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LETTER

Decoupling economic and energy growth: aspiration or reality?

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Abstract

Energy has long been a driving force of economic growth; however, it comes with environmental costs and security challenges. This study analyzes the energy–economy nexus and explores their decoupling possibilities by using cross-country data over the years 1971–2014. The results indicate that, while energy use and economic growth exhibit a typical inverted U-shaped decoupling relationship for the industrialized countries, they have been rising in tandem for the developing economies. Among factors, it is the economic scale, population size, and energy intensity that are the decisive factors. Among countries, it is the U.S., China, and India, which mainly dominate the global economy–energy trend. Overall, we conclude that any global economy–energy decoupling may confront challenges and uncertainty. To better decouple economic growth from energy use, we propose policies for more structural reforms, a clean energy system, improved energy efficiency, and efficient energy demand-side management.

1. Introduction

The world faces the dilemma of balancing economic development with energy consumption [1]. From 1971 to 2014, a globally booming economy witnessed an average annual GDP growth of 1.52% per capita, based on a 0.85% annual increase in energy use [2]. A well-established energy system supports almost every dimension of Sustainable Development Goals, and its access is essential for economic prosperity [3], while its use leads to environmental and security concerns. Since 2015, energy as a critical driver has contributed to over 70% of the total greenhouse gas emissions on a global scale [4]. Moreover, energy is a bigger story about development and overall environmental pressure. In the developed countries, clean energy and climate change have become the focus. Although nuclear and renewables have played a positive role in climate change mitigation [5–7], the environmental costs such as air pollutions from biomass burning, water environment damage led by hydropower, and contamination by nuclear waste, cannot be ignored [8, 9]. Simultaneously, in the developing world, many people do not even have lifeline access to energy. In 2017, there is still leaving about 840 million people (13% of the global population) without access to modern electricity, and 3 billion people rely on wood, coal, charcoal, or animal waste for cooking and heating [10].

These challenges can be addressed if economic development can be achieved with less energy dependency. Existing research, however, disagrees on how this is achievable. An estimated 33% higher primary energy footprint per capita is needed than the current global average to achieve a high level of development [11]. However, economic growth decoupling with energy is also predicted in the decades to come [12]. At the regional level, the relationship between energy use and economic growth is expected to be nonlinear (specifically S-shaped) in many regions [13, 14], highlighting distinct economy–energy patterns in different economic development settings. The literature indicates that economy–energy decoupling is more common in developed countries except during exogenous shock periods [15–17]. Such characteristics are captured by the energy-environmental Kuznets curve (energy-EKC) model, commonly used to investigate economy–energy relations [18–21]. An energy-EKC is similar to the concept of EKC that assumes energy use should increase with economic development to reach a peak and then decline [22]. Such Kuznets-type relationship between energy use and economic growth has been found in industrialized and high-income countries [18, 19]. However, there is a small amount of contrary evidence from OECD regions showing that both renewable and non-renewable energy are positively associated with a higher economic growth rate [23]. In low- and middle-income countries, the economy–energy relation is convoluted. On the one hand, the strong relationship between energy consumption and economic growth cannot be identified [24]. On the other hand, the energy-EKC is not supported, for example, in Latin America and the Caribbean regions [19, 20], which suggests energy use increases with economic growth. The economy–energy relationship is associated with energy efficiency and decarbonization, but this association is not conclusive across regions.

To address the gaps in the literature, we undertake a systematic assessment of global economy–energy decoupling from the context of historical patterns, current drivers, and future leading countries. Our work contributes to the existing knowledge in three aspects. First, by fact excavating, we discuss how emerging economies have shown significant linear economy–energy nexus as compared to the decoupling path taken by the industrialized countries. Second, we apply threshold regression to make up for the lack of an energy-EKC model that can only identify one turning point. A typical country has taken around 40 years, on average, from a weak to strong decoupling threshold. Third, we examine the drivers, as the increase in global energy demand in production is driven by economic expansion and population growth, while the decline of energy intensity contributes to reduced energy use. U.S., China, and India steer the global decoupling process. Global path towards economy–energy decoupling confronts challenges and uncertainty. Combined with decoupling experiences, through exploring the structural effects of the economy, designing and implementing green policies, and improving energy demand-side management, the global energy system is expected to be optimized.

