adjust the baseline regressions in a number of ways to assess the robustness of the results. We include linear and quadratic time trends in the regressor vector. We vary the observation frequency by using annual data and non-overlapping five-year averages (rather than three-year averages as in our base-line). Last but not least, we use several sources for the CO_2 emission data.

Data. Our primary CO_2 emissions data come from the OECD Inter-Country Input-Output (ICIO) Tables.[13] The database, described in Wiebe and Yamano (2016), provides country-level estimates of CO_2 emissions caused by the combustion of fossil fuels. This emissions concept excludes CO_2 emissions from land use change and forest fires, fugitive emissions, and emissions from industrial processes. The independent variable, co2, is defined as either

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[13] See: http://www.oecd.org/sti/ind/inter-country-input-output-tables.htm .

PB emissions divided by population or CB emissions divided by population (kgCO_2 per person). PB emissions and CB emissions are available at an annual frequency for 61 countries in the period 1995–2011. The 61 countries account for 89% of global emissions in 2011, both in terms of PB accounting and in terms of CB accounting.

The GDP and population variables come from the Penn World Table (PWT) 9.0 (Feenstra *et al*., 2015). The income variable, *y*, is defined as expenditure-side real GDP at chained PPPs in 2011US$ (PWT variable code "rgdpe") divided by population ("pop"). We simply write "dollar" or "dollar per person" to refer to this unit.

To reduce measurement error and focus on structural relationships, we work with non-overlapping three-year averages. The estimation sample has N = nT = 366 observations, with *n* = 61 and T = 6. Descriptive statistics appear in Table 3. The mean per-capita income level is 25 thousand dollars, the minimum income is approximately one thousand dollars (Cambodia in the first period), and the maximum income is 87 thousand dollars (Luxembourg in the last period). Income at the first quartile is 11.5 thousand dollars; the majority of countries in the sample are high-income countries.[14] PB emissions range from 140–24539 kg CO_2 per person, and CB emissions range from 239–21942 kg CO_2 per person.

Table 3
Summary statistics

variable	N	mean	S.D.	min.	.25	median	.75	max.
y	366	25313.76	15787.73	1137.32	11488.60	24629.05	35873.09	87322.59
log y	366	9.88	0.82	7.04	0.35	10.11	10.49	11.38
d log y	305	9.31	8.87	-16.31	3.36	8.58	14.60	35.91
CO_2-prod	366	7325.29	4584.46	140.04	3887.53	7071.44	9851.02	24539.37
logCO_2-prod	366	8.63	0.88	4.94	8.27	8.86	9.20	10.11
*d*logCO_2-prod	305	1.63	8.34	-24.57	-3.98	0.96	6.39	35.18
CO_2-cons	366	7988.22	4663.45	239.11	4121.05	8145.92	11186.65	21941.96
logCO_2-cons	366	8.72	0.86	5.48	8.32	9.01	9.32	10.00
*d*logCO_2-cons	305	2.33	10.55	-38.39	-3.72	2.69	8.73	34.34

[14] The World Bank defines high-income countries as those with income higher than 12 thousand dollars (the World Bank's unit is slightly different because the underlying PPP exchange rates are different).

Robustness. The literature documents how country-level emission estimates vary substantially depending on the underlying input-output table (Wiedmann *et al.* 2011; Moran and Wood 2014; Rodrigues *et al.* 2018; Wieland *et al.* 2018). To check the robustness of our main results, we source additional CO_2 emission data from the "Environmental Footprint Explorer" (EFE).[15] The EFE, a collaborative research project (Stadler *et al*. 2015), strives to eliminate differences between existing global multi-regional input-output (MRIO) tables and the associated environmental satellite accounts to provide harmonized estimates of various environmental stressor variables, including CO_2 emissions both from the consumption perspective and the production perspective. The EFE takes existing environmentally extended MRIO tables as input (Eora, Exio, GTAP, WIOD, and OECD).[16] It harmonizes the economic transactions matrices by converting them to a common industry classification standard. It combines the harmonized MRIO tables with various CO_2 emission concepts to produce estimates of PB emissions and CB emissions. For the purpose of this study, we select CO_2 emissions from fossil fuel combustion as the environmental stressor variable, because it is conceptually identical to the variable used in the OECD's ICIO Tables. We select the latest available and the most detailed version of each database; we drop the GTAP sample because it does not provide observations at annual frequency. We end up with four samples of harmonized CO_2 emission variables, each derived from an original MRIO table and associated environmental satellite account (Eora, Exio, OECD, WIOD).[17] By construction each harmonized sample provides less spacio-temporal coverage than the corresponding original MRIO table. The harmonized Eora sample covers 1990–2013, Exio covers 1995–2012, OECD 1995–2011, and WIOD 1995–2009.

