Development and application of energy decoupling index as Cartesian Vector: evidence from world-wide regional data

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Abstract. Economic growth and energy consumed is critical for sustainable global development. In this paper, an extended Vector version of the commonly used Decoupling Index De of energy elasticity to Gross Domestic Product (GDP) and Decoupling Ratio of Energy Intensity of GDP are used to investigate decoupling phenomenon for the period 1990 to 2014 in the main regions of the World. Using Vector properties, this study overcomes some well-known deficiencies of Energy to Growth elasticity Decoupling Index and suggests the Decoupling Angle as a suitable indicator when describing decoupling. The relationships with aggregate and per capita indicators are also examined. A general finding was that in emerging economies, even when moving to "disconnected" states of decoupling, reduced energy rates were paired with reduced growth rates and accelerated growth rates with increased energy consumption rates. This statement raises questions over long-term decoupling of energy consumption from economic growth.

1. Introduction
Long before “Indicators to Measure Decoupling of Environmental Pressure from Economic Growth” proposed by OECD [1] on 2002, decoupling was already a well-studied phenomenon among scholars. Park et al [2], while investigating energy consumption in selected developed and developing counties on behalf of the United Nations Industrial Development Organization, presented a graphical representation of energy elasticity to product-output to depict energy efficiency in manufacturing, while Ang [3] studied commercial energy to national output relation for several Asian countries with elasticities coefficient indices. Panayotou [4] and Grossman & Krueger [5] introduced the Environmental Kuznets Curve hypothesis to verify if there is a turning point where the pressure of economic growth to the environment is finally released. Tapio [6], while studying the decoupling level between transport volume and the CO₂ emissions in European Countries, presented an elaborated Decoupling Index De of energy to output elasticity, distinctly defining different states of decoupling on a graphical representation like the one of Park et al. The Tapio’s version, adopted in United Nations Environment Programme, year 2011 reports [7], was widely used by scholars to analyze decoupling of energy use or other environmental pressures either alone [8], [9], [10] or in combination with other methods [11], [12], [13], [14].

This study introduces a vector presentation of commonly used indicators in decoupling, like Decoupling Index De of energy elasticity to GDP proposed by [6] and Decoupling Ratio R of energy intensity proposed by [1], to investigate long-term decoupling in regions of the world. By exploiting vector properties, this new approach not only overcomes well-known deficiencies of conventional
indicators mentioned by scholars [15], [16], but also provides handy mathematical forms to relate aggregate and per Capita terms in decoupling. Finally, it suggests a vector-based criterion to graphically test the Environmental Kuznets Curve hypothesis (EKC) in a long term basis.

2. Methods and theoretical background

Symbols

| Symbols | Description |
|---------|-------------|
| \( E_t, G_t, P_t \) | Energy use, Gross Domestic Product (GDP), Domestic Population year \( t \) |
| \( E_{p_t} = \frac{E_t}{P_t}, G_{p_t} = \frac{G_t}{P_t}, T_t = \frac{E_t}{G_t} \) | Energy per Capita, GDP per Capita, Energy Intensity |
| \( R_t = \frac{T_t}{T_{t-1}} \) | Decoupling Ratio |

Lemma 1: “Percentage change of a ratio of two discrete variables”

If \( X, Y, R = \frac{Y}{X} \) two time-series and the ratio \( Y \) over \( X \), \( x, y, r \) their percentage changes respectively, then \( r = (y - x)/(x + 1) \).

Proof:

\[
\frac{Y_t}{X_t} - 1 = \frac{Y_t}{X_{t-1}} - 1 = \frac{\left( \frac{Y_t}{X_{t-1}} - 1 \right) + 1}{x + 1} - 1 = \frac{y - x}{x + 1}
\]

In case of positive quantities, like Energy, GDP and Population, \( r > -1 \).

