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

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ABSTRACT

De-carbonization to restrict future global warming to 1.5 °C is technically feasible but may impose a "limit" or "planetary boundary" to economic growth, depending on whether or not human society can decouple growth from emissions. In this paper, we assess the viability of decoupling. First, we develop a prognosis of climate-constrained global growth for 2014–2050 using the transparent Kaya identity. Second, we use the Carbon-Kuznets-Curve framework to assess the effect of economic growth on emissions using measures of territorial and consumption-based emissions. We run fixed-effects regressions using OECD data for 58 countries during 2007–2015 and source alternative emissions data starting in 1992 from two other databases. While there is weak evidence suggesting a decoupling of emissions and growth at high-income levels, the main estimation sample indicates that emissions are monotonically increasing with per-capita GDP. We draw out the implications for climate policy and binding emission reduction obligations.

KEYWORDS

Carbon-Kuznets-Curve; climate change; consumption-based CO_2 emissions; decoupling; economic growth; Paris agreement

JEL CODES

F64; Q54; Q55; Q56

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 the 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

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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.

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., Steffen et al. 2018; see also: Millar et al. 2017; Geels et al. 2017).[3] 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 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"[4] 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 unmistakable 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 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* (CEA 2017), Obama claims that during the course of his

[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."

[3]However, it must be emphasized here that the scale at which such technologies as CCS should be deployed to produce any kind of significant climate effect is highly problematic. See the critical review of ecomodernist technologies, including CCS, by Bellamy-Foster (2018).

[4]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."

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."

Many others have highlighted similar trends, including (recently) Hatfield-Dodds et al. (2015) for Australia; Apergis (2016) for 15 OECD countries during 1960–2013; Shuai et al. (2017) for a panel of 164 countries; Liddle and Messinis (2018) for 21 OECD countries (during 1870–2010); Apergis, Christou, and Gupta (2017) for U.S. states; and Wagner, Grabarczyk, and Hong (2020) for Austria, Belgium, Finland, the Netherlands, Switzerland and the U.K.[5] Likewise, the *International Energy Agency* (IEA) has argued—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). 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 (territorial) 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* (New Climate Economy 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 Organization* (CSIRO), concludes that the country could achieve "strong economic growth to 2050 … . in scenarios where environmental pressures fall or are stable" (Hatfield-Dodds et al. 2015).[6] And *International Monetary Fund* economists Cohen et al. (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 that the G20 countries can achieve "strong" and "inclusive" economic growth at the same time as reorienting their economies toward development pathways featuring substantially lower GHG emissions.

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). We decompose global CO_2 emission growth in terms of its primary drivers using historical data for the period 1971–2015, and then develop a long-term prognosis of the rate of global per-capita income growth for the period 2014–2050 based on IEA-OECD assumptions concerning future energy and carbon efficiency changes consistent with the Paris pledges. We conclude that "green" growth predicated on carbon decoupling is impossible if we rule out truly game-changing technological progress and revolutionary social change.

In the next section, we present the results of a systematic econometric analysis of the relationship between economic growth and carbon dioxide emissions. We use the Carbon-Kuznets-Curve (CKC) framework and run panel data regressions using emissions data for 58 countries during 2007–2015 from the OECD's Trade-in Embodied CO_2 Database (OECD 2019). To check the

[5]We already note here that these studies reporting 'decoupling' are based on territorial (production-based) carbon emissions (and not on consumption-based emissions).

[6]According to Hatfield-Dodds et al. (2015), real GDP in Australia can grow at a rate of 2.41% per year during 2015-2050 while emissions are reduced. For a critique, see Ward et al. (2016).

robustness of our findings, we source alternative emissions data from two other databases, with observations starting in 1992.[7] We pay particular attention to the difference between production-based (PB) emissions and consumption-based (CB) emissions, which include the impact of international trade (Peters 2008; Peters and Hertwich 2008). In our main estimation sample, we find no evidence of decoupling economic growth and emissions, neither for PB emissions nor for CB 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 Schellnhuber (Watts 2018) are right to call for large-scale climate mobilization. Without a concerted (global) policy shift to deep de-carbonization (Fankhauser and Jotzo 2018; 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). Marginal, incremental, improvements in energy, and carbon efficiency cannot do the job and what is needed is a structural transformation.

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.[8] 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 Yokobori 1997), which decomposes global CO_2 emissions (in million tonnes), denoted by C, into measurable "drivers" directly relevant to climate and energy policy:

$$\mathrm{C} = P \times \frac{Y}{P} \times \frac{C}{E} \times \frac{E}{Y} = P \times y \times c \times e \tag{1}$$

where P = world population (billions of persons), Y = world GDP (in 2010 US$), E = total primary energy supply or TPES (in PJ), y = global per-capita income (in 2010 US$), $c = C/E$ = carbon intensity of primary energy supply, or CO_2 emissions per TPES, and $e = E/Y$ = energy intensity of GDP. External factors influence the variables that make up the identity, and the variables interact with one another in various ways. Whatever the underlying causal mechanisms, the identity has to be satisfied ex-post. Carbon emissions rise, ceteris paribus when world population 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 output. Carbon intensity declines when the share of renewable energy sources in electricity generation increases and the share of fossil-fuel energy goes down. In the growth-rate from the Kaya identity can be approximated by:

$$\hat{C} = \hat{P} + \hat{y} + \hat{c} + \hat{e} \tag{2}$$

Global carbon emissions growth is driven by population growth $\hat{P}$, per-capita income growth $\hat{y}$, the growth of the carbon intensity of energy $\hat{c}$, and the growth of energy intensity of GDP $\hat{e}$. Table 1 shows the results of a decomposition of global CO_2 emissions for the period 1971–2017

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

[8]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 (1970–2010), 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.