Regression results. Figure 2 plots CKCs for the "average country and average time period", that is, it shows predicted emissions at varying income levels at the mean of the country-specific effects and the mean of the time-specific effects (the country-specific effects and the time-specific effects shift the intercept, moving the curves up or down). The figure summarizes the result of our baseline regressions, which provide evidence for the existence of

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15 https://environmentalfootprints.org/

16 For details on the construction of the underlying MRIO tables, see Dietzenbacher *et al.* 2013; Lenzen *et al.* 2013; Tukker *et al.* 2013; Aguiar *et al.* 2013; and Wiebe and Yamano 2016.

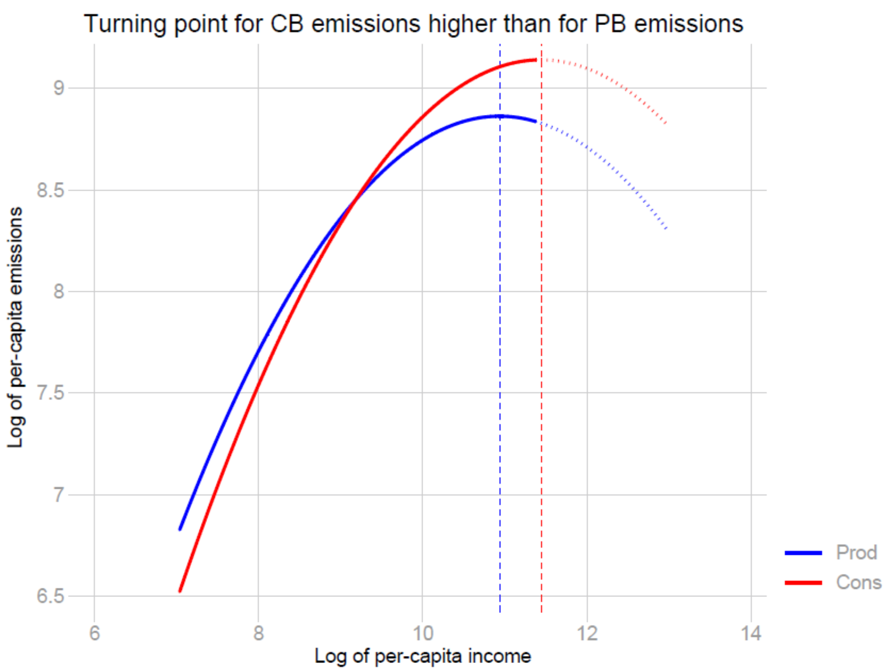
17 Eora = Eora v199.82; Exio = EXIOBASE3.3; OECD = OECD 2016 Edition; WIOD = WIOD 2013 release.

an CKC for production-based CO_2 emissions with a turning point at 56 thousand dollars per capita. The turning point for consumption-based CO_2 emissions is at 93 thousand dollars – outside the sample range.

When interpreting this result, recall that the statistical model's prediction performance is best at the center of the data and it deteriorates at the observed extremes. Only 12 out of 366 observations (3.3 percent) have income higher than 56 thousand dollars, the turning point for PB emissions. The claim that eventually CB emissions will fall as income grows, requires a willingness to extrapolate the found statistical relationship beyond the extreme values in the sample to an unobserved domain. The data determines the shape of the curve in the sample range, but it cannot tell us whether the population parameters and the functional form are stable at unobserved income levels. The extrapolation has no base in recorded history (see Tables 1 and 2). In fact, the historical record suggests that CB CO_2 emissions monotonically increase with income (see also Rosa and Dietz 2012; Knight and Schor 2014; Mir and Storm 2016).

