

Low-carbon economic development in Central Asia based on LMDI decomposition and comparative decoupling analyses Postprint

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Abstract

Low-carbon economic development is a strategy that is emerging in response to global climate change. Being the third-largest energy base in the world, Central Asia should adopt rational and efficient energy utilization to achieve the sustainable economic development. In this study, the logarithmic mean Divisia index (LMDI) decomposition method was used to explore the influence factors of CO₂ emissions in Central Asia (including Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan and Turkmenistan) during the period 1992–2014. Moreover, decoupling elasticity and decoupling index based on the LMDI decomposition results were employed to explore the relationship between economic growth and CO₂ emissions during the study period. Our results show that the total CO₂ emissions decreased during the period 1992–1998, influenced by the collapse of the Soviet Union in 1991 and the subsequent financial crisis. After 1998, the total CO₂ emissions started to increase slowly along with the economic growth after the market economic reform. Energy-related CO₂ emissions increased in Central Asia, mainly driven by economic activity effect and population effect, while energy intensity effect and energy carbon structure effect were the primary factors inhibiting CO₂ emissions. The contribution percentages of these four factors (economic activity effect, population effect, energy intensity effect and energy carbon structure effect) to the total CO₂ emissions were 11.80%, 39.08%, -44.82% and -4.32%, respectively, during the study period. Kazakhstan, Uzbekistan and Turkmenistan released great quantities of CO₂ with the annual average emissions of 189.69×10^6 , 45.55×10^6 and 115.38×10^6 t, respectively. In fact, their economic developments depended on high-carbon energies. The decoupling indices clarified the relationship between CO₂ emissions and economic growth, highlighting the occurrence of a “weak decoupling” between these two variables in Central Asia. In conclusion, our results indicate that CO₂ emissions are still not completely decoupled from economic growth in Central Asia. Based on these results, we suggest four key policy suggestions in this paper to

help Central Asia to reduce CO₂ emissions and build a resource-conserving and environment-friendly society.

Full Text

Preamble

Low-carbon economic development in Central Asia based on LMDI decomposition and comparative decoupling analyses

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Abstract: Low-carbon economic development is emerging as a strategic response to global climate change. As the world's third-largest energy base, Central Asia must adopt rational and efficient energy utilization to achieve sustainable economic development. This study employs the logarithmic mean Divisia index (LMDI) decomposition method to explore the factors influencing CO₂ emissions in Central Asia (including Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan, and Turkmenistan) during 1992-2014. Additionally, decoupling elasticity and a decoupling index based on LMDI decomposition results are used to examine the relationship between economic growth and CO₂ emissions. Our results show that total CO₂ emissions decreased during 1992-1998, influenced by the collapse of the Soviet Union in 1991 and the subsequent financial crisis. After 1998, total CO₂ emissions began to increase slowly alongside economic growth following market economic reforms.

Energy-related CO₂ emissions in Central Asia increased, primarily driven by economic activity and population effects, while energy intensity and energy carbon structure effects were the main inhibiting factors. During the study period, the four factors contributed 11.80%, 39.08%, -44.82%, and -4.32% to total CO₂ emissions, respectively. Kazakhstan, Uzbekistan, and Turkmenistan released substantial quantities of CO₂, with annual average emissions of 189.69×10^6 t, 45.55×10^6 t, and 115.38×10^6 t, respectively, as their economic development depended on high-carbon energy sources. Decoupling indices clarified the relationship between CO₂ emissions and economic growth, revealing "weak decoupling" between these variables in Central Asia. Our findings indicate that CO₂ emissions remain incompletely decoupled from economic growth in the region. Based on these results, we propose four key policy recommendations to help Central Asia reduce CO₂ emissions and build a resource-conserving, environment-friendly society.