Lemma 2: “Ratio of percentage changes of two discrete variables divided by third”

If \( X, Y, P \) thee time-series, \( x, y, p \) their percentage changes, \( X_p = X/P, Y_p = Y/P \) the ratios of \( X, Y \) over \( P \), with \( x_p, y_p \) their percentage changes respectively, then \( y_p/x_p = (y - p)/(x - p) \).

Proof:

By using Lemma 1 twice for \( X \) and \( Y \) over \( P \) gives:

\[
y_p/x_p = ((y - p)/(p + 1))/((x - p)/(p + 1)) = (y - p)/(x - p)
\]

2.1. Data Collection

For the study period, from 1990 to 2014, freely available annual data from World Bank Open Data site, concerning the main world regions, were compiled. Energy data are of primary use in kg of oil equivalent, GDP in PPP constant 2017 international $ (either aggregate values or per capita), while population is the total population of the world regions. For smoothing purposes, a 5-year moving average was applied to data, restricting observable time period to 1992-2012. The World is divided in 8 geopolitical regions as mentioned in Results and discussion section.

2.2. The Vector interpretation of Decoupling Indicators

Decoupling Indicators, such as Decoupling Index \( D_e = e/g \) and Decoupling Ratio \( R_t = 1 + t \), although frequently depicted in Cartesian plane, are usually treated as scalar variables, namely ratios. In Figure 1, as far as ratios of percentage changes of Energy use to GDP are equal in two alternative decoupling scenarios of economy, case A1 and A2 respectively, both cases will lie on the same
Decoupling Index line $De=0.25$. However the cases represent extremely different growths in terms of GDP and Energy use. Moreover, Decoupling Ratio in case A1 is on line $t = -0.2$ and on $t = -0.4$ in case A2, denoting that Energy Intensity converges faster in case A2. The same argument is valid for Decoupling Ratio in alternative decoupling cases A2 and A3, both lying in same $R$ with $t=0.4$, while A2 is a weak decoupling state and A3 a strong one, as signified by Decoupling Index $De$.

In the vector space of percentage changes $g, e$ on Cartesian plane the (Euclidian) vectors of Decoupling indicators are set as

- $\vec{D}e(g,y)$: Vector of Elasticity Decoupling Indicator $D_e$, origin $(0, 0)$

- $\theta = \arctan(g,e)$: The Decoupling Angle of $\vec{D}e(g,y)$ from axis x

- $\vec{R}(1 + g, 1 + y)$: Vector of Decoupling Ratio Indicator $R$, origin $(-1, -1)$

With only the Decoupling Angle given, as Akizu-Gardoki et al. [18] mentioned, the decoupling state is uniquely defined, whereas in case of Decoupling Index $De$ the sign of $g, y$ should be also provided.

2.3. Define a Direction of strong Decoupling changes

The characteristic line “Balanced Decoupling” where $De=-1$ has been marked diagrammatically by scholars either as a potential boundary between different states of decoupling [19] or as a desirable direction for higher decoupling [20]. For a given length of $\vec{D}e(g,y)$ in Figure 1, the greatest reduction in Decoupling Ratio is achieved when the vectors $\vec{D}e, \vec{R}$ are vertical with each other, or having inner product equal to 0.

$$\vec{D}e \cdot \vec{R} = 0 = g \cdot (1 + g) + e \cdot (1 + e) = g + g^2 + e + e^2 = 0$$

In case $|g|, |e| < 1$ the squared values could be ignored and equation (1) yields that $g = -e$ or $De=-1$.

By redefining Decoupling Angle $\phi^0$ as the angle of $\vec{D}e$ from Strong Change line, namely the line of $De = -1$, the new schema for measuring Decoupling by time-step “Decoupling Angle”, with no
need of extra information and the instances of Decoupling over time can be straightforwardly presented in a time graph of Decoupling Angle, symmetrically deployed around the Balanced Line.