Figure 2

The Carbon-Kuznets Curve, 1995-2011 (61 countries)



Note: Based on estimations by the authors. See Table 4 for fixed-effects estimations results.

The fixed-effect regression results that underpin Figure 2 are summarized in Table 4. The two columns on the left include time period dummies in the regressor vector and the two columns on the right do not. A Wald test for the joint significance of the time period dummies suggests that they should be included in the regression model (it rejects the null that the coefficients on the time period dummies are jointly zero). With or without the time-specific effects, all estimates of β_1 and β_2 are statistically significant at the one-percent level, and their signs imply an inverted-U-shaped relationship between emissions and income. The turning points are lower in the regression without the time period dummies. Note how small changes in the coefficients generate large changes in the turning points, because the turning points are calculated as an exponential function of the coefficient estimates.

Table 5 confirms the result that turning points are higher for CB CO_2 emissions than for PB emissions. The table reports the results generated by the first-difference estimator. Once again, the two columns on the left include time period dummies and the two columns on the right do not. A Wald test suggests the time period dummies are jointly significant. All estimates of β_1 and β_2 are statistically significant at the one-percent level and yield an inverted U. The turning point for PB emissions (column 1) is at 66 thousand dollars, inside the sample range, and the turning point for CB emissions (column 2) is at 445 thousand dollars, far outside the sample range. Switching the estimator increases the turning point for PB emissions somewhat; it dramatically increases the turning point for CB carbon emissions. Once again, income and PB emissions may have decoupled in the very richest countries, but there is no evidence in favor of decoupling income and CB emissions.

Table 4

Turning points calculated using the fixed-effect estimator

	with time-dummies		without time-dummies	
Variable	co2_prod	co2_cons	co2_prod	co2_cons
log y	2.9305124	3.089049	3.0116499	3.1961656
s.e.	0.71888883	0.70555447	0.72252531	0.67774503
t-value	4.08	4.38	4.17	4.72
$(\log y)^2$	-0.13398885	-0.13499277	-0.14333067	-0.1476856
s.e.	0.03688135	0.03775542	0.03672735	0.03481623
t-value	-3.63	-3.58	-3.90	-4.24
constant	-7.1391554	-8.5037588	-7.0436673	-8.3413655
s.e.	3.5373119	3.324235	3.5483254	3.2907054
t-value	-2.02	-2.56	-1.99	-2.53
n	366	366	366	366
R^2	0.47305479	0.5929978	0.44522298	0.54686075
R^2_o	0.74773402	0.85963594	0.69310671	0.8084212
R^2_b	0.76514524	0.87346022	0.71965167	0.83196878
R^2_w	0.47305479	0.5929978	0.44522298	0.54686075
σ_u	0.6068324	0.47068667	0.66596077	0.56102137
σ_e	0.09096439	0.08800606	0.09256234	0.09209093
rho	0.97802369	0.96622168	0.98104768	0.97376218
Fstat	5.8164236	5.4173622	.	.
turning point	56144	93110	36532	50054

Note: Inference is robust to serial correlation and heteroskedasticity (cluster-robust standard errors). "Fstat" is the Wald test statistic for joint significance of time period dummies; the 1% critical value of F distribution with five df in the numerator and 60 df in denominator is 3.339.

The statistical approach to the CKC is based on the notion that we have a sample at our disposal, and we would like to make inferences about a population. This statistical approach begs the question: what is the population of interest? The 61-country sample accounts for 89% percent of global emissions in 2011, and it includes all the major emitters. One could argue that the sample is the population of interest. In this case the estimated regression coefficients are the population parameters, their value is known with certainty, and the confidence intervals collapse to a point. One could argue that the population of interest is the same set of countries, but at future dates. The world might look similar in one, three, or five years—structural change is slow—thus the sample is arguably representative of the population. Yet if the population of interest is the world in 10, 30, or 50 years, the sample can tell us little about it. Dramatic changes to the climate system, the depletion of fossil fuel resources, the adoption of forceful climate policies—whatever the driving force, major structural change is upon us, and the future will be different from the past.