Keywords: energy-related CO₂ emissions; low-carbon economy; LMDI decomposition; decoupling elasticity; decoupling index; Central Asia

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1 Introduction

Given the significant impacts of climate warming on social and economic development, interest in the low-carbon economy has grown globally (Olcott, 2006; Pablo-Romero et al., 2017). The essence of a low-carbon economy is to sever the link between economic growth and greenhouse gas emissions through innovations in energy technology and policy (Mohsen et al., 2016; Nepal et al., 2017; Wang et al., 2017). A correct understanding of the evolving relationship between economic growth and greenhouse gas emissions is therefore essential for evaluating regional low-carbon economy achievements and formulating dedicated development strategies.

Earlier studies on the relationship between energy consumption and economic development have employed the environmental Kuznets hypothesis, gray relational degree method, co-integration relationship, and coordination degree model (Organization for Economic Co-operation and Development, 2005; Feng et al., 2011; Zhang et al., 2011; Wang et al., 2012). Since the 21st century, however, research in this field has primarily focused on environmental Kuznets curve (EKC) and decoupling theories.

EKC theory simulates the relationship between carbon emissions and economic growth using historical data (Oh and Yun, 2014; Asane-Otoo, 2016). This technique is highly sensitive to sample selection, data quality, and measurement methods, resulting in no consensus on carbon emissions calculated using this approach. Decoupling theory, by contrast, can calculate the synchronicity between economic growth and resource consumption rates. An early decoupling index was defined as the ratio between the ending and initial values of the ratio between environmental pressure and gross domestic product (GDP). This index could effectively identify decoupling occurrence but could not distinguish different decoupling states (Hunter, 1994; Organization for Economic Co-operation and Development, 2005). Subsequently, the Tapio decoupling index was proposed to study the relationship between carbon emissions and economic growth in Europe during 1970-2001 (Tapio, 2005). This index overcomes the sensitivity of early decoupling models to the base period and demonstrates notable decoupling state recognition ability, making it widely applicable in empirical research (Gao et al., 2012; Liu et al., 2014).

The decomposition of carbon emission drivers (i.e., Kaya identity) was proposed by Kaya (1983) and includes Divisia and Laspeyres indices as factor decomposition methods. Sun (1998) improved the residual problems of the Laspeyres index, while Ang and Zhang (2000) proposed the logarithmic-mean Divisia index (LMDI), which can decompose multiple factors of carbon emissions and reduce residual error to zero. Consequently, LMDI is widely applied in factor decomposition of energy-related carbon emissions (Wang et al., 2011; Hu et al., 2014). For example, Lai and Zheng (2017) analyzed carbon emissions from industrial energy consumption in Dalian, China, using the LMDI model, considering energy structure, energy intensity, industrial structure, and output scale. Yao et al. (2018) used the LMDI model to study driving effects of spatial differences in provincial water consumption, decomposing them into intensity, structure, income, and population effects.

Central Asia is one of the world's most environmentally vulnerable regions. It possesses abundant energy resources, potentially exceeding those of Kuwait, the Gulf of Mexico, and the North Sea (Dorian et al., 2006; Mercure and Salas, 2012). Since the beginning of the 21st century, increasing energy consumption in Central Asia has resulted in higher CO₂ emissions, further raising temperatures in the Central Asian arid region by approximately 1°C–2°C (Lioubimtseva and Henebry, 2009). To reduce such high CO₂ emissions, developing a low-carbon economy in this region is essential.

This study examines the factors influencing energy-related CO₂ emissions in Central Asia by applying the LMDI model. Additionally, we explore the relationship between CO₂ emissions and economic growth using the Tapio decoupling model and a decoupling index. The overall aim is to provide a scientific reference for low-carbon economy development, CO₂ emission reduction, and climate change mitigation in Central Asia.

2.1 Study Area

In its narrow sense, Central Asia includes five countries—Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan, and Turkmenistan—located between 46°28'–87°29' E and 35°08'–55°25' N. This region is simultaneously one of the world's most sparsely populated areas, with a total area of approximately 4.00×10^6 km² (Siegfried et al., 2012; Mannig et al., 2013). It also serves as a geopolitical center connecting many regions of the Northern Hemisphere.