Table 1. A Kaya identity decomposition of global CO_2 emissions, 1971–2017 and 2017–2050.

	Actual change			Projection
	1971–1990	1991–2017	1971–2017	85% Reduction in CO_2 emissions 2017–2050
Global CO_2 emissions	2.05	1.80	1.88	−6.92
World population	1.81	1.30	1.52	0.79
Real GDP per capita	1.52	1.54	1.49	−1.34
Energy intensity (TPES/GDP)	−0.86	−1.05	−0.96	−2.69
Carbon intensity (CO_2/TPES)	−0.41	0.01	−0.17	−3.68

Sources: Data for 1971–2017 are from IEA (2019) "CO_2 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 rates are given in percentages. Average annual growth rate are compound average annual growth rates. Calculations are based on the IEA-IRENA (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 (2017–2050) has been estimated as a residual (using the Kaya identity (3)), as explained in the text.

and our projection for the period 2017–2050, which satisfies Equation (2). We focus on CO_2 emissions from the energy system which represent more than 70% of global GHG emissions in 2010.[9]

Let us first consider historical changes during 1971–2017 when global CO_2 emissions increased by 1.88% yr^{-1}. Growth in the population (at 1.52% yr^{-1}) and in per capita real GDP (at 1.49% 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 0.96% yr^{-1}) and lower carbon intensity (which declined by 0.17% yr^{-1}).[10] These downward trends in energy and carbon intensity are still insufficient to delink economic growth and carbon emissions. Table 1 signals some improvement over time however, as energy intensity has begun to decline appreciably faster post-1990, recording a decline of 1.05% yr^{-1} during 1991–2017 as compared to 0.86% during 1971–1990. There is no similar sign of declining carbon intensity—the carbon intensity declined by 0.41% yr^{-1} during 1971–1990 but did not decline further during 1991–2017

Global average changes are the net outcomes of underlying regional changes. Table 2 shows 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 1971–2017. Country trajectories differ, but there are four general developments that are of critical importance to changes in emission trajectories. First, population growth has been lower during 1991-2017 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 1991–2017, 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 1991–2017 compared to the years 1971–1990. The E.U. carbon intensity decline recorded during 1991–2017 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, 120). The non-OECD countries as a whole experienced somewhat lower carbon intensity growth during 1971–2017, as China, India, and Indonesia managed to substantially lower their (still high) carbon intensity growth rates. For instance,

[9]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).

[10]For similar decomposition results for global emissions, see Peters et al. (2017). Csereklyei, Rubio-Varas and Stern (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 2. A Kaya Identity decomposition of CO_2 emissions, 1971–2017.

	1971–1990	1991–2017	1971–2017
OECD			
CO_2 emissions	0.89	0.16	0.47
Population	0.96	0.68	0.80
GDP per capita	2.28	1.42	1.75
Energy intensity (TPES/GDP)	−1.62	−1.53	−1.54
Carbon intensity (CO_2/TPES)	−0.73	−0.41	−0.55
U.S.A.			
CO_2 emissions	0.60	0.00	0.23
Population	0.98	0.97	0.98
GDP per capita	2.23	1.57	1.78
Energy intensity (TPES/GDP)	−2.17	−2.08	−2.06
Carbon intensity (CO_2/TPES)	−0.44	−0.47	−0.48
E.U.-28			
CO_2 emissions	0.12	−0.73	−0.33
Population	0.33	0.41	0.38
GDP per capita	2.42	1.25	1.73
Energy intensity (TPES/GDP)	−1.43	−1.59	−1.48
Carbon intensity (CO_2/TPES)	−1.20	−0.80	−0.96
Non-OECD			
CO_2 emissions	4.15	3.15	3.51
Population	2.05	1.44	1.70
GDP per capita	1.61	3.22	2.47
Energy intensity (TPES/GDP)	0.10	−1.82	−1.02
Carbon intensity (CO_2/TPES)	0.40	0.30	0.36
China			
CO_2 emissions	5.32	5.68	5.52
Population	1.59	0.72	1.09
GDP per capita	6.09	8.96	7.74
Energy intensity (TPES/GDP)	−3.20	−4.26	−3.98
Carbon intensity (CO_2/TPES)	0.85	0.27	0.68
India			
CO_2 emissions	5.81	5.26	5.54
Population	2.29	1.59	1.89
GDP per capita	2.08	5.16	3.74
Energy intensity (TPES/GDP)	−0.63	−2.66	−1.70
Carbon intensity (CO_2/TPES)	2.07	1.16	1.61
Indonesia			
CO_2 emissions	9.20	4.85	6.69
Population	2.29	1.39	1.77
GDP per capita	4.04	3.26	3.62
Energy intensity (TPES/GDP)	−0.78	−1.27	−1.08
Carbon intensity (CO_2/TPES)	3.65	1.48	2.39

Average annual growth rates are given in percentages.
Sources: Data for 1971–2017 are from IEA (2019) "CO_2 Emissions from Fuel Combustion."