2.4. Examine the long-term Energy to GDP Decoupling
In order to test Decoupling hypothesis over an adequate period of years from 0 to T, a modified Environmental Kuznets Curve (EKC) is introduced, where axis x corresponds to \( G_t / G_0 \) and y to \( E_t / E_0 \), as in Figure 2b. Having both axes starting from 1, the Vector from the beginning of axes to any point of the EKC is the overall Decoupling Index \( \vec{D} \) for period 0 to t according to equation (5) and Decoupling convergence over time could be tested again on a time diagram of overall Decoupling Angle \( \Phi \) like this of step Decoupling Angle \( \phi \).

\[
g_{t,0} = \frac{G_t}{G_0} - 1 \quad \text{and} \quad e_{t,0} = \frac{E_t}{E_0} - 1
\]

In case of small percentage changes, when \( |g|, |y| \ll 1 \), the ln-ln version of EKC could be used. In that case \( \ln(G_t / G_{t-1}) = g, \ln(E_t / E_{t-1}) = e \) and \( \Delta \hat{D} (t,t-1) \) approximates the Vector of time-step or annual Decoupling Index \( \vec{D} \).

![Figure 2. (a) Define decoupling state only by step Decoupling Angle ‘\( \phi \)’. (b) overall Decoupling Angle ‘\( \Phi \)’ on EKC.](image)

2.5. The Population Effect on Decoupling Indicators
The Decoupling Ratio is not affected by the population, since the terms of P’s, as denominator of Energy and GDP per Capita in Energy Intensity T, are mutually eliminated. However, a change in Population results a different Decoupling Index\( \hat{D} \) for aggregate and per Capita values, a phenomenon mentioned by scholars [3].

According to Lemma 2,
\[
\hat{D} \text{ per Capita} = \frac{e_p}{g_p} = \frac{(e - p)}{(g - p)}
\]

While by definition for aggregate values
\[
\hat{D} = \frac{e}{g}
\]
To the extent of our knowledge, this is the first time that Equation (6) for the per Capita Decoupling Index $De$ is introduced in decoupling literature, at least in that simplified form. In case of per Capita decoupling analysis, the decoupling states are defined by the signs of $(e - p)$ and $(g - p)$ instead of $e, g$. While $p$ is less than $g$ and $e$, aggregate and per Capita decoupling states are the same. When $p$ exceeds either $g$ or $e$, aggregate and per Capita decoupling states might differ from each other dramatically due to the value of $p$. The above is also valid in special case, where $e = g$, although Decoupling Index $De$ for aggregate and per Capita values both equals 1. It is worth noting that, since both aggregate and per Capita Decoupling Index $De$ are always lying on the same Decoupling Ratio $R$, they always are on the same side of the coupling line $De = 1$.

3. Results and discussion

3.1. Implementation of methods

To investigate the decoupling phenomenon, both conventional and vector representations of indicators are utilized in this paper. In tabulated Figure 3, for every world region the time shift of annual Decoupling Index $De$ in $e, g$ plane and the corresponding EKC are presented. First year in $De$ series is denoted with solid bullet, characteristic Decoupling Ratio lines with dashed lines and characteristic Decoupling Index lines, such as $De = 1.2, 0.8$, with gray lines. The coupling line $De = 1$ is also drawn in EKC and if a turning point present is labeled with a time stamp. In order to study Population Effect on Decoupling Index, $De$ per capita is also drawn with the red line in annual Decoupling Index diagram. Figure 4 shows the vector version with just one time diagram, including annual Decoupling Angle $\phi$ and overall Decoupling Angle $\Phi$, for every world region.

As easily seen, the little extra work of calculating $\phi, \Phi$ Decoupling Angles ends up with one net and “handy” time diagram for testing decoupling hypothesis both annually and over a period of years with no lack of information. Diagrammatically speaking, the annual Decoupling Angle is a leading indicator while the overall Decoupling Angle is following. Furthermore, the study of Decoupling Angles $\phi, \Phi$ diagram might give useful “sings”, such as “alarms”, when used by experienced users.

Figure 3. Decoupling Index $De$ and EKC over time, conventional representation.
Figure 4. Annual (step) Decoupling Angle \( \varphi \) and overall Decouple Angle \( \Phi \) over time.