Central Asian landforms are higher in the southeast than in the northwest. Mountains in the southeastern area (Eurasian hinterland) block warm-humid airflow from the Indian and Pacific Oceans, maintaining a temperate continental climate. The most prominent climate feature is low precipitation (average annual precipitation <300 mm; Mannig et al., 2013), combined with strong solar radiation and high evaporation. The total population in Central Asia amounts to 67.70×10^7 , while cultivated lands occupy 32.30×10^6 hm² and water resources total 25.00×10^{11} m³ (Yao et al., 2013).

Additionally, Central Asia possesses abundant energy resources, ranking third globally, surpassed only by the Middle East and Siberia (Dorian, 2006). Kazakhstan, Turkmenistan, Uzbekistan, Kyrgyzstan, and Tajikistan have energy reserves of 26.90×10^9 , 3.30×10^9 , 4.41×10^9 , 0.59×10^9 , and 0.51×10^9 t, respectively (Cobanli, 2014). These energy resources have been central to industrial development in Kazakhstan, Turkmenistan, and Uzbekistan, driving their rapid economic growth. However, agriculture remains the main industry in Tajikistan and Kyrgyzstan.

2.2 Data Sources

Data on CO₂ emissions, population, GDP, and energy use for each Central Asian country during 1992–2014 were obtained from the World Bank (<http://data.worldbank.org.cn>). We converted GDP data to constant 2010 USD to eliminate inflation effects and transformed all energy use data into oil equivalents. Energy consumption data were obtained from the Carbon Dioxide Information Analysis Center (CDIAC; <http://cdiac.ess-dive.lbl.gov>).

2.3.1 Decoupling Elasticity

The decoupling elasticity theory was first proposed by Tapio (2005) for analyzing causal relationships among variables. Results can be divided into three statuses—connection, decoupling, and negative decoupling—corresponding to three threshold values (0.0, 0.8, and 1.2, respectively). These statuses can be further subdivided into eight categories: strong decoupling, weak decoupling, strong negative decoupling, weak negative decoupling, expansive negative decoupling, expansive connection, recessive decoupling, and recessive connection (Fig. 1 [Figure 1: see original paper]) using the following equation:

where ϵ is the decoupling elasticity indicator of CO₂ emissions and economic growth; ΔC and ΔG refer to changes in CO₂ emissions (t) and GDP growth (USD), respectively; and C and G are CO₂ emissions (t) and GDP (USD) in the baseline year (1992).

2.3.2 Kaya Identity

The Kaya identity was proposed by Kaya (1990) during the first IPCC seminar as a means of decomposing carbon emissions. It can be expressed as follows:

where C , P , G , and E refer to total energy-related CO₂ emissions (t), regional population, gross domestic product at constant 2010 prices (USD), and total end-use energy consumption (t), respectively; and j represents the year. The Kaya identity reveals CO₂ emission impact factors: P expresses population growth as a determinant of energy demand (i.e., population effect; unit: people), A refers to increased CO₂ emissions caused by per capita GDP growth (i.e., economic activity effect; unit: USD/person), I corresponds to energy consumption per

unit of GDP (i.e., energy intensity effect; unit: t/USD), and S describes CO emissions per unit of energy consumption (i.e., energy carbon structure effect).

2.3.3 LMDI Decomposition Method

The LMDI decomposition method includes additive and multiplicative versions with similar results. This paper applies the additive decomposition method, expressed by the following equations:

where C indicates the increment in total CO emissions (t) from year t to year 0; C and C represent CO emissions (t) in year t and the baseline year (1992); C , C_c , C_i , and C_s indicate changes in CO emissions (t) linked to population, economic activity, energy intensity, and energy carbon structure effects, respectively; w indicates the estimated weight; i represents the year; P , A , I , and S are population, economic activity, energy intensity, and energy carbon structure effects in the baseline year (1992), respectively; and P , A , I , and S are the corresponding effects in the i th year.