China brought down carbon intensity growth from 0.85% yr^{-1} during 1971–1990 to 0.27% yr^{-1} during 1991–2017, 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, 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 large enough to ensure a decoupling of growth of CO_2 emissions and growth of real GDP. The world as a whole has achieved only *relative* decoupling but no absolute decline in carbon emissions during 1971–1990 and 1991–2017.

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 potential 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. But most models cannot identify emission pathways consistent with the 66% "below 2 °C" goal without a large-scale ramp-up of CCS facilities (Peters et al. 2017, 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, 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 growth projection for the period 2017–2050 is provided in the last two columns of Table 1.

We use the transparent Kaya identity in growth rate form to explore the scope for economic growth in a climate-constrained world:

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

We assign values to the right side of Equation (3) to determine per-capita real income growth. First, we adopt the United Nation's population projection (the "medium variant" from UN DESA 2015), which implies $\hat{P} = 0.79\%\ \text{yr}^{-1}$ until 2050. Next, in line with the "2050 Low Carbon Economy Roadmap" adopted by the E.U., we assume that global CO_2 emissions in 2050 will be 85% lower than in 1990; this implies an annual average reduction in global carbon emissions $\hat{C}$ by 6.92% yr^{-1}. Our numbers refer to CO_2 emissions caused by the combustion of fossil fuels in the energy sector. The latest IPCC target—net zero emissions by 2050—refers to all climate-relevant GHGs (IPCC 2018). CO_2 emissions from land-use changes and the transport sector, as well as other GHG emissions, are probably harder to reduce or more expensive to reduce than energy-sector CO_2 emissions; and it is doubtful that negative-emission technologies can be ramped up to the equivalent of 15% of the 1990 global emissions level. Therefore the 85% reduction target is a soft one (the IPCC target is stricter). Next, we borrow from the OECD (2017, Table 2.18) the projected decreases in energy intensity and carbon intensity: $\hat{e} = -2.69\%\ \text{yr}^{-1}$ and $\hat{c} = -3.68\%\ \text{yr}^{-1}$. These ambitious intensity reductions originally come from the IEA-IRENA 66% 2 °C scenario (IEA-IRENA 2017), which refers to the G20, and we assume they apply to the whole world.

Based on the assumptions made, the climate-constrained growth rate of global real per-capita income is found to be *negative* ($-1.34\%\text{yr}^{-1}$) during the next three decades:

$$\hat{y} = \hat{C} - \hat{P} - \hat{c} - \hat{e} = -6.92\% - 0.79\% + 3.68\% + 2.69\% = -1.34\% \tag{4}$$

Even with a relatively "soft" emission-reduction target, climate-constrained growth is not just well below the historical income growth rate (of $1.49\%\text{yr}^{-1}$ during 1971–2017), but negative—which means there is a conflict between growing the world economy and keeping global warming from becoming dangerous and unstoppable. The sobering bottom line is this: taking the 85% reduction target as given, even under the techno-optimistic assumption that we manage to bring about historically unprecedented reductions in carbon intensity and energy intensity, the climate constraint is binding in the sense that future global economic growth would have to be not just significantly lower than historical growth, but even negative.[11] An argument in favor of greater scope for economic growth has to rely on even more optimistic assumptions concerning technological progress—even more potent climate policies would have to be adopted to bring about even sharper reductions in carbon intensity and energy intensity. The growth implications of uncompromising climate policies are not obvious. Our plea is that we do whatever it takes to

[11]Hickel (2019) reviews scenarios from various models and reaches a similar conclusion.

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.

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 absolute decoupling over long periods 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., that are growing their GDP while at the same time reducing their 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 today's high-income countries have crossed the turning point of the ubiquitous "inverted U-shaped" CKC (see Dinda 2004; Kaika and Zervas 2013a, 2013b; Stern 2017). 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 and enforcement. 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 PB 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 guidelines, GHG emissions are counted as the *national* emissions coming from domestic production. This geographical definition hides the GHG emissions embodied in international trade. Rich countries including the EU-27 and the United States. 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. 2013). *Vice versa*, most developing (and industrializing) countries are net carbon exporters. What this implies is that, because of cross-border carbon leakages, CB emissions are higher than PB emissions in the OECD countries but lower in the developing countries (Aichele and Felbermayr 2012). This indicates that while there may well be a Kuznets-like delinking between per-capita income and per-capita PB emissions, it is as yet unclear whether such delinking is also occurring in terms of CB emissions (e.g., Rosa and Dietz 2012; Knight and Schor 2014; Jorgenson 2014; Mir and Storm 2016).[13] If not, the notion of "carbon decoupling" has to be rethought—in terms of a delinking between income and CB 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

[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).