The appendix presents the results of several robustness tests. Table 6 and 7 present regressions with alternative specifications of the time dimension. Table 8 and 9 present regressions that use different sources for the CO2 emissions data. Overall, we find in-sample turning points for PB emissions, but the turning point for CB emissions is outside the sample range, far beyond the maximum observed per-capita income. We conclude that CB emissions monotonically increase with income – there is no decoupling.

Conclusions. Our econometric analysis yields three conclusions. First, there is econometric evidence in support of a CKC pattern for production-based CO_2 emissions. However, the estimated per-capita income turning point implies a level of annual global carbon emissions of 63.3GtCO_2e, which is 66% higher than the 2014 level and not compatible with the IPCC (2018) pathway consistent with keeping global warming below 1.5ºC.[18] The production-based inverted U-shaped CKC is, in other words, not a relevant framework for climate change mitigation. Second, our results suggest that economic growth has not decoupled from consumption-based emissions. Some of OECD countries have managed to some extent to delink their production systems from CO_2 emissions by relocating and outsourcing carbon-intensive production activities to the low-income countries. 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 (Rosa and Dietz 2012; Knight and Schor 2014; Mir and Storm 2016). Corroborating evidence provided by Jorgenson (2014) who finds that in North America, Europe, and Oceania, increases in human well-being (measured as life expectancy) are associated with a rising carbon intensity of well-being.

Third, and most importantly, what the statistical analysis shows is that, to avoid environmental catastrophe, the future *must* be different from the past. However, the dominant

[18] The revised IPCC (2018) global carbon budget for a 66% of avoiding warming of 1.5°C is 420 GtCO_2e—or about 11 years of current (2018) emissions. If global emissions increase to 63.3GtCO_2e (as per the PB turning point, assuming world population is 7.6 billion persons), the global carbon budget is depleted in only 6½ years.

‘green growth’ approaches remain squarely within the realm of ‘business-as-usual’ economics, proposing solutions which rely on technological fixes on the supply side and voluntary or ‘nudged’ behaviour change on the demand side, and which are bound to extend current unsustainable production, consumption and emission patterns into the future. The belief that any of this half-hearted tinkering will lead to drastic cuts in CO_2 emissions in the future is altogether too reminiscent of Saint Augustine’s ‘Oh Lord, make me pure, but not yet’. If past performance is relevant for future outcomes, our results should put to bed the complacency concerning the possibility of ‘green growth’. We have to stop the self-deception.

Table 5

Turning points calculated using first-differences estimator

Variable	co2_prod	co2_cons	co2_prod	co2_cons
*Δ*log y	2.4698389	2.5203637	2.4891894	2.5728446
s.e.	0.71056299	0.64760815	0.72453889	0.6333245
t-value	3.48	3.89	3.44	4.06
*Δ(*log y)^2	-0.11133297	-0.09689898	-0.11634873	-0.11082594
s.e.	0.03555642	0.03436124	0.03655803	0.03289814
t-value	-3.13	-2.82	-3.18	-3.37
constant	-0.00971501	-0.02424573		
s.e.	0.01294064	0.01368054		
t-value	-0.75	-1.77		
n	305	305	305	305
R^2	0.28333931	0.42270946	0.25230836	0.34247151
rho				
Fstat	6.7195542	6.1339746	.	.
turning point	65652	444680	44228	109930

Note: Inference is robust to serial correlation and heteroskedasticity (cluster-robust standard errors). “Fstat” is the Wald test statistic for joint significance of time period dummies; the 1% critical value of F distribution with five df in the numerator and 60 df in denominator is 3.339.