2. The historical economy–energy pattern

Figure 1(A) illustrates a significantly positive and linear economy–energy nexus on the global scale, indicating that energy use has closely tracked economic growth. From 1971 to 2014, this positive linear trend shows no remarkable change, even though there were a few structural breaks, such as during the Second Oil Crisis (early 1980s) and the Gulf War (early 1990s) [25]. Period 1 started in 1971 and ended in the Second Oil Crisis, during which energy use increased rapidly. The line with a steeper slope (0.1344) means that 134.4 kg oil equivalent (kgoe) energy per capita is needed to support an increase of \$1000 GDP per capita. The decoupling index (DI), defined as the percentage change in energy use due to single percentage growth in GDP per capita, assesses the economy–energy nexus. There are four types of DIs. The 'recession' means that the economic growth rate is negative. The 'no decoupling' refers to the positive growth rate of economy and energy use, and DI is greater than 1. The 'weak decoupling,' the value of DI is range 0 and 1 while keeping per capita GDP and per capita energy use increase. The 'strong decoupling' status is defined as when the per capita GDP increases while per capita energy use decreases, the value of DI is negative (see section 5.1). The DI score for period 1 (0.66) indicates weak decoupling. During period 2, energy use was growing comparatively slowly, evident with a flatter slope coefficient (0.0962) and the DI score (0.56), implying a weak decoupling. Period 3 started in 1994, after the Gulf War, and the slope is flatter here with a coefficient (0.0648) indicating that to yield \$1000 GDP per capita, the energy use was only half of that in period 1 and 2/3 of that in period 2, with a DI value (0.39) indicating another period of weak decoupling. The overall trend during 1971–2014 is significantly linear, with energy use significantly and linearly associated with economic growth. The weak economy–energy decoupling dominated, with a global DI (0.46) indicating that a 0.46% growth rate of energy use supported the global economy increase by 1%.

The economy–energy patterns are diverse at regional levels. The first of the three grouped regions in figure 1(B) displays a linear trend, covering East Asia and Pacific (EAP), Latin America and Caribbean (LAC), and South Asia (SA), and suggesting that economic growth accompanies energy demand in production. These regions follow the trajectory of weak decoupling with declining DI scores, as shown in figure 1(C). The second group in figure 1(D) shows North America (NA) and the European Union (EU) displaying an inverted-U shape, noting how the slope first flattens and then declines. The DI trend in figure 1(E) shows a similar decline evolution for these regions. It is noted that before the 1980s, both regions are in the weak decoupling state; then they move in parallel towards the strong decoupling position with a negative value of DI (−0.32 for NA, −0.23 for EU). Other regions are classified as a miscellaneous group because no remarkable trend emerges (see supplementary figure 1 (available online at stacks.iop.org/ERL/16/044017/mmedia)).

To validate the observed patterns, we use fitting models to identify the economy–energy patterns quantitatively, including the linear model and energy-EKC model, which contains energy use per capita and GDP per capita (see section 5.1). The linear pattern shown in figure 1(B) is statistically confirmed for EAP, LAC, and SA. Consistent with other studies, energy-EKC type is not supported in low-