[13]For example, it is often claimed that the UK has undergone an *absolute* decoupling of economic growth from carbon emissions, and the UK experience is widely used to justify a 'green growth' narrative. But according to the British Office for National Statistics (2019), absolute decoupling is only apparent when one measures carbon emissions on a territorial basis; there is only relative decoupling when one looks at the British consumption-based carbon emissions which increased by more than 30% from 1990 to their peak in 2007 and then declined to their 1990 levels by 2017 (partly helped by the financial crisis of 2008).

GHG, while raising consumption and living standards (e.g., Rothman 1998; Bagliani, Bravo, and Dalmazzone 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:

$$\ln co2 = \beta_0 + \beta_1 \cdot \ln y + \beta_2 \cdot (\ln y)^2 + \alpha_t + a_i + u \tag{5}$$

The dependent variable, *co*2, is either PB per-capita CO_2 emissions or CB per-capita CO_2 emissions. y is "real" per-capita GDP, and u is the unobserved disturbance term. $t = 1, 2, \ldots,$ T indexes time periods, and $i = 1, 2, \ldots, n$ indexes countries. α_t is a time-specific effect, and a_i is a country-specific effect (the population model, as written here, includes a regression constant, so $\sum_t \alpha_t = 0$ and $\sum_i a_i = 0$). 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

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

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. The fixed-effect estimator (FE) addresses this endogeneity problem. 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.

Equation (5) represents the "standard EKC regression model" (Stern 2017, 13), relating the log of per-capita emissions to the log of per-capita income. With the fixed-effects estimator, we are using the most common, tried, and tested estimation method. Alternative estimation methods including non-parametric ones tend to produce similar results (Stern 2017). The fixed-effects estimator exploits the variation over time to estimate the parameters of the model in Equation (5). Over a time period of one or two decades, the within-variation is relatively small compared to the variation across countries. Consequently, the standard errors will be relatively large. This is the price to pay for the ability to control for country-specific effects. Structural change means that the parameters of the model (5) will in general not be constant over time, but given our time horizon of one or two decades, there is no point in testing for structural breaks.

When predicting the *level* of per-capita CO_2 emissions for the average country, we use Duan's smearing estimate to address the re-transformation bias (Duan 1983). Simply re-transforming the estimated conditional expectation would lead to underestimation of the per-capita emission level. We predict the per-capita emissions level at the mean of the estimated time-specific effects and the mean of the (implicitly) estimated country-specific effects:

$$\widehat{co2}_0 = h \cdot \exp\left(\hat{\beta}_0 + \hat{\beta}_1 \cdot \ln y_0 + \hat{\beta}_2 \cdot (\ln y_0)^2 + \frac{1}{T}\sum\nolimits_{t=2}^{T} \hat{a}_t\right) \tag{7}$$

where

$$h = N^{-1}\sum\nolimits_i\sum\nolimits_t \exp(\hat{a}_i + \hat{u}_{it})$$

is the adjustment factor. $\hat{a}_i + \hat{u}_{it}$ is the combined residual, the sum of the implicitly estimated

Table 3. Summary statistics of estimation samples.

	n	Mean	SD	Min	p25	p50	p75	Max
TECO2 (balanced panel: 58 countries 2007–2015):								
Income	174	10.03	0.7287	7.753	9.613	10.19	10.61	11.22
Prod-based CO_2	174	8.627	0.8357	5.734	8.262	8.815	9.226	10.05
Cons-based CO_2	174	8.712	0.7882	6.267	8.354	8.883	9.318	9.944
OECD-ICIO-2015 (balanced panel: 55 countries 1997–2011):								
Income	275	9.828	0.8169	7.08	9.327	10.04	10.47	11.11
Prod-based CO_2	275	8.558	0.8792	5.046	8.193	8.783	9.149	9.898
Cons-based CO_2	275	8.663	0.8701	5.545	8.235	8.945	9.29	9.998
Eora (unbalanced panel: 131 countries 1992–2015):								
Income	1,044	8.826	1.266	5.651	7.84	8.887	9.914	11.38
Prod-based CO_2	1,044	7.502	1.613	3.827	6.367	7.848	8.899	10.37
Cons-based CO_2	1,044	7.622	1.585	4.2	6.257	7.832	9.014	10.89

Notes: Income = log of real per-capita GDP (2011 US$ per person); Prod-based CO_2 = log of production-based per-capita CO_2 emissions (kg per person); Cons-based CO_2 = log of consumption-based CO_2 emissions (kg per person).
Sources: PWT, TECO2, OECD-ICIO-2015, and Eora.

country-specific effect and the idiosyncratic residual. Duan's assumptions (homoscedasticity and i.i.d. data) are not satisfied here (heteroscedasticity and possible dependence across time), but it is better to make the adjustment than to knowingly underestimate the per-capita emission level.

Data

Our primary CO_2 emissions data come from TECO2, the OECD's Trade-in Embodied CO_2 Database (OECD, 2019).[14] The database, described in Wiebe and Yamano (2016), provides county-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, *co*2, is defined as either PB emissions divided by population or CB emissions divided by population (kg CO_2 per person). TECO2 covers 64 countries between 2005–2015.