Conclusions: optimism, pessimism and realism

According to the latest IPCC (2018) analysis, humanity has until 2030 to avert a global warming catastrophe and keep warming below 1.5 °C. The early optimism about the Paris COP21 is giving way to widespread pessimism that the COP21 will not be working soon enough. Climate scientists and Earth systems scientists attempt to counter the growing pessimism by showing that limiting the global mean temperature increase to 1.5 °C is not a geophysical impossibility, nor a technical fantasy. But their well-intended analyses appear to reinforce the pessimism, because they reveal that the challenges posed by global warming are larger than plain technical ones: the required degree and speed with which we have to de-carbonize our economies and improve energy efficiency are quite difficult to imagine within the context of our present socioeconomic system (Sachs 2008; Speth 2008; Storm 2017; Aronoff 2018). Hence, to bring about the 'zero-carbon' revolution, we first need a political revolution—in the absence of which we are doomed to end up in a 'Hothouse Earth'. Prospects of political change favouring drastic de-carbonization are simply awful, not just in the U.S. but also in Brazil, Australia, and elsewhere. The challenge thus turns into a deadlock—and the earlier over-optimism morphs into an equally unwarranted pessimism. Those opposing climate policies tap into this pessimism: after initially denying the degree of human causation and then disputing the evidence, they now argue that it is economically impossible to keep warming below 1.5 °C and that it is anyway too late.

Going beyond this lazy dichotomy, our paper has offered a *realistic* evaluation of the nexus between economic growth and carbon emissions. We find no evidence of decoupling of rising standards of living and consumption-based carbon emissions—which means that the future *has to be different* from the past, because 'business-as-usual' economics will lead us to 'Hothouse Earth'. We do find, based on optimistic assumptions concerning future reductions in energy and carbon intensities, that future global growth will be compromised by the climate constraint. Taken together, this means we have reached a fork in the road and have to choose. One path is that we continue to 'green'-grow our economies in close to 'business-as-usual' ways, but that implies adapting to mean global temperature increases of 3°C and possibly more already by 2100 and to 'Hothouse Earth' thereafter. The adaptation also means that we have to come to terms with the impossibility of material, social and political progress as a universal promise: life is going to be worse for most people in the 21st century in all these dimensions. The political consequences of this are hard to predict.

The other path that should lead us to a 'Stabilized Earth' (Steffen *et al*. 2018), is technically feasible according to Earth Systems and climate and energy scientists (Grubb 2014; Millar *et al.* 2017; Steffen *et al.* 2018; IPCC 2018). The real barrier is the present fossil-fuel based socioeconomic system (aka 'fossil-fuel capitalism'), which was built up step by step over two-and-a-half centuries (McNeil and Engelke 2016; Malm 2016) and which now must be comprehensively overhauled in just 30 years, and not in a few countries, but globally. Such radical change does not square with the 'hand-off' mindset of most economists and policymakers (Sachs 2008). There are at least four reasons why we have to discard the prevalent *market-oriented belief system*, in which government intervention and non-market modes of coordination and decision-making are by definition inferior to the market mechanism and will mostly fail to achieve what they intend to bring about (Sachs 2016). First, a deep overhaul of energy systems and production and consumption structures cannot be done through small incremental steps, but requires disruptive system-wide re-engineering. Market prices give short-term (often myopic) signals only for incremental change and can block larger, non-marginal steps in innovation and economic restructuring (Wade 2018). If markets plan only 10-15 years ahead, as is typical in the energy sector, rather than 50 or more years (as is needed now), they will tend to make poor system-related choices; electricity providers will move from coal to lower-carbon natural gas, for example, but continue to underinvest in the much more decisive shift to (zero-carbon) renewable energy. Second, there are still large technological uncertainties in moving to a low-carbon energy system—and the radical innovation needed is beyond the capacities of even very large firms (Mazzucato and Semieniuk 2018). What is needed, writes the Global Apollo Programme (2015, p. 12), is "the application of basic science to produce fundamental disruptive technical change of the kind we have seen in telecommunications and IT. Those revolutions all began with publicly supported Research, Development & Demonstration." Third, climate stabilization requires international cooperation in emission reduction, mission-oriented investment in the renewable energy transition, technology development and dissemination, and the sharing of the global burden of fighting global warming (Stiglitz 2008). Finally, powerful vested interests in the fossil-fuel industry are resisting change.