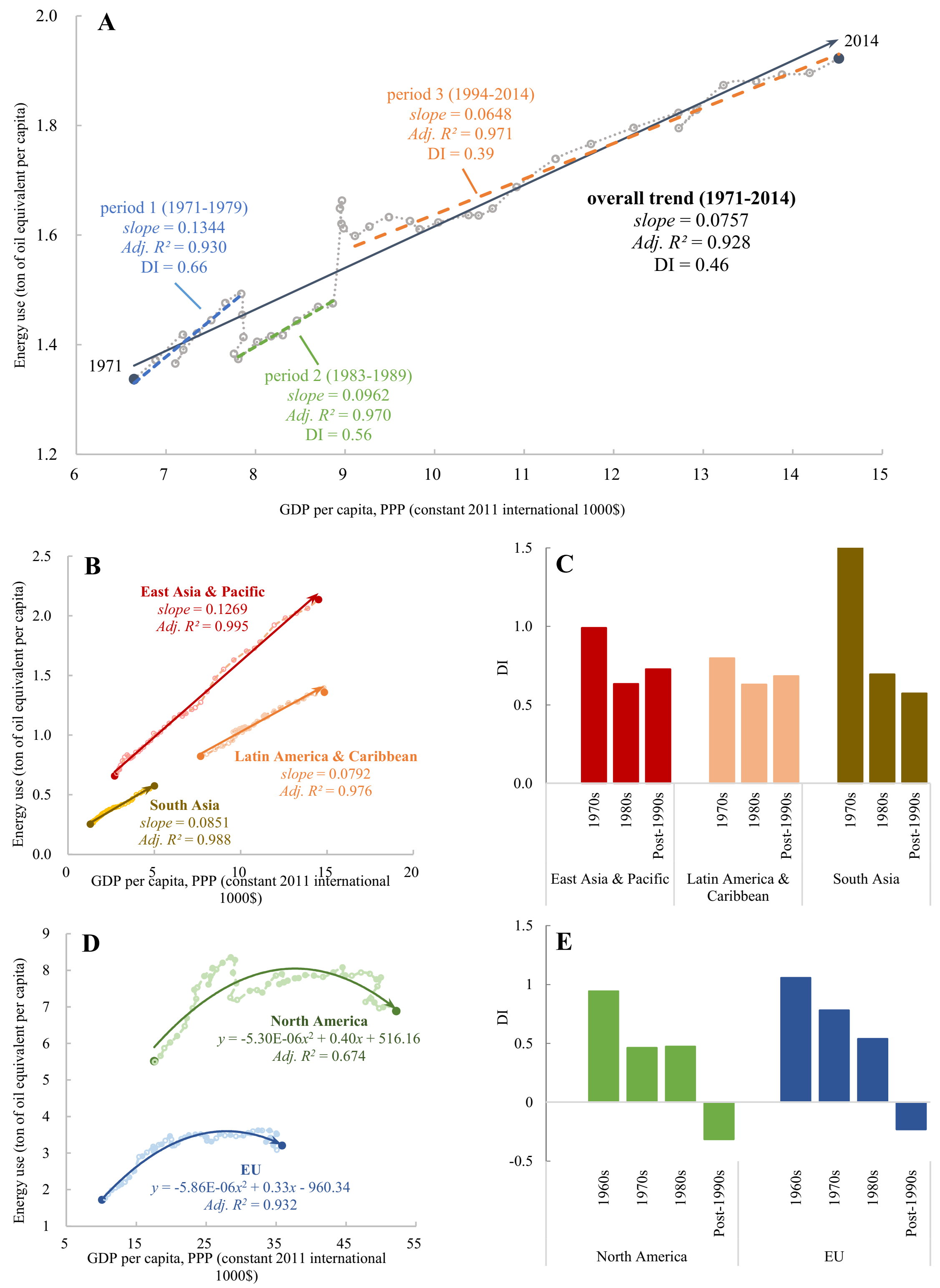

Figure 1. Economy–energy nexus. (A) Global trend during 1971–2014. (B) Linear pattern for World, East Asia and Pacific, Latin America and Caribbean, and South Asia during 1971–2014. (C) Decoupling index trend for East Asia and Pacific, Latin America and Caribbean, and South Asia during 1971–2014, except for early 1980s and early 1990s. (D) Inverted-U pattern for North America and EU during 1960–2015. (E) Decoupling index trend for North America and EU during 1960–2015, except for early 1980s and early 1990s.
Note: dark dot marks the beginning year and the ending year, as time goes in the direction of the arrow. See the Methods section for data sources and region classification.

and middle-income countries [19, 20]. LAC and SA approximate the global trend with a lower slope coefficient (0.0792 and 0.0851, respectively), indicating that an additional $1000 GDP/capita requires energy use/capita of 79.2 kgoe and 85.1 kgoe, respectively. EAP has a greater slope (0.1269), showing more energy demand in production for similar economic output. Figure 1(D) suggests that the inverted-U pattern holds for NA and EU. As previous literature revealed [18, 19], the energy-EKC model is the best-of-fit specification, with the turning point at $37 698 for NA (in 1994–1995) and $27 884 for EU (in 1997–1998). It suggests that these regions had moved to the decoupled stage in the 1990s, implying economic growth was accompanied by less energy dependency. Further examination is reported in supplementary note.

We were also interested in the economy–energy nexus switching pattern (instant or transitionary) and whether this transformation for decoupled countries represents an inverted-V or inverted-U shape with a long plateau. We apply thresholds regression with fixed-effect on panel data covering 14 countries from NA and EU during 1960–2015, which contains two main variables, the natural logarithm of GDP per capita and the natural logarithm of energy use per capita that are I (1) process and cointegrated, and the time variable to control common shocks (see section 5.1). The first threshold (at $11 895 GDP per capita at a 1% significance level, the upper and lower limits are [11 824, 12 052]) shows energy use changed with economic growth from rising to a plateau, and DI decreased from 1.17 ± 0.19 to 0.81 ± 0.37, implying a weak decoupling. The second threshold (at $36 444 GDP per capita at a 1% significance level, the upper and lower limits are [35 735, 36 495]) where DI decreases to -0.08 ± 0.48, indicates strong decoupling. A sample country has taken approximately 40 years from an observed weak decoupling threshold to a strong decoupling threshold on average; the U.S., the earliest decoupled one, for example, was at weak decoupling status in the 1960s, then reached strong decoupling until 1992, highlighting how decoupling economic growth from energy use is feasible but long-drawn. The supplementary note further discusses practices and actions for decoupled countries.

3. Economic and other driving factors

Economic growth and other factors driving global energy use are examined from 1971 to 2014 by the Kaya Identity and the Logarithmic Mean Divisia Index (LMDI) decomposition approach (see section 5.1). Figure 2(A) illustrates the decomposition result for four decades (1970s to post-2000s), during which the global energy demand in production increased from 5 Gtoe (1971) to around 14 Gtoe (2014) with an annual growth rate of 2.40%. In summary, the role of economic growth has become an increasingly dominant factor compared to population impact and, post-2000 has started playing a key role in affecting global energy use compared to before, contributing to 40% in energy use increase (equivalent to 4 Gtoe). Second, population growth impact on energy use is sizeable and should not be underestimated. Population growth mostly has a sizable effect on energy use increase when compared to the very evident economic boom, as was the case in the 1980s, when population growth-driven energy use had increased by 19%, exceeding the effect of economic growth. Third, the energy intensity effect is the biggest deceleration factor: producing the same economic output with lower energy use or producing more GDP when using the same energy input. In addition to the implementation of energy efficiency strategies globally, energy intensity experienced a substantial decrease. Consequently, the gains to lower the energy demand in production from energy-intensity effects are increasing over the years; however, the energy intensity effect is not large enough to compensate for economic and population growth.