The GDP and population variables come from the Penn World Table (PWT) 9.1 (Feenstra, Inklaar, and Timmer 2015). The income variable, *y*, is defined as expenditure-side real GDP at chained PPPs in 2011 US$ (PWT variable code "rgdpe") divided by population ("pop"). We simply write "dollars" or "dollars per person" to refer to this unit.

We work with non-overlapping three-year averages to reduce measurement error and focus on structural relationships. We exclude small countries from our main estimation sample; more specifically, we exclude countries with a 1990–2015-average population below the first quartile in the PWT (fewer than 1.92 million people). The main estimation sample has $N = 174$ observations with $n = 58$ and $T = 3$. Table 3 reports descriptive statistics of the main sample (based on TECO2) and the other two samples. The mean per-capita income level in the main sample is $28,000, the minimum income is $2300 (Cambodia), and the maximum income is $75,000 (Singapore). The majority of countries in the main sample are high-income countries; income at the first quartile is $15,000. PB emissions range from 310 to 23,105 kg CO_2 per person, and CB emissions range from 527 to 20,867 kg CO_2 per person. The 58 countries account for 85% of global emissions in 2015 (both in terms of PB accounting and in terms of CB accounting).

Robustness

We adjust the baseline regressions in a number of ways to assess the robustness of the results. We include linear and quadratic time trends; we vary the observation frequency by switching

[14] http://www.oecd.org/sti/ind/carbondioxideemissionsembodiedininternationaltrade.htm

Table 4. Turning points calculated using TECO2 (2007–2015).

	Production-based CO_2			Consumption-based CO_2		
	(1)	(2)	(3)	(4)	(5)	(6)
Income	3.490***	3.493***	3.490***	2.581**	2.573**	2.581**
	(1.000)	(0.996)	(1.000)	(0.965)	(0.959)	(0.965)
Income sq.	−0.144**	−0.144**	−0.144**	−0.085	−0.084	−0.085
	(0.052)	(0.052)	(0.052)	(0.051)	(0.051)	(0.051)
Constant	−11.780*	−11.720*	−11.709*	−8.524	−8.383	−8.421
	(4.787)	(4.770)	(4.786)	(4.600)	(4.572)	(4.597)
N	174	174	174	174	174	174
R^2	0.571	0.571	0.571	0.523	0.523	0.523
F-statistic	28.615	55.558	28.615	28.097	55.889	28.097
Time	Dummies	Linear	Quadratic	Dummies	Linear	Quadratic
Turning point	188,736	188,722	188,736	4,200,928	4,254,828	4,200,928

Notes: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$. In the columns 1–3 the dependent variable is the log of production-based per-capita CO_2 emissions. In the columns 4–6 the dependent variable is the log of consumption-based per-capita CO_2 emissions. Income is the log of real per-capita GDP in international dollars. Inference is robust to serial correlation and heteroskedasticity (cluster-robust standard errors). The columns 1 and 4 include time-specific effects, the columns 2 and 5 include a linear time trend, and the columns 3 and 6 include a quadratic time trend. The *F*-statistic is the Wald test statistic for joint significance of time period dummies/time trends. The (within) R^2 measures the explained portion of the variance within countries over time.
Sources: PWT and TECO2.

from three-year non-overlapping averages to annual data; we include the small countries that are excluded from the main estimation sample; and finally, we use several sources for the CO_2 emission data. This last robustness check is particularly important because the literature documents how country-level CB emission estimates vary with the underlying input-output table (Wiedmann et al. 2011; Moran and Wood 2014; Rodrigues et al. 2018; Wieland et al. 2018). Therefore, we source alternative CO_2 emission data from Eora[15] and the OECD-ICIO-2015[16]. Both databases provide country-level estimates of PC and CB CO_2 emissions caused by the combustion of fossil fuels. Eora (Lenzen et al. 2013) covers 190 countries between 1990 and 2015. The OECD-ICIO-2015 (OECD 2015) covers 61 countries between 1995 and 2011.

Regression Results

Figure 1 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 curves in the upper panel are derived from regressions based on the main estimation sample. The regressions provide no evidence for the existence of a CKC, neither for PB emissions nor for CB emissions. Over the sample range, emissions monotonically increase with income. There is no turning point.

The claim that eventually emissions will fall as income grows—there are turning points, but they are outside the sample range—would require a willingness to extrapolate the 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 statistical analysis of historical data cannot justify extrapolation.