"Shifting to a low-carbon energy system will therefore require considerable planning, long lead times, dedicated financing, and coordinated action across many parts of the economy, including energy producers, distributors, and residential, commercial, and industrial consumers," concludes Sachs (2016). This requires a (new) reconsideration of the role of the role of public action—what is needed is the directional thrust of the state through publicly funded R&D, 'technology-forcing' performance standard-setting and mission-oriented public strategies—as happened with computers, semiconductors, the internet, genetic sequencing, satellite communications, and nuclear power (Block and Keller 2011; Mazzucato and Perez 2014). Regulation has to be reconsidered in term of what Wolfgang Streeck (1997) calls 'beneficial constraints': the variety of normative and institutional constraints on markets and firms which are not 'distortions', but do, in real life, enhance economic performance. Importantly, Streeck's notion draws on Polanyi's central proposition

> "that a self-regulatory free market system that makes the rational pursuit of economic gain the only maxim of social action, will ultimately destroy its own human, social and natural conditions. …. rational individualism is described, not just as socially destructive, but as inherently destructive and unable to attain even narrow economic objectives unless properly harnessed by noneconomic social arrangements"
> (Streeck 1997, 207).

It is high time that we do whatever it takes to stop the self-destruction of capitalism, not just in the interest of society and nature, but in the economic interest as well.

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Appendix: robustness checks

Table 6 shows that the turning points hardly change with the specification of the time trend. The table reports the results of fixed-effect regressions. The two columns on the left include a linear time trend and the two columns on the right include a quadratic time trend. Statistical significance, coefficient estimates, and the implied turning points are essentially the same as in the baseline specification with time period dummies in Table 4. In fixed-effect regressions, the turning points are robust with respect to alternative specifications of the time dimension.

Table 7 reports the results of first-difference regressions, again exploring alternative time trend specifications. Statistical significance and coefficient estimates are essentially the same as in the baseline specification with time period dummies in table 5. But, comparing columns (2) and (4) in Table 7, small changes to the coefficient estimates produce large changes in the implied turning points. The estimated turning point for CO_2 emissions is 436 thousand dollars with the linear time trend and 340 thousand dollars with the quadratic time trend. The result that survives both changes in the estimation method and alternative time trend specifications, is that the turning point for CO_2 emissions is outside the sample range.

Next we explore variation in the underlying source data. Table 8 shows the results of fixed-effect regressions using four different sources for the CO_2 emissions data (Eora, Exio, OECD, WIOD). While turning points vary across databases, the turning point for CO_2 emissions is always higher than for PB emissions. The results change from one database to the next because the value for a given observation varies across databases and because the spacio-temporal coverage varies across databases. In spite of measurement variation and sampling variation, there is a common pattern: $\hat{\beta}_1^{FE}$ is positive and $\hat{\beta}_2^{FE}$ is negative and both estimates are statistically significant (the lowest *t*-statistic is $|t|$ = 2.1). That is, the data indicate an inverted-U-shaped relationship between emissions and income. The estimated turning points vary. The turning point for PB emissions ranges from 17–85 thousand dollars, and the turning point for CB emissions ranges from 155–943 thousand dollars, which is far beyond the observed maximum income level.

Table 9 again explores the implications of variation in the source data, this time using the first-difference estimator. Some coefficient estimates cease to be significant (in the sense that $|t| > 2$). The Exio sample does not yield a single significant coefficient. In the case of PB emissions, the other three databases yield a positive $\hat{\beta}_1^{FE}$ and a negative $\hat{\beta}_2^{FE}$, which represents evidence for the existence of a turning point. But the evidence is weak: the OECD and WIOD samples have fewer than 200 observations, the *t*-ratios barely exceed two, the coefficients are not precisely estimated. The OECD sample and the WIOD sample do not yield an inverted-U-shaped relationship between CB emissions and income: the coefficient on the linear term is significant, but the term on the quadratic term is not. The Eora sample does yield inverted U-shaped curves for both PB emissions and CB emissions: the turning point for CB emissions is much higher than for PB emissions, and both turning points are outside the sample range. The first-difference estimator, when applied to the relatively small samples of harmonized emission data, produces no evidence in favor of a turning point in the sample range, neither for PB emissions nor for CB emissions.