Figure 2(B) shows the declining role of NA and EU against the increasing dominance of EAP, with this region accounting for less than 30% of global energy demand in production growth pre-1990, increasing to 52% in the 1990s, and reaching 60% post-2000. Contrarily, the contribution of NA and EU in total energy use increases has declined, and the absolute energy use has declined during post-2000. The three key findings here are: first, the economic growth effect in most regions strongly stimulated energy use, of which EAP had the highest, followed by NA and EU, and finally SA. In the 1970s, NA (39%), EU (35%), and EAP (29%) were the top contributors to energy use increase resulting from economic growth. From 1980, EAP overtook NA, becoming the largest contributor. By 2000, the top three contributors were EAP (64.2%), SA (11.5%), and NA (8.8%). Second, the population effect across regions has increased moderately over the years. EAP contributed 17%–19% of total population-led energy use increase while NA contributed 15%–20%. The EU's contribution is relatively small, declining from 6.6% (1970s) to 3.4% (post-2000s). Finally, the increasing energy-intensity effect on a decoupled world is attributable to the collaborative efforts of many regions; NA, EAP, and EU have contributed to more than 80% reduction in energy use via energy intensity improvement since 2000.

4. The role of U.S., China, and India

U.S., China, and India are influential contributors to the global decoupling process. From 1971 to 2014, energy use in these countries increased by 628.7, 2660.5, and 672.9 Mtoe, accounting for 7.1%, 29.8%, and 7.5% of global change, respectively [2]. The heat map in figure 3 suggests three points. Figure 3(A) shows China being substantially different from others with red color in most years, indicating a robust increase of economy-driven energy use, followed by India and the U.S., who also experienced increased energy demand in production resulting from economic growth (except in certain years). Figure 3(B) shows blue color for Germany in some

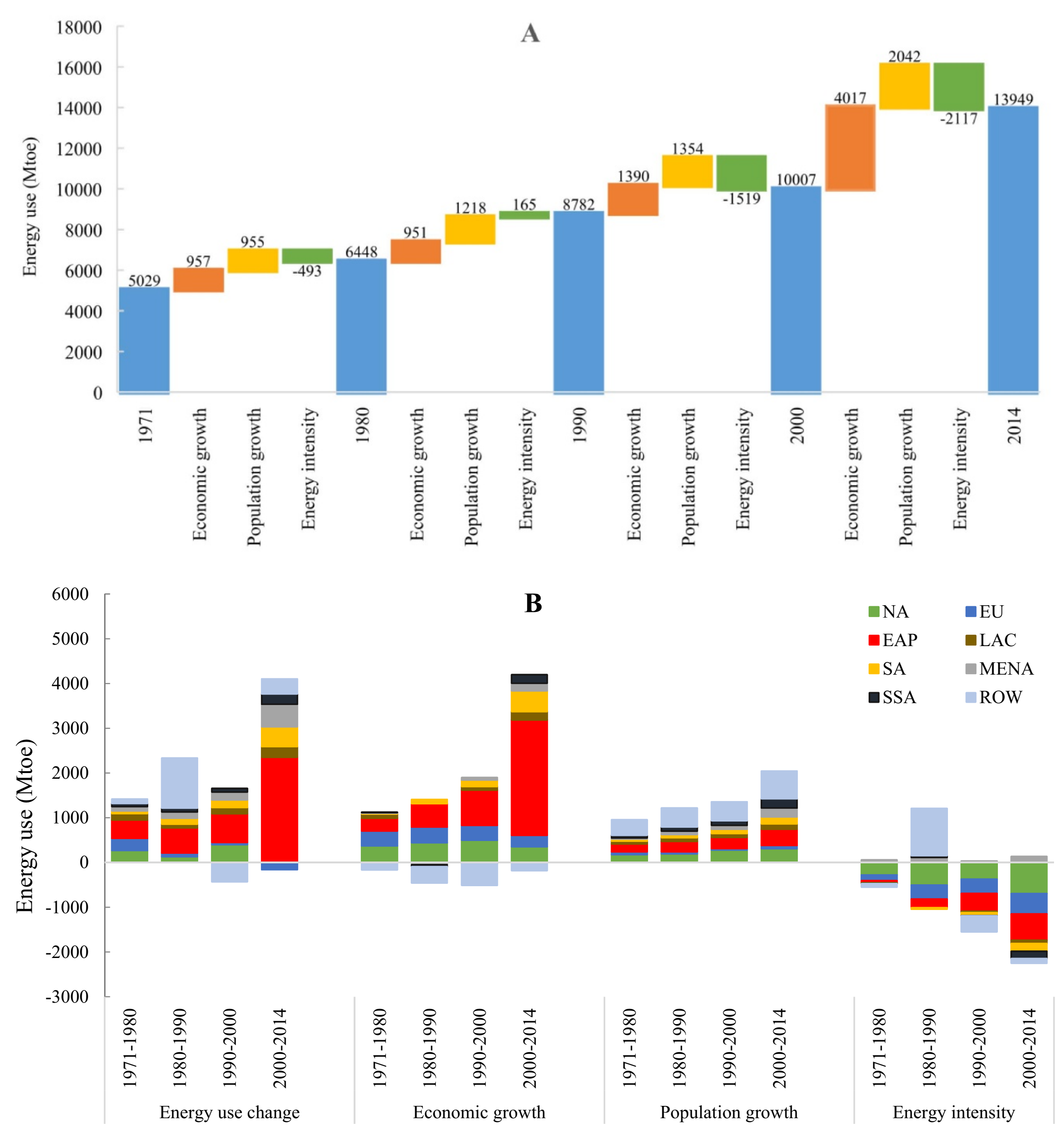

Figure 2. Contributions of economic growth, population growth, and energy intensity during 1971–2014. (A) By drivers and periods; (B) by regions, drivers, and periods; the rest of the world (ROW) includes ECA whose statistic started in 1990 and other states and islands with missing data.