The fixed-effect regression that underpins Figure 1 is summarized in Table 4. Columns 1 and 4 report results from the baseline specification that includes time period dummies in the regressor vector. A Wald test for the joint significance of the time period dummies suggests that they

[15]See: https://worldmrio.com/footprints/carbon/
[16]See: http://oe.cd/io-co2

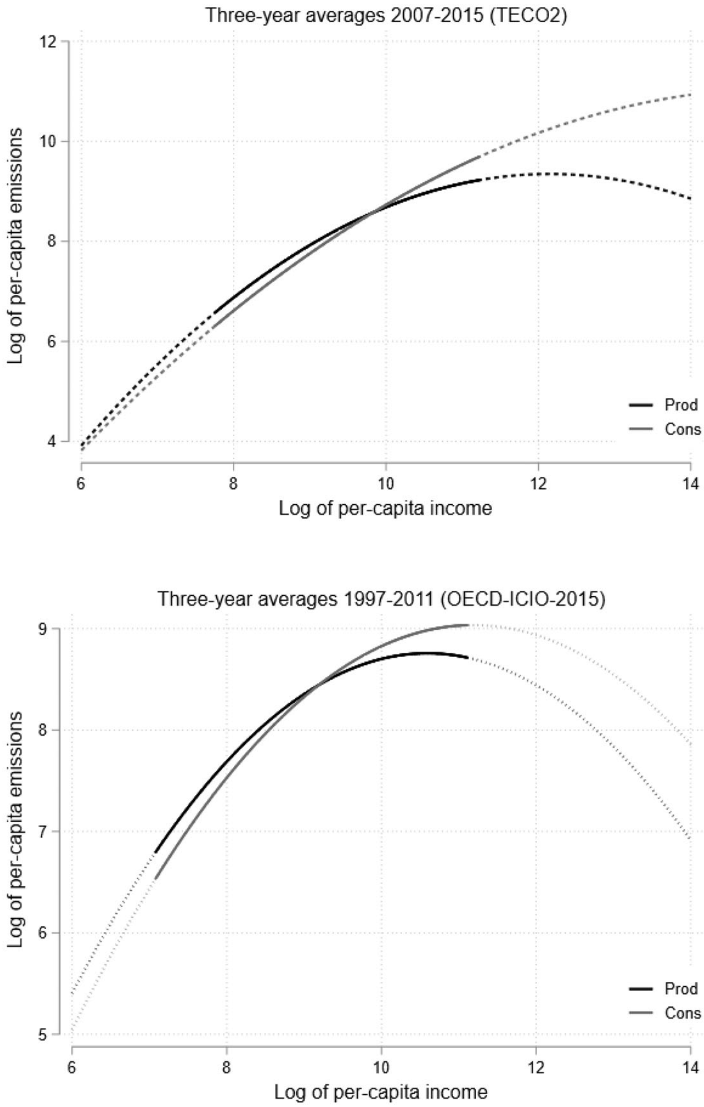

Figure 1. The Carbon-Kuznets-Curve. *Note*: Based on calculations by the authors as described in the Method section. For the underlying fixed-effect estimations results, see Table 4, column 1, and Table 5, column 1. The CKCs are drawn as solid lines inside the range of observed per-capita incomes and as dotted lines outside the sample range (dotted when higher than the sample maximum or lower than the sample minimum).

should be included in the regression model (it rejects the null that the coefficients on the time period dummies are jointly zero). The signs of the regression coefficients are consistent with the existence of a CKC, but their magnitude implies turning points far outside the estimation sample range. In the case of CB emissions, the coefficient on the log of income squared is not statistically significant at the 5% level, suggesting a linear positive relationship between emissions and income.[17] Replacing the time period dummies with a linear time trend (columns 2 and 5) or with a quadratic time trend (columns 3 and 6) changes little: coefficient signs, magnitudes, and their statistical significance are essentially the same as in the specification with time period dummies.

[17]That is, the curvature of the CKC drawn in Figure 1 derives from a regression coefficient that is not statistically significant.

Table 5. Turning points calculated using OECD-ICIO-2015 (1997–2011).

	Production-based CO_2			Consumption-based CO_2		
	(1)	(2)	(3)	(4)	(5)	(6)
Income	3.366***	3.356***	3.358***	3.319***	3.295***	3.297***
	(0.699)	(0.697)	(0.695)	(0.740)	(0.728)	(0.733)
Income sq.	−0.159***	−0.159***	−0.158***	−0.148***	−0.148***	−0.146***
	(0.036)	(0.036)	(0.036)	(0.040)	(0.039)	(0.039)
Constant	−9.057*	−8.943*	−9.105**	−9.512**	−9.319**	−9.544**
	(3.395)	(3.388)	(3.381)	(3.452)	(3.413)	(3.431)
n	275	275	275	275	275	275
R^2	0.550	0.515	0.543	0.642	0.593	0.634
F-statistic	11.525	2.280	10.503	12.827	4.803	15.856
Time	Dummies	Linear	Quadratic	Dummies	Linear	Quadratic
Turning point	39,874	38,864	41,310	72,070	70,754	77,860

Notes: $^*p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$. In the columns 1–3 the dependent variable is the log of production-based per-capita CO_2 emissions. In the columns 4–6 the dependent variable is the log of consumption-based per-capita CO_2 emissions. Income is the log of real per-capita GDP in international dollars. Inference is robust to serial correlation and heteroskedasticity (cluster-robust standard errors). The columns 1 and 4 include time-specific effects, the columns 2 and 5 include a linear time trend, and the columns 3 and 6 include a quadratic time trend. The *F*-statistic is the Wald test statistic for joint significance of time period dummies/time trends. The (within) R^2 measures the explained portion of the variance within countries over time.
Sources: PWT and OECD-ICIO-2015.

