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Can Declining Energy Intensity Mitigate Climate Change? Decomposition and Meta-Regression Results

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Abstract

Drawing on the Kaya identity, we assess the role of the main driver of the decline in carbon intensity, namely the (economic) energy intensity. Using meta-significance testing for a sample of 44 studies, dealing with the causality between energy and GDP, we find that both variables are strongly coupled. Hence, after having exhausted energy savings from nonrecurring structural changes, the economic energy intensity may soon converge than being arbitrarily reducible. We suggest, therefore, not to rely on further reductions of economic energy intensity but rather to invest in the reduction of the carbon intensity of energy to mitigate climate change.

Key words: Climate change mitigation, Kaya identity, Energy intensity, Meta-significance testing
JEL: C83, Q43, Q51

1. Introduction

Ever since the First Assessment Report on Climate Change by the Intergovernmental Panel on Climate Change (IPCC) in 1990, there has been an ongoing debate on the quantification of future greenhouse gas emission (e.g. Hoffert et al., 1998; Canadell et al., 2007; Le Quéré et al., 2009). In the economic field, the carbon intensity, i.e., the ratio between carbon emissions and economic production (GDP), is often used to assess the state of an economy in climate change mitigation. An economy that is able to sustain GDP growth without having a negative impact on environmental conditions is said to be decoupled. Exactly how, if, or to what extent this can be achieved is a subject of much debate.

To assess the determinants of carbon intensity analysts often use the Kaya identity, which was originally proposed by the Japanese energy economist Yoichi Kaya (see, e.g., Raupach et al., 2007; Galiana and Green, 2009). The Kaya identity relates the carbon intensity to its main driving factors: the energy intensity of production (Energy/GDP) as well as the carbon intensity of energy (CO_2/Energy). It plays a core role, e.g., in the IPCC Special Report on Emissions Scenarios (SRES, see Nakicenovic et al., 2000).

In achieving today's lower carbon intensity, however, some argue that the extent to which its main driver, the energy intensity, has declined will not proceed. Still, most SRES scenarios rely on a rapid and ongoing decline in energy intensity (exceeding 1.0% per year). Apart from

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energy savings due to technological progress, a significant part of the decline can be attributed to structural changes such as sectoral shifts as well as offshoring of industrial production. However, the effect of the described structural changes on the relation between energy and GDP is twofold. Apart from contributing to lower energy intensity, these factors also have biased national statistics (Kander, 2005; Henriques and Kander, 2010; Gross, 2012). All of these effects tend to hide the true relationship, namely that energy and GDP are closely related (Cleveland et al., 1984).

If, in fact, energy and GDP go hand in hand, the energy intensity cannot be arbitrarily reduced. Using meta-significance testing (Stanley, 2005; 2008) for a sample of 44 studies and 534 causality tests, which deal with the causality between energy and GDP, we find that energy and GDP are strongly coupled. In addition, we find support for our reasoning that the described structural changes play a major role in hiding the true relationship.

This finding has some strong implications for emission scenarios based on the Kaya identity, since it does not account for possible interactions among the (explaining) variables. When the described structural changes come to a halt, the decline in energy intensity cannot pass on unchanged. It is more likely that it will converge to a (high) level, as will the carbon intensity in the short term. If the coupling between energy and growth persits, the consumption of energy must further increase to enable economic growth in the future. As a consequence, carbon emissions will catch up unless the carbon intensity of energy has been reduced sufficiently. Similarly, the only strategy to reach our climate targets in the long run is to invest in the decarbonization of energy use today, widely irrespective of the development of energy intensity.

We proceed as follows: in Section 2 we discuss the particular role of energy intensity in emission scenarios. In Section 3 we present the dataset which we use for meta-significance testing. It is followed by a discussion of the results. Section 4 concludes.

2. The Role of Energy Intensity in Climate Change Mitigation

In order to assess the trends in decoupling and its economic and technological drivers, we decompose carbon emissions according to the Kaya identity[1] (Nakicenovic et al., 2000; Nakicenovic, 2004):

$$\frac{\mathrm{CO_2}}{\mathrm{GDP}} = \frac{\mathrm{CO_2}}{\mathrm{Energy}}\frac{\mathrm{Energy}}{\mathrm{GDP}}. \tag{1}$$

Accordingly, carbon intensity is the product of carbon intensity of energy (measured, e.g., in grams of carbon dioxide released per megajoule of energy consumed) as well as (economic) energy intensity (measured, e.g., in megajoule of energy consumed per Dollar of output). Overall, the decline in carbon intensity over the last decades is mainly driven by the lower energy intensity (Table 1). The carbon intensity, in contrast, remains almost constant, since the increase in carbon intensity of energy in Low- and Middle-income countries outweighs the decline in High-income countries (see also Fig. A.1 and A.2).