years (especially strong in 2011), and for Japan in recent years, implying they experienced declining energy use as their population growth reduced. Comparatively, the U.S. is marked with red that darkens with time, implying a large energy use increase due to population growth, higher even than populous countries such as China and India. In figure 3(C), China and U.S. are marked with dark blue colors in most years, showcasing their achievement in controlling energy demand in production by reducing energy intensity. Even without a sizeable effect, India falls into the same cluster with China, U.S., Germany, and Japan in terms of energy-intensity effect.

These three countries will steer global economy–energy decoupling in subsequent decades, with China and India predicted to strongly demand global energy [26, 27]. In three scenarios we applied (see supplementary table 1) [28, 29], from 2020 to 2040, the U.S., China, and India will account for 43%–45% of global energy use (figure 4(A)). The U.S. will mitigate global energy use by decoupling economic growth; its current policy (CPS) will reduce energy use during 2030–2040. However, China and India are dominated by weak decoupling and will increase global energy demand in production before China enters a decoupling stage under sustainable development scenario (SDS).

Figures 4(B)–(D) illustrate driving factors across countries. U.S., China, and India contributed to 80% of total economic growth effect globally, in every scenario (2010–2020). In the next two decades, their contribution will decline to 62%–65% under various scenarios. However, China and India will dominate as they contribute more than half of the global energy use induced by economic growth. Economy–energy decoupling will require

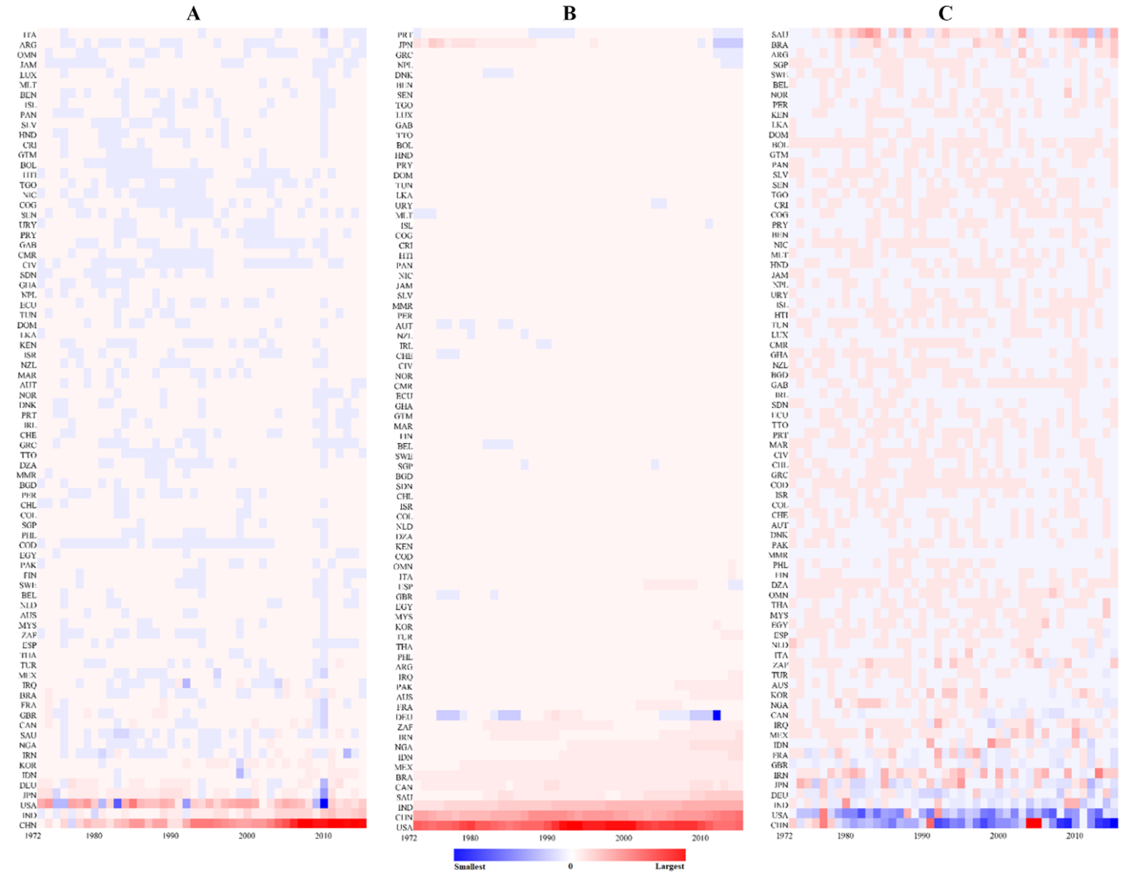

Figure 3. Contributions by country during 1971–2014. (A) Economic growth effect. (B) Population growth effect. (C) Energy intensity effect.
Note: In the heatmap, energy use change results from three macroeconomic drivers in 81 sample countries are listed in columns and the observed period from 1972 to 2014 (based on 1971) are listed in rows. Blue colors indicate negative values of each driver's contribution, while red colors indicate positive values. The columns are clustered using the Euclidean distance and the maximum linkage.

