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COMMENTARY

Decoupling Economic Growth and Carbon Emissions

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All economic activity requires energy; to the extent this energy comes from fossil fuels, the energy use results in emissions of carbon dioxide, CO_2. The nature of this link between the growth in economic activity and carbon emissions is a critical question for climate change.[1] Linkage implies that deep emission reductions will constrain economic growth; decoupling implies that deep emission reductions are possible with little or no effect on growth. An answer to this question is important for the United States, but more crucial for rapidly growing emerging economies such as China and India that seek to improve their citizens' access to low-cost energy while respecting the need to protect the global environment.

Shortly before leaving office, President Obama wrote an article, *The Irreversible Momentum of Clean Energy*, that stressed the importance of "decoupling" energy sector emissions from economic growth.[2] He reported that during the period of his presidency (2008–2015), CO_2 emissions from the energy sector fell by 9.5% while the economy grew by over 10%, based on statistics in the 2017 Economic Report of the President (ERP-2107).[3] Other senior members of his administration have made similar observations about the irreversible trend of maintaining economic growth with lower carbon emissions.[4,5]

The most instructive tool for analyzing this "irreversible trend" and "decoupling" is the Kaya identity, which establishes an ironclad connection between emissions and economic growth.[6] In differential form, the Kaya identity states that for a region, over any given time period, the following relation must hold between gross domestic product (GDP), Y, energy use, E, and carbon emissions, C.[7]

$$\frac{\delta C}{C} = \frac{\delta(E/Y)}{(E/Y)} + \frac{\delta(C/E)}{(C/E)} + \frac{\delta Y}{Y} .$$

The Kaya identity decomposes the linkage between economic growth and carbon emission in two links: energy intensity (E/Y) and carbon intensity (C/E). 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, for example, when utilities shift from coal to natural-gas-fired generation since coal emits almost twice as much CO_2 per kWe-hr as natural gas.

Table 1 and Figure 1 present data for the time period 2008–2015 and projections for the period 2015–2040, which satisfy the Kaya sum rules.[7] As shown in the 2008–2015 panel, during this period, the United States improved energy and carbon intensity sufficiently to enjoy modest economic growth (1.4% annually) and reduced emissions (−1.4% annually). In contrast, during this period, China and the world experienced increased carbon emission with economic growth. While both carbon and energy intensity improved in China and globally, the improvement was insufficient to reduce carbon emissions over the period.

Short-term trends are not an adequate guide to the future. Indeed, recently the International Energy Agency (IEA) announced that during the period 2014–2017, global CO_2 emissions were stable while economic grow was positive.[9]

Projections about future economic growth, energy and carbon intensities, and accompanying carbon emissions are highly sensitive to assumptions about markets, policy measures, and technology change. Both the Energy Information Administration (EIA) and the IEA offer several scenarios in order to span the range of outcomes from different assumptions. The 2015–2040 panel in Table 1 presents projections for one common scenario, the EIA

Table 1. Kaya Identity Relationships in Two Time Periods

Fractional Changes[a]	Recent Past: 2008–2015			Future: 2015–2040		
	US	China	World	US	China	World
GDP (%)	10.2	109	44	81	193	128
	(1.4)	(11.1)	(5.3)	(2.4)	(4.4)	(3.4)
$\frac{\text{Energy use}}{\text{GDP}}$ (%)	−12.4	−28	−21	−40	−50	−38
	(−2.2)	(−4.6)	(−3.3)	(−2.0)	(−2.7)	(−1.9)
$\frac{\text{Carbon emissions}}{\text{Energy use}}$ (%)	−6.5	−11	−2.5	−5	−18	−9
	(−0.7)	(−1.6)	(−0.3)	(0.0)	(−0.8)	(−0.4)
Carbon emissions (%)	−9.7	34.2	11	2.2	21	29
	(−1.4)	(4.3)	(1.5)	(0.0)	(0.8)	(1.0)

Data sourced from Ref.[8] All quantities in parentheses represent the annual average % change over that time period.

[a]$\Delta X/X$ where X is the quantity in the left-hand column of the table.