2.3.4 Decoupling Index

We applied a novel decoupling method to verify the relationship between economic growth and CO emissions in Central Asia based on additive LMDI results (Diakoulaki and Mandaraka, 2007; Vehmas et al., 2007). This approach's advantage is achieving decoupling targets for each factor rather than providing a rough, superficial relationship between economic growth and CO emissions (Wang et al., 2016). This method can identify which factors enhanced or curtailed CO emissions and to what extent. It can be expressed by the following equations:

where E represents the total inhibiting effect on CO emissions (t); D is the total decoupling index; and D_p , D_i , and D_s represent decoupling in population, energy intensity, and energy carbon structure in the i th year, respectively. D values can be ≥ 1 , between 0 and 1, or ≤ -1 , indicating strong, weak, or null decoupling, respectively.

3.1.1 CO Emissions Across Central Asia

We calculated change rates of total CO emissions and per capita CO emissions in Central Asia during 1992-2014 (Fig. 2 [Figure 2: see original paper]). Based on these trends, we subdivided the study period into two stages: 1992-1998 and 1999-2014.

During the first stage (1992-1998), total CO emissions and per capita CO emissions decreased (average annual growth rates of -6.35% and -7.09%, respectively). This decline resulted from the collapse of the Soviet Union in 1991 and the Asian financial crisis in 1998 (Rowland, 2001; Mao, 2014). Following independence, each Central Asian country's industrial sector lacked equipment and

production capacity, leading to considerable economic recession and population emigration, which reduced energy consumption and CO₂ emissions.

During the second stage (1999–2014), total CO₂ emissions and per capita CO₂ emissions increased (average annual growth rates of 2.90% and 1.44%, respectively). Notably, a substantial increase occurred during 1999–2008 following successful market economic reform implementation (Plyshevskii, 2014). However, this was followed by a sharp reduction during 2008–2009 due to the global financial crisis of September 2008 (Ruziev and Majidov, 2013). After this brief phase, Central Asian countries benefited from improvements in the international macroeconomic and financial environment, reflected by increased total and per capita CO₂ emissions from 2009 to 2011. Finally, during 2012–2014, carbon emissions were controlled and even slightly decreased due to environmental protection laws and regulations (Nepal et al., 2017).

Overall, total and per capita CO₂ emissions in Central Asia reflected the region's economic development. However, population growth after 1998 maintained per capita CO₂ emissions at relatively low levels.

3.1.2 CO Emissions in Each of the Five Central Asian Countries

Kazakhstan, Uzbekistan, and Turkmenistan rank among the top 100 countries worldwide for heavy CO₂ emissions (Dorian, 2006; González, 2015). CO₂ emissions in these three countries during 1992–2014 are shown in Figure 3 [Figure 3: see original paper]. These countries are rich in energy resources and rapidly developing industries using high-carbon energies (e.g., coal, oil, and natural gas; Dorian, 2006). In contrast, CO₂ emissions in Kyrgyzstan and Tajikistan changed only slightly during the study period, as these countries have relatively weak industrial bases and depend mainly on agricultural production for economic development (Tang and Chen, 2015).

3.2 Decoupling Elasticity Between CO Emissions and Economic Growth

We investigated the relationship between economic growth and CO₂ emissions using yearly decoupling elasticity data within the Tapio decoupling model framework (Table 1). We identified five decoupling statuses in Central Asia: strong decoupling, weak decoupling, recessive decoupling, expansive negative decoupling, and weak negative decoupling. Strong decoupling occurred mainly during 1996–1997 and 1999–2000, and in 2005, 2009, 2012, and 2014, when CO₂ emissions changed substantially while economic growth did not. Weak decoupling occurred during 2001–2004, 2006–2008, and 2010–2011, and in 2013, when economic growth prompted CO₂ emission increases but at lower rates than economic growth. Recessive decoupling occurred in 1993 and 1995 due to the Soviet Union collapse, as all Central Asian countries experienced unstable po-

litical and economic environments during early independence years, reducing industrial output and CO emissions.