improvement in energy-intensity through benefits of technological progress, structural and policy change, and other factors [29–31]. This sizeable effect exceeds the economic growth effect in some scenarios. In the next two decades, global energy use will reduce by more than half, every decade, because of these countries' efforts. The U.S. energy-intensity effect shows potential to compensate for the increased energy use from economic and population growth. China plays a critical role here, focusing on conserving more than 1000 Mtoe and reducing global energy demand by 1/3 every decade in 2020–2040. The population growth effect is very weak, and in any scenario, energy use change caused by the weak population effect in the U.S., China, and India is less than 20% every decade in 2020–2040. Despite China's populous state, its population growth effect is only 2% of the total global effect every decade.

5. Discussion and policy implications

The global assessment shows that the economy and energy relationship has remained positively linear in most emerging regions, although NA and EU have embraced a decoupling era. Energy efficiency improvement is the key to slowing down their energy demand in production. Economic-energy decoupling aims to breakthrough growth constraints and mitigates environmental pressure, which provides a chance for the developing world to establish a sustainable growth model. Nevertheless, the global path towards an economy–energy decoupling may confront challenges and uncertainty. China and India are two influential contributors in the global decoupling process, and the two are economy–energy weak decoupling as energy use is emerging. The impact of the COVID-19 pandemic on the global economy–energy trend is also uncertain [32–35]. The world is under lockdown and economic recession. The total energy consumption is projected to decline, and renewables are regarded as a kind of secure energy [32, 33]. Meanwhile, there are concerns that energy use will increase in the residential sector and buildings, and fossil energy use may rebound due to economic stimulus [33, 34].

One way of addressing these challenges is by exploring the economic structural effects on energy saving to balance economic growth and energy use. More global industrial output from energy-intensive

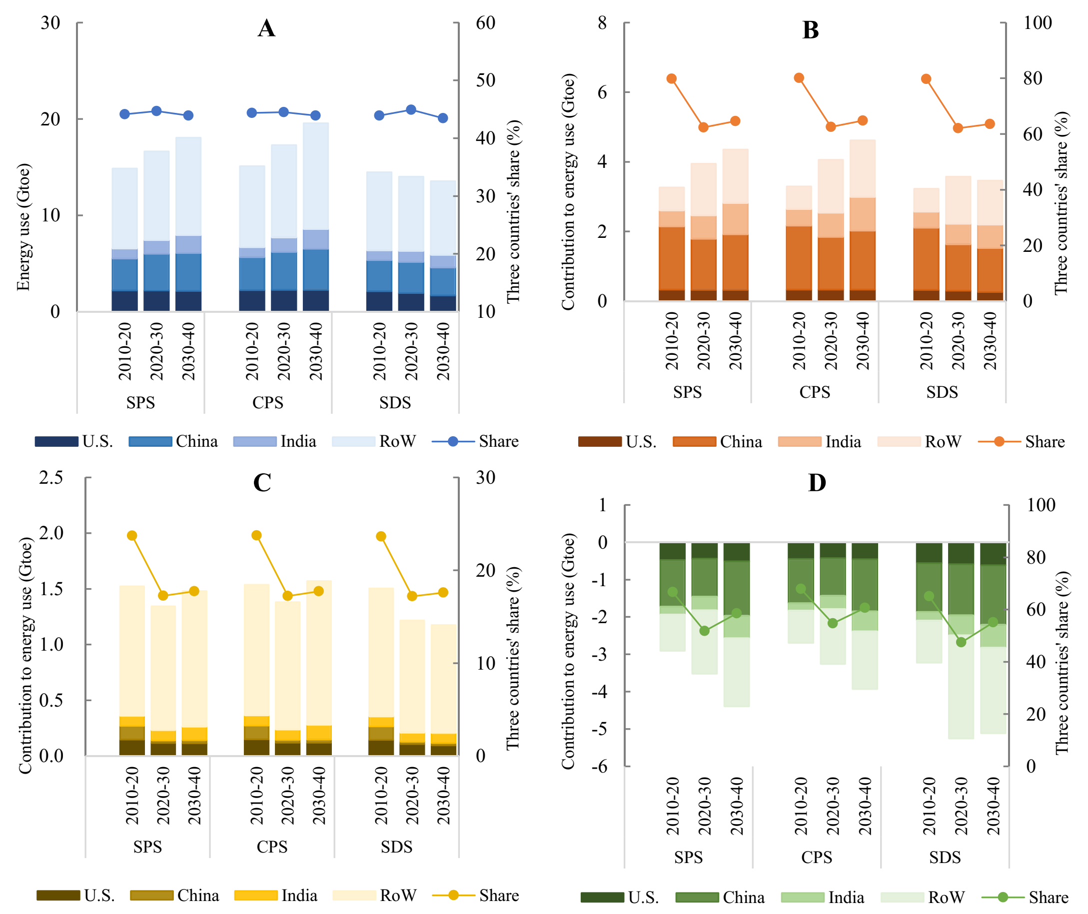

Figure 4. Contribution of U.S., China, and India toward 2040 under various scenarios. (A) Total energy use; (B) economic growth effect; (C) population growth effect; (D) energy intensity effect.
SPS, CPS and SDS refer to the stated policies scenario, current policies scenario, and sustainable development scenario, respectively.