"reference case." For the United States, the EIA "reference case scenario" is reasonable, not disruptive, and assumes current policies stay in place throughout the time period; it projects essentially flat CO_2 emissions. However, Figure 2 demonstrates that the EIA "reference case scenario" has over the years overestimated the amount of CO_2 emitted in the United States and provides a valuable reminder of the uncertainty of such projections.[10]

For the United States, the Kaya identity allows only an annual 1% decline in CO_2 emissions from more ambitious de-carbonization assumptions of a −1% decrease in carbon intensity, a −2% decrease in energy intensity, and 2% annual economic growth. If a trend as favorable as the annual 1.4% decline in CO_2 emissions experienced during 2008–2015 (a period of tepid economic growth) continued until 2050, CO_2 emissions in 2050 would be 56% below 2005, far below the 80% mid-century Obama administration target.[11]

For rapidly growing, emerging economies such as China, now the globe's largest greenhouse gas emitter, the Kaya identity presents a different stark reality. China in its submission to the Paris Accord pledged to reduce CO_2 emissions per unit GDP by 60%–65% from 2005 levels by 2030 (an annual rate of 4.1%–4.7%). At the pace indicated in Table 1, China may well meet this target but at the expense of a lower average annual economic growth rate of 6%, which does not align with the economic goals of the Chinese government.[12]

The Kaya decomposition shows that the extent of "decoupling" economic growth and emissions depends entirely on reductions in energy and carbon intensity. The downward trend in both these quantities is welcome and likely it is "irreversible." But the decline is insufficient to avoid significant average global temperature increase in the second half of this century. It is misleading to suggest that, while this trend may create jobs and benefit the United States, it will successfully avoid the risks of climate change.

Given the size and complexity of the US and global energy infrastructure, a stable policy is required to guide public and private investments for the innovation necessary to develop, demonstrate, and deploy low carbon technologies in priority areas such as energy efficiency; smart electricity distribution systems; CO_2 capture utilization and disposal; energy storage, especially batteries; and increase in the uptake of CO_2 by the terrestrial biosphere.

It seems unlikely that the Trump administration will pursue this course. The much celebrated Paris agreement is based on the highly unlikely