The declining average carbon intensity of energy over time is referred to as decarbonization. In general terms, it can be achieved through technical progress or a switch to energy sources with lower carbon emissions (e.g., Pacala and Socolow, 2004; Ragauskas et al., 2006; Shinnar and Citro, 2006; Tilman et al., 2006; Muradov and Veziroglu, 2008). Historically, the decarbonization rate of the world's energy system was found to be constant at a rate of about 0.3% per year throughout previous decades (Nakicenovic, 1996). The median of all the SRES scenarios indicates a continuation of the historical trend, with a decarbonization rate of about 0.4% per year, which is similar to the trend in the IPCC IS92a baseline scenario (Leggett et al., 1992). Deviating from

[1] Another variant of the decomposition takes population growth into account. It would additionaly scale up projections for the carbon intensity (O'Neill et al., 2010).

Table 1 — Values for the Kaya Identity

Income class	CO_2/GDP		CO_2/Energy		Energy/GDP	
Low/Middle	1.77	(2.08)	2.67	(2.07)	0.66	(1.01)
High	0.43	(0.88)	2.35	(2.83)	0.18	(0.31)
World	0.79	(1.21)	2.70	(2.80)	0.29	(0.43)

Note: Values for 2008 (1971) are taken from the World Development Indicators (2012a-c).

that, Fig. A.3 indicates even a tendency of re-carbonization ever since the turn of the millennium. This can mainly be explained by the accelerated industrialization of China and India (Raupach et al., 2007).

A timely question therefore is, which factors facilitated the rapid decline in energy intensity — still, the main driver of decoupling. Can the decline in energy intensity persist in the future? First, a distinction must be drawn between economic energy intensity (used for the Kaya decomposition) and technical energy intensity. The overall effect of increasing technical efficiency on energy consumption has been discussed controversially. What is labeled the 'rebound effect' describes the circumstance that a new energy-saving technology may partly, or entirely, offset the initial or direct energy saving due to substitution and income effects (see, e.g., Brännlund et al., 2007; Druckman et al., 2011). Since the relationship between decreasing technical energy intensity and economic energy intensity is not well enough understood (Sorrell, 2009), the primary reliance of most SRES emission scenarios on declining economic energy intensity should be critically scrutinized (Pielke et al., 2008)[2].

Instead of effective energy-saving technological innovations, some argue that structural changes are a major determinant of the recent decline in energy intensity. Particular attention is given to shifts in economic activity from industrial production to less energy consuming services as well as the increasing neglect of indirect energy consumption due to an offshoring of industrial production. With regard to shifts in economic activity, a decline of energy intensity of about 20% (±10%) can be expected (Baksi and Green, 2007). Apart from effective energy savings, it has been argued that the observed decline in energy intensity is overrated (Kander, 2005; Henriques and Kander, 2010). Since the average price of output of most services is inflated, the ratio between GDP and energy diverges even more than solely due to sectoral shifts. With regard to the neglect of indirect energy consumption, the increasing imports of non-energy (intermediate) goods from low-wage countries entails an overvaluation of the value added from goods producing sectors in importing countries as well as a neglect of indirect energy consumption from exporting nations (OTA, 1990; Houseman et al., 2010; Gross, 2012). Hence, the energy intensity recorded by national statistics declines, although the energy consumed for end-use products, and thus the global energy intensity, remains unaffected.

Ultimately, the debate revolves around the core question whether, or to what extent, the coupling between energy and GDP can be broken up. Apart from the potential to effectively reduce energy intensity, the question is yet unanswered whether there is still an underlying causal relationship between both variables (Ozturk, 2010; Payne, 2010). In a meta-regression analysis of the relationship between energy and GDP, Bruns et al. (2012) find that the relationship between energy and GDP has become noticeably weaker. Card and Krueger (1995) argue that such a finding can have two reasons, either publication bias or structural changes, which hides the true effect between the variables, namely that energy and GDP are closely related (Cleveland et al., 1984)[3].

[2] When the term "energy intensity" is used in the remainder, we mean economic energy intensity.