manufacturing may slow energy intensity improvement [31]; this approach means optimizing industry structure can improve energy efficiency from the economic system. A continuing shift from industrial to service economies in fast-growing countries, such as India and China, will lead to a notable decline in the energy intensity of GDP [13].

Green policies are needed to promote non-fossil energy utilization. Promoting and reshaping an environmental-friendly energy system will depend on adapting policies and regulations, their implementation speed, and the level of resources committed [35]. Though there are different transforming paths for different regions, the common policies include cutting fossil energy subsidies, expanding renewables investments, encouraging nuclear energy development, promoting electrification based on clean energy, and sustained financial supporting clean energy technologies.

Energy efficiency is fueling decoupling between economic growth and energy use. Energy-related innovations also offer traction in energy intensity reduction [30, 31, 36]. The U.S., EU, and Japan have issued energy policy and strategy to improve energy efficiency, including diversified funding programs and investments. The *European Strategic Energy Technology Plan (SET-Plan)* and *Horizon 2020* are two well-known funding programs [37, 38]. The proper funding schemes would guide research programs by clarifying issues, objectives, research areas, and priorities. Governments can also promote cooperation with enterprises, universities, research institutes, and international agencies. Furthermore, support technology application and promotion by offering low-interest loans to enterprises.

Improve efficiency on energy demand-side management. Demand response is expected to improve energy efficiency by controlling and shifting demand and promote efficient digitalized energy supply [31, 39]. Digitalization will increase demand response capacity more than ten-fold [31]. Energy efficiency standards are mandatory measures of demand-side management in each sector, being applied globally to guide and regulate energy-use behavior. The social agency, such as professional energy consultants, has played a significant role in improving energy efficiency in the residential sector, commercial and public sector, and productive activities [40]. The energy association can encourage the social agency to provide high-quality service, for example, by guidance and qualification. Moreover, governments can take advantage of social agency by contracting and consulting.

Finally, besides the economic scale, the structure of that growth also matters. To decompose and quantify the economic structure effect in economy–energy relations would be the focus of future work. The embodied-energy or energy footprint should be paid more attention [11, 16, 41]. The patterns of economy–energy would be quite different under embodied-energy flow according to net embodied-energy importer or exporter. At the same time, the GDP reflects domestic economic activities. From development connotation and globalization, a potential alternative measure, HDI is a multi-dimensional indicator. Following this reasoning, the HDI and embodied-energy relationship and their dynamic trend should be discussed in future studies.

5.1. Methods

5.1.1. Data sources and region classification

All indicators are extracted from the World Development Indicators (WDI) database, the World Bank's (WB's) premier compilation of comparable cross-country data on development [2]. Energy use is measured as energy use per capita (kg of oil equivalent). Economic growth is measured by GDP per capita, PPP (constant 2011 international $). The original series of GDP per capita, PPP (constant 2011 international $), starts from 1990 to the most recent years. To extrapolate this series back to earlier years, real GDP per capita growth (annual %) is applied to calculate GDP per capita, PPP (constant 2011 international $) before 1990. The population is measured by the total population (persons). Most data, except that of note, covers the period from 1960 to 2014 and 1971 to 2014 (see supplementary table 2).

We follow the WB's region classification. It divides the world into seven regions, including EAP, LAC, Middle East and North Africa, SA, Sub-Saharan Africa, NA, and Europe and Central Asia. Considering the important role of the EU, we separate this region into two parts: EU and Europe and Central Asia (excluding EU). In total, we have eight regions.

According to WDI's statistics, the total population of regions aggregated together is equal to the global population, but energy use and GDP are not. This is because some states and islands are not informative in different periods (supplementary table 3 lists the variable and countries in 2014).

5.1.2. Decoupling Index.

The DI is a common indicator, which allows an understanding of how the world, regions, and countries reduce environmental burden [42–44]. It is also used to measure the relationship between resource and energy use and economic growth [15–17, 27, 45]. In this case, we combine the method in Tapio (2005) and the definition of decoupling state in the OECD (2002) to avoid unexpected impact from exogenous shocks such as economic recession and energy crisis [42, 44]. It can be presented as:

$$\mathrm{DI} = \frac{\%\Delta\mathrm{Energy}}{\%\Delta\mathrm{GDP}} \qquad (1)$$

where the growth rate of energy per capita (%ΔEnergy) and the growth rate of GDP per capita (%ΔGDP) can be calculated year on year or as an average annual growth rate in a given period. Supplementary figure 2 illustrates four types of DIs, including recession, no decoupling, weak decoupling and strong decoupling.