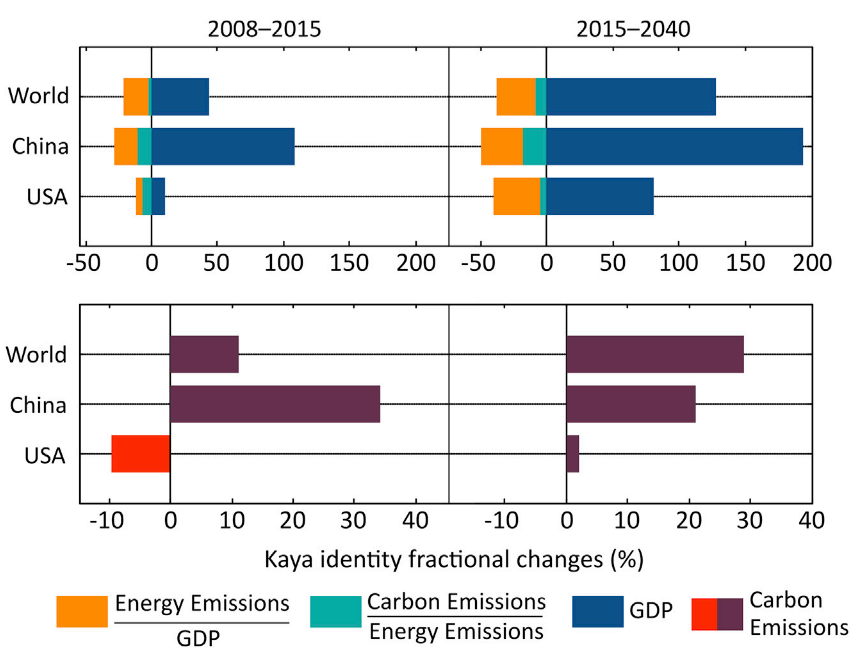

Figure 1. Kaya Identity Relationships in Two Time Periods

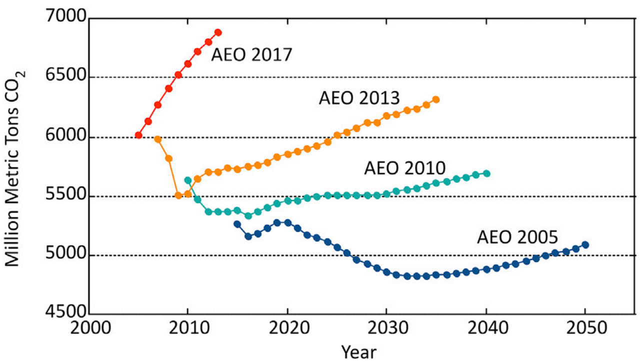

Figure 2. EIA Estimates of US CO_2 Emissions by Year

expectation that a ground-up international process will lead to reductions in carbon emissions at the necessary scale and pace, gigatonnes per year. This nation and the world seek insurance against the catastrophic risks of climate change. It is difficult to be optimistic that mitigation on its own will protect the globe from the consequences of climate change. The United States and the world must urgently turn to learning how to adapt to climate change and to explore the more radical pathway of geoengineering.

1. Carbon emissions refer to CO_2 emissions plus the emissions of other greenhouse gases, (GHGs) expressed as CO_2 (equivalent) emissions. The CO_2 (equivalent) is the amount of the GHG multiplied by the ratio of the radiation force, (global warming potential) of the GHG to the global warming potential of CO_2, each over a given time horizon, usually 100 years.

2. Obama, B. (2017). The irreversible momentum of clean energy. Science *355*, 126–129.

3. Obama refers to data presented in the 2017 Economic Report of the President, ERP, Chapter 7, *Addressing Climate Change*, p. 424; available at: https://obamawhitehouse.archives.gov/administration/eop/cea/economic-report-of-the-President/2017.

4. John Podesta, former Counselor to Barack Obama, Battling Climate Change in the Time of Trump, Center for American Progress, March 21, 2017.

5. Deese, B. (2017). Paris isn't burning. Foreign Affairs *96*, 83.

6. Kaya, Y., and Yokoburi, K. (1997). Environment, Energy, and Economy: Strategies for Sustainability (United Nations University Press), ISBN 9280809113.

7. For discrete changes, the integrated form has $(\delta X/X)$ replaced by $\log[1+(\Delta X/X)$. The differential relation between GDP and GDP per capita is $\delta(Y/P)/(Y/P) = (\delta Y/Y) - (\delta P/P)$. The US population growth rate is −0.7% per annum so the per capita rate is lower. By contrast, China's population growth rate is −0.1% per annum.

8. Sources for Table 1. All data are drawn from the EIA International Energy Outlook for 2011 and 2016, with the exception that data for the United States in the time period 2008–2015. Kaya factor projections are found in Annex H and J of the 2011 and 2016 IEO. Data for the United States in the time period 2008–2015 comes from the IEA Annual Energy Outlook of 2011 and 2016; the IEA Annual Energy Outlook was the source indicated for the data presented in Ref.[10]

9. International Energy Agency. IEA finds CO_2 emissions flat for third straight year even as global economy grew in 2016. https://www.iea.org/newsroom/news/2017/march/iea-finds-co2-emissions-flat-for-third-straight-year-even-as-global-economy-grew.html, March 17, 2017.

10. The Council of Economic Advisors report: The Economic Record of the Obama Administration: Addressing Climate Change, September 2014, makes a similar point in its analysis. See, especially Figure 27, p. 49. The report includes a clever use of Kaya decomposition, comparing projected and actual outcome in order to identify "surprises."

11. United States Mid-Century Strategy for Deep De-carbonization, The White House, November 2016. https://search.archives.gov/search?query=Deep+Decarbonization&op=Search&affiliate=obamawhitehouse.

12a. Fergus Green & Nicholas Stern, China's Changing Economy: Implications for its Carbon Dioxide Emissions, Climate Policy, http://dx.doi.org/10.1080/14693062.2016.1156515 forecasts Kaya parameters for China's energy future See Table 1, page 13.

b. Grubb, M., Sha, F., Spencer, T., Hughes, N., Zhang, Z., and Agnolucci, P. (2015). A review of Chinese CO_2 emission projections to 2030: the role of economic structure and policy Climate Policy *15* (suppl 1), S7–S39.

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COMMENTARY

Photosynthetic Water Splitting Provides a Blueprint for Artificial Leaf Technology

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