[3] With regard to the first objection, Bruns et al. (2012) argue that, in the case of the literature on energy and

Accordingly, with regard to the relationship between energy and GDP, we hypothesize that the true effect can only be found, if the relation between energy and GDP has not been distorted by structural changes. If such a causal mechanism exists, energy and GDP are not adequately represented by a ratio in a simplified decomposition analysis. To give an example, if GDP strongly depends on the consumption of energy, a reduction of energy would not necessarily lower the energy intensity. Instead, economic growth would slow down too so that the energy intensity remains constant after all. Since the carbon intensity of energy is fixed in the short term, the carbon intensity would stay constant, too.

3. Empirical Analysis

3.1. Data Selection and Estimation Strategy

Our empirical analysis is based on 44 studies which investigate the causality between total energy consumption and total GDP according to, e.g., Granger (1969) and Engle and Granger (1987). Most of the studies are recorded in two recently published surveys (Ozturk, 2010; Payne, 2010). In addition, we searched Scopus, EconLit, as well as Google Scholar for combinations of the keywords "Energy", "Growth", "Income", "Output", "Economy", "Causality", "Cointegration", and "Relation"[4]. In sum, the sample contains 534 causality tests for 77 different countries.

We use meta-significance testing (MST) to investigate the presence of a true empirical effect (Stanley, 2005, 2008). Given the presence of a true effect, the standardized test statistic of a regression coefficient increases with the square root of the degrees of freedom. If there is no true empirical effect, the test statistic should be independent of the degrees of freedom and vary randomly around zero. This relationship is represented by the test regression

$$\ln |t_i| = \beta_0 + \beta_1 \ln df_i + \varepsilon_i, \tag{2}$$

where t is the value of the test statistic and df the degrees of freedom. If $\beta_1 > 0$, there is evidence for a true effect. Alternatively, if $\beta_1 = 0$, there is no effect. If $\beta_1 < 0$, the relationship between energy and GDP is subject to structural changes (Card and Krueger, 1995).

We disentangle the impact of structural changes on the relationship between energy and GDP by subsequently dividing the dataset into subsamples. Then, we run the MST regression in each subsample. We drop outliers which lie outside a distance of two standard errors around the mean in both dimensions, namely the test statistic and the degrees of freedom[5]. Following our theoretical considerations, the reductions in energy intensity occured mainly due to sectoral shifts, as well as the neglect of indirect energy consumption due to offshoring.

Almost all countries are characterized by a transition toward services. Hence, we define structural stability as a permanently high industry share in GDP. As the amount of energy required per unit of output is considerably higher in the industries than in the services, the distortion of the link between energy and GDP at the macro level is lower if the industry share remains constantly high. To select the subsample of countries with a high share of industry in GDP we, first, take a high initial industry share in the earliest available period (1960-1980). Subsequently, we break up the subsamples into studies from countries with a sufficiently high share in the latest available period (2005-2010). This procedure allows us to identify those countries with low distortions due to sectoral shifts. Finally, in order to approximate offshoring, we subdivide the resulting subsamples into studies for countries where there is a low share of imports in GDP in the latest available

GDP, publication bias is negligible. As neutrality between energy and GDP is also considered a relevant finding, those studies with insignificant results have not been systematically excluded from publication.

[4] For a detailed discussion of the data collection see Bruns et al. (2012).

[5] Since we drop outliers in every subsample individually, the sample size of subsamples may not add up to the sample size of the corresponding original sample.

Table 2 — Estimations for Beta 1 Coefficients: Energy Causes GDP

Industry share (early)			And industry share (late)			And import share (late)		
> 40%	-0.09	[50]	> 25%	0.53	[39]	> 30%	−0.59	[15]
						< 30%	1.47***	[23]
			< 25%	−0.01	[11]	> 30%	−0.01	[11]
						< 30%		[0]
< 40%	−0.77***	[198]	> 25%	−0.53*	[136]	> 30%	−0.67**	[73]
						< 30%	−0.70·	[61]
			< 25%	−0.79***	[63]	> 30%	−0.41·	[22]
						< 30%	−0.64*	[43]

Note: ***,**,*,· denotes significance at the 1%, 5%, 10%, 15% level; number of observations in squared brackets; inference based on bootstrapping.

period (2005-2010). We take the first and, respectively, the last values within the described time frames, because the starting and ending date of the times series varies among the countries. By doing so, we assure that we do not loose too many observations. The time frames chosen for early and late values coincide with the usual time frame of the underlying studies. The corresponding data are taken from the World Development Indicators (2012d-e).