Table 6
Fixed-effect regressions including linear and quadratic time trends

	Linear time trend		Quadratic time trend	
Variable	co2_prod	co2_cons	co2_prod	co2_cons
log y	2.9161	3.0591876	2.9412693	3.0965753
s.e.	.71967275	.70057321	.71760131	.7001365
t-value	4.05	4.37	4.10	4.42
$(\log y)^2$	-.13359008	-.13372173	-.13460561	-.13523025
s.e.	.03698029	.03742206	.03684668	.03736417
t-value	-3.61	-3.57	-3.65	-3.62
Time	-.01217567	-.01745474	.02476763	.03742252
s.e.	.00845967	.00817337	.01585442	.01667449
t-value	-1.44	-2.14	1.56	2.24
time^2			-.00535375	-.00795271
s.e.			.00190022	.00219579
t-value			-2.82	-3.62
Constant	-7.0144531	-8.2994848	-7.2114291	-8.5920819
s.e.	3.5334421	3.3071813	3.5277544	3.3092642
t-value	-1.99	-2.51	-2.04	-2.60
n	366	366	366	366
R^2	0.45390637	0.56158654	0.46780748	0.58689768
R^2_o	.74597459	.85891288	.7471248	.86003532
R^2_b	.76383665	.87335502	.76452979	.87373818
R^2_w	.45390637	.56158654	.46780748	.58689768
σ_u	.61096009	.4743621	.60737226	.46874577
σ_e	.09198709	.09073206	.09095948	.08822017
rho	0.9778337	0.96470634	0.97806421	0.96579071
Fstat	2.0714713	4.5606243	5.3057589	8.4574246
turning point	54960	92840	55576	93832

Note: Inference is robust to serial correlation and heteroskedasticity (cluster-robust standard errors). "Fstat" is the Wald test statistic for joint significance of time period dummies; the 1% critical value of F distribution with five df in the numerator and 60 df in denominator is 3.339.

Table 7
First-difference regressions including linear and quadratic time trends

	Linear time trend		Quadratic time trend	
Variable	co2_prod	co2_cons	co2_prod	co2_cons
Δlog y	2.4518747	2.4599135	2.5460938	2.6125068
s.e.	.73207641	.6628862	.7194105	.63026034
t-value	3.35	3.71	3.54	4.15
$\Delta(\log y)^2$	-.11102438	-.09471208	-.11587582	-.10256927
s.e.	.03685285	.03487262	.0362709	.03309348
t-value	-3.01	-2.72	-3.19	-3.10
Δ Time	-.01145912	-.03468044	.01950482	.01546744
s.e.	.00756515	.00881649	.01534189	.01622461
t-value	-1.51	-3.93	1.27	0.95
Δ (time^2)			-.00442494	-.00716644
s.e.			.00182449	.0019986
t-value			-2.43	-3.59
n	305	305	305	305
R^2	.26077231	.39049458	.28234936	.42555325
Fstat	2.2943917	15.473129	4.7861238	14.880942
turning point	62446	436382	59060	339534

Note: Inference is robust to serial correlation and heteroskedasticity (cluster-robust standard errors). "Fstat" is the Wald test statistic for joint significance of time period dummies; the 1% critical value of F distribution with five df in the numerator and 60 df in denominator is 3.339.