Abbreviations: Historical developed regions: [WE]: Western Europe, [NAC]: North America, [EECA]: East Europe & Central Asia. The rest of the world: [LNC]: Latin America & Caribbean, [EAS]: East Asia & Pacific, [SAS]: South Asia, [MEA]: Middle East & North Africa, [SSF]: Sub-Saharan Africa., where Western Europe and East Europe & Central Asia data derived from the original Europe & Central Asia World Bank data.

3.2. Discussion on decoupling trends for the 8 regions of the world.

According to the analysis presented above:

- Only Western Europe and North America move close to strong decoupling for the overall study period, while the last years Western Europe performs better having consecutive years of strong decoupling, verifying the Technical Efficiency of EU mentioned by previous studies [21]. A turning point in decoupling is present in both regions around 2006, close to the economic crisis.
- East and South Asia along with Latin America seem to fluctuate just below or around expansive coupling area. However a part of aggregate energy and GDP percentage increase is due to Population Effect, namely increase of population.
- Su-Saharan Africa shows a remarkable shift from expansive negative decoupling in 90’ to weak decoupling afterwards. However the region is highly dominated by Population Effect due to high population increase. In early 90’ the per Capita Decoupling Index reveals economic and energy poverty. Stronger Population Effect might hurt the fragile economies of the region in foreseeable future.
- Middle East and North Africa, place of the Arabic world, is the only world region that moves steadily in expansive negative decoupling. Energy-based Economies with a substantial Population Effect, might be subject to oil prices turmoil or future oil peak.
- East Europe and Central Asia, after a troublous times following the political collapse, seem to rise again around 1990. In recent years the region is in weak decoupling.
The World as a whole stands in weak decoupling state although is moving slowly to Expansive Coupling, as a result of changes in population and GDP redistribution from Europe, North America and Central Asia to the rest of the world.

A “good” decoupling state for Index De in aggregate volume for non-renewable sources, such as fossil fuels or even minerals and land, is a positive sign for the decoupling hypothesis. However, low rates of energy use, combined with strong Population Effect in upcoming "Third World" areas, such as sub-Saharan Africa, may mask energy poverty per capita, as it was shown in Figure 3 [SSF]. The Population Effect could also be important in case of decreasing population, something that is expected in some of the European Union member states in the near future accordingly to Eurostat. However, it was not notable in our regional data.

3.3. Questions not answered and work to be done.
Well-developed regions of Western Europe and North America, even when annual De values differ dramatically over time, they present respectively small rates of changes in energy and GDP sifting within a narrow range of Decoupling Ratio values. On the contrary, rising economies in regions of Middle East & North Africa, South and East Asia along with Sub-Saharan (in second half of study period) move upwards on a steady in average value of Decoupling Index. These remarks set a question on how practical is to declare changes in decoupling states when triggered by small changes in energy and GDP. If for comparison reasons the Energy and GDP are presented in per capita terms, it is obvious that the overall absolute changes in well-developed regions are not significant compared to changes in rising economies in other regions of the world. This fact is not highlighted from existing decoupling indicators De, R or even Decoupling Angles, asserting the need of exploiting the Decoupling length of vector version more adequately.

4. Conclusions
The “Decoupling Angle” of the De index, as introduced in this text, turned out to be a much more convenient indicator as the index itself, resulting in a sufficient time-domain representation of annual and overall decoupling process instead of the conventional energy versus GDP diagrams (Tapio’s and EKC graphs). Empirical findings on Energy Decoupling (study period 1992-2014) reveal that although the economies of the historically developed regions of Western Europe and North America are in a state of Strong decoupling, the world economy is in a slow transition from Weak to Expansive decoupling, mainly due to changes in global population and redistribution of global “GDP” from Europe, North America and Central Asia to the rest of the world. The Arab economies seem to be the most energy depended, while the sub-Saharan economies are dominated by the (over) Population Effect, as indicated by substantial divergence between aggregate and per capita values of De.

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