3.2. Results

The results for MST are listed consecutively as paths of structural change and/or structural stability (Table 2). To give an example, a path of structural stability is "Industry share (early) > 40%", followed by "Industry share (late) > 25%", as well as "Import share (late) < 30%". This economy is characterized by an initially high industry share without marked tertiarization: the average industry share of the underlying countries is 58% at the beginning of the period and 42% at the end. In line with our hypothesis, namely that evidence for the true effect can be found in subsamples of structural stability, we find a significantly positive beta coefficient. Accordingly, we conclude that energy consumption causes economic growth, which also implies that energy and GDP are strongly coupled. This subsample of 23 significantly positive causality tests comprises studies which are conducted for China, Japan, and Argentina. On the contrary, even though the late industry share remains high, MST cannot detect a coupling for those countries with a high level of imports.

All countries with a low industry share at the beginning show significantly negative beta coefficients throughout. Since the degrees of freedom coincide with the respective time span of each study, the negative coefficient suggests that structural changes have increasingly confounded the initial coupling between energy and GDP. With regard to the reverse direction of causality, namely from GDP to energy, the results for MST show a fairly similar pattern (Table A.1). However, most of the results are not found to be significant. It indicates that the coupling between energy and GDP tends to be asymmetric.

In addition, we systematically check the robustness of the results. The observed patterns are robust with regard to alternative classifications of subsamples. However, we find that an initially high industry share is needed to identify the true effect. Otherwise, the true effect is overlapped by structural changes already from the outset.

3.3. Discussion of Results

Our findings indicate that the true effect, namely that energy and GDP are strongly coupled, is potentially confounded by several structural changes. Apparently, in those countries where the changes occured, it is unlikely that the changes will continue as they did in the past. The (relative) size of the industrial sector cannot be randomly reduced. Similarly, the incentives to further offshore industrial production may disappear when environmental regulations in developing are strengthened or if the labor costs increase. Hence, we infer that the energy intensity will converge to a level considerably larger than zero, since economic growth will continue to be dependent on a sufficient supply of energy. In other words, economic growth cannot be decoupled from energy consumption if the causal link persists.

In a similar vein, the decline of the carbon intensity will not continue to decline unless the carbon intensity of energy is sufficiently reduced. Hence, we should not uncritically rely on the promising decoupling of carbon emissions from GDP observed over the last decades. Not only was the decoupling partly driven by nonrecurring structural changes but these structural changes also resulted in an overvaluation of the decline in energy intensity. Instead, attention should be focused on the decarbonization of energy use, widely irrespective of the development of the energy intensity.

4. Conclusion

Starting from the question whether declining energy intensity can mitigate climate change, we decompose the determinants of carbon intensity reduction according to the Kaya identity. A shortcoming of such a simplified decomposition approach, we argue, is that it cannot account for possible interactions between the (explaining) variables. Using meta-significance testing based on 44 studies dealing with the causality between energy and GDP, we find evidence for a strong interdependence between both variables. We conclude that the energy intensity cannot be arbitrarily reduced but may converge to a level, which is likely to be too high to reach our climate targets. In order to effectively mitigate climate change, we should, therefore, not rely on a persistently declining energy intensity. Instead, there is an urgent need to invest in the decarbonization of energy use, widely irrespective of the development of energy intensity.

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A. Appendix

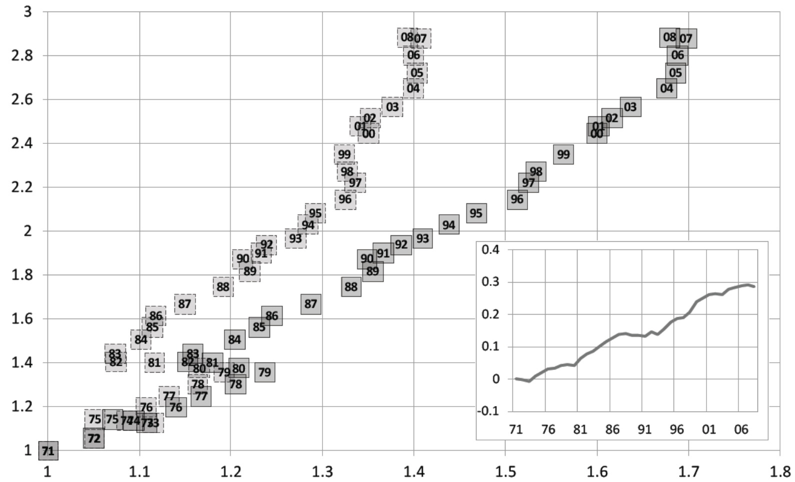

Fig. A.1: GDP as a function of CO_2 emissions (dashed boxes) and energy (solid boxes) for high income countries, 1971-2008 (1971=1); small graph shows decarbonization factor relative to 1971.