3.3.1 LMDI Decomposition of CO Emissions in Central Asia

Decoupling elasticity results (Table 1) indicated significant environmental pressure from economic growth and CO emissions in Central Asia. Therefore, analyzing factors influencing CO emissions is necessary to achieve emission reduction targets.

We applied the additive LMDI method to decompose total CO emissions in Central Asia into four factors: population effect, economic activity effect, energy intensity effect, and energy carbon structure effect. The annual contribution percentage of each factor to total CO emissions is shown in Figure 4 [Figure 4: see original paper]. Among these, economic activity and population effects generally increased CO emissions. The economic activity effect contributed most to CO emissions (approximately 25.44×10^6 t; 39.08% contribution) during 1992–2014, while the population effect contributed about 76.80×10^6 t (11.80% contribution). Energy intensity and energy carbon structure effects primarily played inhibiting roles, reducing CO emissions. Specifically, the energy intensity effect was more significant, reducing CO emissions by approximately -291.78×10^6 t (-44.82% contribution) during 1992–2014. The energy carbon structure effect showed an inconsistent pattern, lowering CO emissions by about -28.09×10^6 t (-4.32% contribution).

Overall, cumulative changes in total CO emissions increased over time during 1992–2014, except during 1992–1998 (transition from planned to market economy) and 2008–2009 (global financial crisis onset). Total CO emissions increased by only 11.33×10^6 t by 2014 compared to the 1992 baseline, due to socioeconomic developments and energy use structure impacts in Central Asia during the study period.

3.3.2 LMDI Decomposition of CO Emissions in Each of the Five Central Asian Countries

We explored and compared contributions of influence factors to total CO emissions across the five Central Asian countries, as shown in Figures 5 and 6.

This analysis demonstrated that population and economic activity effects are the two driving factors of CO emissions during 1992–2014 in all countries. Economic activity effects in Kazakhstan, Turkmenistan, and Uzbekistan were particularly significant, leading to CO emission increments of 119.17×10^6 t (41.46% contribution), 50.07×10^6 t (52.69% contribution), and 85.55×10^6 t (32.91% contribution), respectively. Although Turkmenistan had lower CO emissions, its economic activity effect contributed most to these emissions. Due to considerable population growth during the study period, the population effect was

particularly high in Uzbekistan, increasing CO₂ emissions by 41.13×10^6 t.

The energy intensity effect was the main inhibiting factor for CO₂ emissions across all five Central Asian countries. Specifically, the largest CO₂ emission reductions occurred in Kazakhstan and Uzbekistan, with decreases of -139.74×10^6 and -121.48×10^6 t, respectively. However, larger inhibiting contribution percentages were recorded in Kyrgyzstan and Tajikistan, with values of -60.61% and -54.7% , respectively (total CO₂ emission reductions of -1.61×10^9 and -2.13×10^9 t). The energy intensity effect also had a relatively large inhibiting contribution in Kazakhstan (-48.62% contribution). The energy carbon structure effect generally played a minor role in total CO₂ emissions in Central Asia, tending to inhibit CO₂ emissions in all countries except Kyrgyzstan.

Overall, total CO₂ emissions during the study period decreased in Kazakhstan, Kyrgyzstan, Tajikistan, and Uzbekistan (by -13.73×10^9 , -1.61×10^9 , -2.13×10^9 , and -6.59×10^9 t, respectively), while increasing in Turkmenistan (by 35.39×10^9 t). Turkmenistan's special case might result from higher energy consumption and could have been favored by the lack of energy efficiency and conservation policies in this country (Dong et al., 2016).