Table 8
Fixed-effect regressions using several sources for emissions

variable	prod_eora	cons_eora	prod_exio	cons_exio
log y	2.8403155	2.070185	2.4584807	1.9775055
s.e.	.64713628	.47508557	.761806	.5232718
t-value	4.39	4.36	3.23	3.78
$(\log y)^2$	-.12508191	-.07524147	-.11326541	-.07725697
s.e.	.03468599	.0266528	.0392721	.0279664
t-value	-3.61	-2.82	-2.88	-2.78
Constant	.14866813	3.0469457	2.6277513	3.9389672
s.e.	3.0949235	2.1909193	3.751106	2.515931
t-value	0.05	1.39	0.70	1.57
n	311	311	234	234
R^2	.37896112	.491818	.35833976	.35833976
R^2_o	.66620745	.83295483	.63249413	.82844053
R^2_b	.68430915	.85149244	.65918474	.84514596
R^2_w	.37896112	.491818	.35833976	.6129175
σ_u	.43934106	.35242233	.52395012	.40879099
σ_e	.12226849	.11408267	.08937469	.07535683
Rho	.92811668	.90515084	.97172564	.96713529
Fstat	9.9330396	12.963935	7.4742075	8.3484711
turning point	85290	943112	51676	361578

variable	prod_oecd	cons_oecd	prod_wiod	prod_wiod
log y	2.5618849	2.0808734	2.9309881	1.3368667
s.e.	.83720141	.64206502	1.0356831	.41862915
t-value	3.06	3.24	2.83	3.19
$(\log y)^2$	-.1238777	-.08707236	-.1506605	-.04948234
s.e.	.04288642	.03431762	.05548886	.02361401
t-value	-2.89	-2.54	-2.72	-2.10
Constant	2.5738492	3.7660645	1.5306581	7.4418377
s.e.	4.1327023	3.045265	4.8516	1.8910987
t-value	0.62	1.24	0.32	3.94
n	234	234	195	195
R^2	.33603449	.54221848	.29591427	.64118308
R^2_o	4892676	.81815557	.15120966	.85072459
R^2_b	.51710103	.83993699	.15745072	.87298049
R^2_w	.33603449	.54221848	.29591427	.64118308
σ_u	.57250068	.43921261	.64052162	.46695243
σ_e	.07747649	.07467248	.08030231	.06116378
rho	.98201518	.97190711	.98452554	.98313232
Fstat	3.874322	7.847441	9.0567288	9.0462421
turning point	30958	154678	16766	735660

Note to Table 8: Inference is robust to serial correlation and heteroskedasticity (cluster-robust standard errors). "Fstat" is the Wald test statistic for joint significance of time period dummies; the 1% critical value of F distribution with five df in the numerator and 60 df in denominator is 3.339.

Table 9
First-difference regressions using several sources for emissions

variable	prod_eora	cons_eora	prod_exio	cons_exio
Δlog y	2.7160271	1.9285643	1.3723191	1.002175
	.4223908	.40787098	.85160203	.53690556
	6.43	4.73	1.61	1.87
Δ (log y)^2	-.1134769	-.05641677	-.05403827	-.01798794
	.0233793	.0248811	.04330073	.02772271
	-4.85	-2.27	-1.57	-0.65
constant	-.04073998	-.09557986	-.02662636	-.03963912
	.01498264	.03009815	.01695334	.01472367
	-2.72	-3.18	-1.57	-2.69
n	272	272	195	195
R^2	.46276808	.49672882	.24306451	.47024348
Fstat	8.9182058	11.94534	8.6971852	9.8977102
turning point	157520	26485792	326982	1.253e^{12}

variable	prod_oecd	cons_oecd	prod_wiod	cons_wiod
Δlog y	1.7643169	1.4163681	2.2426871	1.1113956
	.79627984	.4875757	1.0250188	.44683909
	2.22	2.90	2.19	2.49
Δ (log y)^2	-.08025861	-.0439789	-.10969259	-.03264383
	.03966039	.02652628	.05360924	.02377461
	-2.02	-1.66	-2.05	-1.37
Constant	-.03079024	-.0336849	-.0118576	.01993955
	.01464319	.02031181	.01993955	.01681588
	-2.10	-1.66	-0.59	-1.24
n	195	195	156	156
R^2				
Fstat	5.4811015	9.5849824	9.8349066	12.441622
turning point	59634	9848346	27518	24718398

Note: Inference is robust to serial correlation and heteroskedasticity (cluster-robust standard errors). "Fstat" is the Wald test statistic for joint significance of time period dummies; the 1% critical value of F distribution with five df in the numerator and 60 df in denominator is 3.339.