5.1.3. Fitting models

Fitting models, including linear models and parametric polynomial models, are used to identify economy–energy patterns. The linear model is specified as $\mathrm{Energy} = \alpha + \beta \cdot \mathrm{GDP}$, where 'Energy' indicates energy use per capita (kg of oil equivalent), and 'GDP' indicates GDP per capita, PPP (constant 2011 international $). The second-order polynomial, called the energy-EKC model assumes an inverted U-shape curve between economic growth and energy use. The statistical information for all models is listed in supplementary table 4.

5.1.4. Thresholds regression and FE panel regression

We test the threshold effect of economic development level on economy–energy trend by fixed-effect panel threshold model [46, 47]. The data covers 14 countries in NA and EU, including Austria, Belgium, Demark, Finland, France, Greece, Italy, Netherlands, Portugal, Spain, Sweden, United Kingdom, Canada, and United States, with the observation period from 1960 to 2015. The descriptive statistics of variables are listed in supplementary table 5. The two variables, the natural logarithm of GDP per capita and the natural logarithm of energy use per capita, are I (1) process and cointegrated (see supplementary tables 6 and 7). Furthermore, to control common shocks during the observed period, a time variable is introduced in the model.

For the multiple k thresholds model, the regression equation is written as:

$$\begin{aligned} \ln \mathrm{Energy}_{\mathrm{i,t}} &= \alpha + \beta_1 \cdot \ln \mathrm{GDP}_{\mathrm{i,t}} \left(\mathrm{GDP}_{\mathrm{i,t}} < \gamma_1\right) \\ &\quad + \beta_2 \cdot \ln \mathrm{GDP}_{\mathrm{i,t}} \left(\gamma_1 \leq \mathrm{GDP}_{\mathrm{i,t}} < \gamma_2\right) \\ &\quad + \ldots + \beta_k \cdot \ln \mathrm{GDP}_{\mathrm{i,t}} \left(\mathrm{GDP}_{\mathrm{i,t}} \geq \gamma_{k-1}\right) \\ &\quad + \mathrm{year} + u_{\mathrm{i}} + e_{\mathrm{i,t}} \end{aligned} \qquad (2)$$

GDP is the independent variable and the threshold variable, γ_k is the threshold parameters that divide the economy–energy trend into $k-1$ regimes with coefficients β_k. The parameter u_{i} is the individual effect, while $e_{\mathrm{i,t}}$ is the disturbance.

To obtain the elasticity of economic growth to energy use, which is instead of DI, we applied the fixed-effect panel regression model with cross terms between GDP and regimes. Dummy variables of regimes can capture time effect and thresholds effect. The regression equation is written as:

$$\begin{aligned}\ln \text{Energy}_{\text{i,t}} &= \alpha + \beta_1 \cdot \ln \text{GDP}_{\text{i,t}} + \beta_2 \cdot \ln \text{GDP}_{\text{i,t}} \cdot \text{regime}_2 \\ &\quad + \ldots + \beta_k \cdot \ln \text{GDP}_{\text{i,t}} \cdot \text{regime}_k + \text{regime}_2 \\ &\quad + \ldots + \text{regime}_k + u_{\text{i}} + e_{\text{i,t}} \qquad (3)\end{aligned}$$

where ‘regime’ indicates regimes divided by thresholds regression. The parameter u_{i} is the individual effect, while $e_{\text{i,t}}$ is the disturbance. The estimated results of thresholds and elasticity of economic growth to energy use are listed in supplementary table 8.

5.1.5. Kaya identity and LMDI

We decompose energy use in each scale using the Kaya identity [48–50]. In this case, energy use (Energy) is decomposed to three factors: population (P), per capita GDP (g = GDP/P), and energy intensity (e = Energy/GDP). Then the Kaya identity can be illustrated as below:

$$\begin{aligned}\text{Energy} &= \text{Population} \times \left(\frac{\text{GDP}}{\text{Population}}\right) \times \left(\frac{\text{Energy}}{\text{GDP}}\right) \\ &= P \times g \times e. \qquad (4)\end{aligned}$$

By applying the LMDI decomposition approach, we can compare a series of indices and discuss their impact on energy consumption trends during a given period [51]. LMDI is preferable for its path independence and adaptability, aggregation consistency, absence of unexplained residual terms appearing in the decomposition, and ability to handle zero values [52, 53]. Kaya identity can be transformed into:

$$\Delta \text{Energy} = \Delta P + \Delta g + \Delta e. \qquad (5)$$

The x refers to P, g, and e, where:

$$\Delta x = \frac{\text{Energy}_{t_2} - \text{Energy}_{t_1}}{\ln \text{Energy}_{t_2} - \ln \text{Energy}_{t_1}} \cdot \ln \left(\frac{x_{t_2}}{x_{t_1}}\right). \qquad (6)$$

Data availability statement

The data that support the findings of this study are openly available at the following URL: https://databank.worldbank.org/reports.aspx?source=World-Development-Indicators#.

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