3.4 Decoupling Index Based on the Additive LMDI Decomposition Results

We explored the relationship between CO₂ emissions and economic growth in Central Asia using a decoupling index based on additive LMDI decomposition results. This index's advantage is expressing detailed decoupling information for each influence factor, including population, energy intensity, and energy carbon structure.

Decoupling results (Table 2) included three statuses: strong decoupling, relative decoupling, and no decoupling. The total decoupling index indicated strong decoupling during 1996–1997 and 1999–2000, and in 2005, 2009, 2012, and 2014—consistent with decoupling elasticity results. Relative decoupling occurred in 1994, during 2001–2003, and in 2006, 2008, 2011, and 2013. All other years showed no decoupling. Overall, CO₂ emissions in Central Asia were strongly related to economic growth, except during a few years of strong decoupling resulting from social and financial crises.

Influence factors showed almost no decoupling regarding population, likely due to population growth. Moreover, energy carbon structure showed either no or only relative decoupling, suggesting suboptimal use and only slight degeneration over several years. Notably, energy intensity experienced strong decoupling during nine years (1996, 1997, 1999, 2000, 2001, 2005, 2009, 2012, and 2014), likely playing a critical role in reducing CO₂ emissions and promoting decoupling from economic growth. We therefore suggest that more advanced energy-use technologies are needed to improve energy efficiency.

4 Conclusions and Policy Implications

Energy-related CO₂ emissions in Central Asia decreased during 1992–1998 and increased during 1999–2014. CO₂ emissions were not completely decoupled from economic growth, with the main status corresponding to “weak decoupling.”

Economic activity and population effects were the primary driving factors of CO₂ emissions, with contribution percentages of 39.08% and 11.80%, respectively. Energy intensity and energy carbon structure effects were the main inhibiting factors, with contribution percentages of -44.82% and -4.32%, respectively.

Contribution percentages of each influence factor differed across the five Central Asian countries. Total CO₂ emission increments decreased in almost every country except Turkmenistan (which increased by 35.39×10^4 t during the study period). Kazakhstan, Turkmenistan, and Uzbekistan were the three main energy-consuming countries, with annual average CO₂ emissions of 189.69×10^4 , 45.54×10^4 , and 115.38×10^4 t, respectively. Kazakhstan has mainly relied on solid fuel consumption for economic development, while Turkmenistan and Uzbekistan have depended on gas fuel. Kyrgyzstan and Tajikistan have lower energy reserves and have developed their economies primarily through the primary sector.

To realize a low-carbon economy in Central Asia, we propose four key policy recommendations based on our results. First, industrial structure should be adjusted and economic development patterns transformed. Specifically, Central Asian countries need to reduce reliance on secondary industry and develop tertiary industries (e.g., tourism and other services). Additionally, emerging industries should be encouraged and international cooperation strengthened to achieve information industrialization and economic transformation. Second, energy should be utilized more efficiently and industrial enterprise supervision improved. Central Asian countries should acquire new emission reduction techniques (e.g., pollution treatment, waste disposal, cleaner production technologies). Simultaneously, high-pollution enterprises should bear greater responsibility through accountability and higher taxation. Third, renewable energy resources should be further developed and the energy utilization structure optimized. Central Asia possesses abundant renewable energy resources (e.g., wind, solar, hydro, and biomass) with outstanding exploitation potential. Central Asian countries can effectively replace traditional high-polluting energies by optimizing their utilization structure. Fourth, laws, regulations, and public awareness regarding environmental protection should be improved. Central Asian governments should advocate for “green consumption” through media and educational organizations, guiding and encouraging populations to use recycled and “green products” in daily life. Through these actions, Central Asia could reduce CO₂ emissions and build a resource-conserving, environment-friendly society.

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Note: Figure translations are in progress. See original paper for figures.

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