Table 6. Turning points calculated using Eora (1992–2015).

	Production-based CO_2			Consumption-based CO_2		
	(1)	(2)	(3)	(4)	(5)	(6)
Income	0.734	0.744	0.731	0.519	0.498	0.511
	(0.493)	(0.489)	(0.492)	(0.337)	(0.343)	(0.337)
Income sq.	−0.031	−0.032	−0.030	−0.011	−0.008	−0.010
	(0.027)	(0.027)	(0.027)	(0.019)	(0.019)	(0.019)
Constant	3.390	3.408	3.376	3.939*	3.895*	3.928*
	(2.237)	(2.212)	(2.236)	(1.553)	(1.568)	(1.550)
n	1044	1044	1044	1044	1044	1044
R^2	0.217	0.210	0.216	0.355	0.337	0.342
F-statistic	2.185	1.688	3.635	9.199	0.008	2.312
Time	Dummies	Linear	Quadratic	Dummies	Linear	Quadratic
Turning point	162,120	123,852	162,280	1.98e + 10	6.83e + 12	2.68e + 11

Notes: $^*p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$. In the columns 1–3 the dependent variable is the log of production-based per-capita CO_2 emissions. In the columns 4–6 the dependent variable is the log of consumption-based per-capita CO_2 emissions. Income is the log of real per-capita GDP in international dollars. Inference is robust to serial correlation and heteroskedasticity (cluster-robust standard errors). The columns 1 and 4 include time-specific effects, the columns 2 and 5 include a linear time trend, and the columns 3 and 6 include a quadratic time trend. The *F*-statistic is the Wald test statistic for joint significance of time period dummies/time trends. The (within) R^2 measures the explained portion of the variance within countries over time.
Sources: PWT and Eora.

A different source for emissions data gives different results. We postulate the same statistical model and use the same estimation method but switch the emissions data source. The use of the OECD-ICIO-2015 database leads to the CKCs shown in the lower panel of Figure 1—now the turning points fall inside the estimation sample range. The turning point for PB emissions is at \$39,000–\$41,000 and the turning point for CB emissions is at nearly twice that level at \$71,000–\$78,000, near the estimation sample's maximum. The underlying regressions are summarized in Table 5. In general, the OECD-ICIO-2015 yields more precise coefficient estimates (in the sense that the t ratios are higher than in the baseline regressions) because it covers a longer stretch of time and the fixed-effects estimator relies on time variation. The table reports six regressions that all support the existence of a CKC: the coefficients have the "right" signs and magnitudes and are statistically significant at the 0.1% level.

Table 7. Turning points calculated using TECO2 (2007–2015 including small countries).

	Production-based CO_2			Consumption-based CO_2		
	(1)	(2)	(3)	(4)	(5)	(6)
Income	3.658***	3.673***	3.658***	2.767**	2.752**	2.767**
	(0.931)	(0.929)	(0.931)	(0.956)	(0.952)	(0.956)
Income sq.	−0.153**	−0.154**	−0.153**	−0.094	−0.093	−0.094
	(0.048)	(0.048)	(0.048)	(0.050)	(0.050)	(0.050)
Constant	−12.472**	−12.480**	−12.410**	−9.412*	−9.240*	−9.305*
	(4.543)	(4.531)	(4.541)	(4.569)	(4.548)	(4.567)
n	192	192	192	192	192	192
R^2	0.584	0.583	0.584	0.549	0.549	0.549
F-statistic	42.229	81.393	42.229	34.449	67.287	34.449
Time	Dummies	Linear	Quadratic	Dummies	Linear	Quadratic
Turning point	155,670	154,942	155,670	2,413,798	2,477,858	2,413,798

Notes: $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$. In the columns 1–3 the dependent variable is the log of production-based per-capita CO_2 emissions. In the columns 4–6 the dependent variable is the log of consumption-based per-capita CO_2 emissions. Income is the log of real per-capita GDP in international dollars. Inference is robust to serial correlation and heteroskedasticity (cluster-robust standard errors). The columns 1 and 4 include time-specific effects, the columns 2 and 5 include a linear time trend, and the columns 3 and 6 include a quadratic time trend. The *F*-statistic is the Wald test statistic for joint significance of time period dummies/time trends. The (within) R^2 measures the explained portion of the variance within countries over time.
Sources: PWT and TECO2.

The appendix presents the results of several robustness tests. Table 6 replicates the analysis from Table 4 and 5, this time using Eora as the source for emissions data. The Eora sample contains more developing countries than the other two samples, which introduces additional variation in the dependent variable. The income variables and time dummies capture only a small fraction of this variation. The coefficients have the “right” signs, but are not statistically significant, even after excluding potential outliers (quantitative outlier tests could support the exclusion of observations from Belarus, Moldova, and Ethiopia). The lack of statistical significance stems in part from the high correlation between the log of income and the log of income squared. When either variable is included alone, its regression coefficient becomes statistically significant and indicates a positive relationship between income and emissions (regressions not reported). Table 7 adds six small countries that were excluded from the main estimation sample, meaning it uses data for all 64 countries covered by TECO2. The results are basically the same as in Table 4 and need no further commenting. Table 8 moves from the three-year non-overlapping averages to annual observations. Exploiting the high-frequency variation does improve the precision of the coefficient estimates, and the coefficient on the log of income squared turns up statistically significant. Changes to the size of the coefficients are minor. Overall TECO2 suggests that emissions monotonically increase with income, for the database produces no evidence of turning points inside the sample range, neither for PB emissions nor for CB emissions.