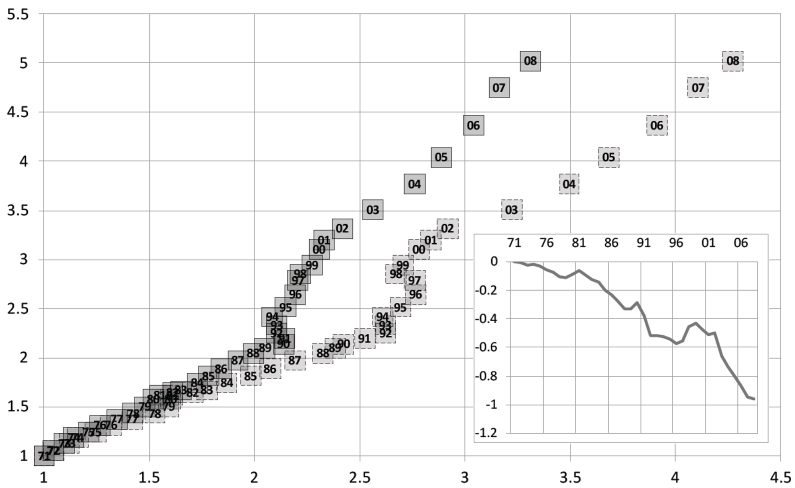

Fig. A.2: GDP as a function of CO_2 emissions (dashed boxes) and energy (solid boxes) for low and middle income countries, 1971-2008 (1971=1); small graph shows decarbonization factor relative to 1971.

Table A.1 — Estimations for Beta 1 Coefficients: GDP Causes Energy

Industry share (early)			And industry share (late)			And import share (late)		
> 40%	−0.12	[50]	> 25%	−0.03	[38]	> 30%	−0.32	[15]
						< 30%	0.38	[22]
			< 25%	0.37	[10]	> 30%	0.37	[10]
						< 30%	−	[0]
< 40%	−0.28*	[197]	> 25%	−0.26	[138]	> 30%	−0.45*	[73]
						< 30%	−0.03	[62]
			< 25%	−0.32	[61]	> 30%	−0.65	[22]
						< 30%	−0.36*	[42]

Note: ***,**,*,· denotes significance at the 1%, 5%, 10%, 15% level; number of observations in squared brackets; inference based on bootstrapping.

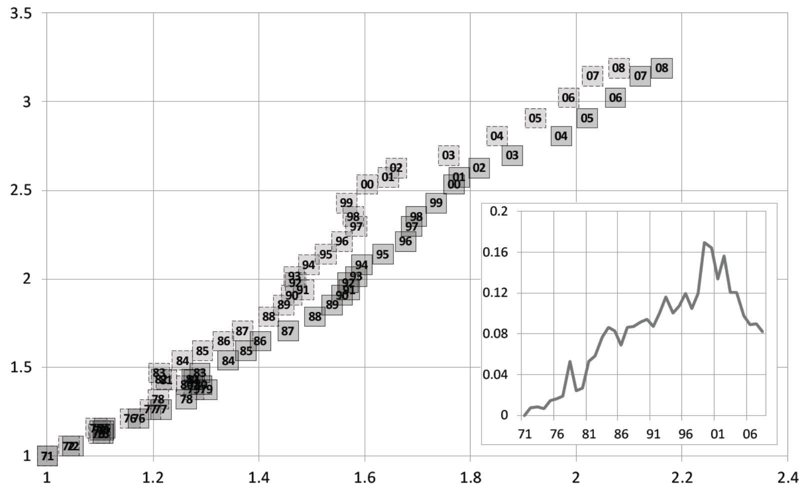

Fig. A.3: GDP as a function of CO_2 emissions (dashed boxes) and energy (solid boxes) for the world, 1971-2008 (1971=1); small graph shows decarbonization factor relative to 1971.