In the case of CB emissions, the regression coefficients vary with the source data (compare the columns 4–6 in Table 4 and Table 5). In the case of PB emissions, the coefficients hardly change. Yet even small changes in the coefficients generate large changes in the turning points (e.g., compare the columns 1–3 and 4–6 in Table 5) because the turning points are calculated as an exponential function of the ratio of the regression coefficients. Given this non-linearity, an innocuous switch of the source for emissions data has dramatic implications for the turning points. Therefore, the exact quantitative implications of the CKC analysis are to be interpreted with caution. Robust quantitative interpretations would presume a level of precision that no statistical analysis can deliver. The implied turning points, whether inside the sample range or outside, are higher for CB emissions than for PB emissions—this qualitative finding is robust and holds across all specifications.

Table 8. Turning points calculated using TECO2 (2005–2015 at annual frequency).

	Production-based CO2			Consumption-based CO2		
	(1)	(2)	(3)	(4)	(5)	(6)
Income	3.576***	3.514***	3.523***	2.932***	2.835***	2.836***
	(0.932)	(0.918)	(0.923)	(0.679)	(0.670)	(0.673)
Income sq.	−0.154**	−0.151**	−0.151**	−0.109**	−0.103**	−0.103**
	(0.048)	(0.048)	(0.048)	(0.035)	(0.035)	(0.035)
Constant	−11.495*	−10.891*	−10.827*	−9.484**	−8.674*	−8.668**
	(4.494)	(4.432)	(4.424)	(3.294)	(3.256)	(3.248)
n	638	638	638	638	638	638
R^2	0.496	0.490	0.490	0.523	0.516	0.516
F-statistic	8.581	45.809	23.275	11.996	60.098	30.051
Time	Dummies	Linear	Quadratic	Dummies	Linear	Quadratic
Turning point	107,030	115,162	117,006	672,950	948,008	949,600

Notes: $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$. In the columns 1–3 the dependent variable is the log of production-based per-capita CO_2 emissions. In the columns 4–6 the dependent variable is the log of consumption-based per-capita CO_2 emissions. Income is the log of real per-capita GDP in international dollars. Inference is robust to serial correlation and heteroskedasticity (cluster-robust standard errors). The columns 1 and 4 include time-specific effects, the columns 2 and 5 include a linear time trend, and the columns 3 and 6 include a quadratic time trend. The *F*-statistic is the Wald test statistic for joint significance of time period dummies/time trends. The (within) R^2 measures the explained portion of the variance within countries over time.
Sources: PWT and TECO2.

Summing Up

Our econometric analysis yields three conclusions. First, the evidence in support of a CKC pattern for PB emissions is fragile at best. Only the OECD-ICIO-2015 database generates the inverted-U-shaped pattern. In any case, global economic development along the CKCs would not be compatible with the IPCC (2018) pathway consistent with keeping global warming below 1.5 °C. If China developed along the path of the production-based CKC, it would exhaust a third of the global carbon budget before even reaching the turning point.[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 CB emissions.[19] Some of the 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 is 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 "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" behavior

[18]Suppose China behaved like the average country and developed along the production-based CKC shown in the lower panel of Figure 1. If China (today approximately $15,000 per-capita income), were to grow by 7.5% annually in per-capita terms, it would take 15 years to pass the turning point. The cumulative emissions until then, assuming a constant population of 1.3 billion people, would be about 139 Gt, a third of the global carbon budget. This calculation uses the per-capita emission level as predicted by Duan's smearing estimate (see the Method section). The predicted per-capita emissions at $15,000 income per capita are 6,420 kg CO_2 per person; the predicted per-capita emissions at $39,874 income per capita, the turning point, are 7,471 kg CO_2 per person. Our calculations refer to emissions from fossil fuel combustion only. The revised IPCC (2018) global carbon budget for a 66% of avoiding warming of 1.5 °C is 420 $GtCO_2e$, and it refers to all climate-relevant emissions.

[19]The OECD-ICIO-2015 database suggests decoupling near the estimation sample's maximum.

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.

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 socio-economic 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 favoring drastic de-carbonization are simply awful, not just in the United States, 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 CB 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 socio-economic system (aka "fossil-fuel capitalism"), which was built up step by step over two-and-a-half centuries (McNeill and Engelke 2016; Malm 2016; Cahen-Fourot and Lavoie 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 "hands-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 almost 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 Program (King et al. 2015, 12), is "the application of basic science to produce a 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 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 (Mazzucato and Perez 2014; Block and Keller 2015). Regulation has to be reconsidered in terms 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 this process of societal self-destruction, not just in the interest of society and nature, but in the economic interest as well (Storm 2017).

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