Front. Earth Sci. 2015, 9(1): 65–76
DOI 10.1007/s11707-014-0442-y

RESEARCH ARTICLE

Decomposition of energy-related carbon emissions in Xinjiang and relative mitigation policy recommendations

Changjian WANG (✉)[1,2], Xiaolei ZHANG (✉)[1], Fei WANG[1,2], Jun LEI[1], Li ZHANG[3]

1 State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography,
Chinese Academy of Sciences, Urumqi 830011, China
2 University of Chinese Academy of Sciences, Beijing 100049, China
3 Fujian Urban & Rural Planning Design Institute, Fuzhou 350003, China

Abstract Regional carbon emissions research is necessary and helpful for China in realizing reduction targets. The LMDI I (Logarithmic Mean Divisia Index I) technique based on an extended Kaya identity was conducted to uncover the main five driving forces for energy-related carbon emissions in Xinjiang, an important energy base in China. Decomposition results show that the affluence effect and the population effect are the two most important contributors to increased carbon emissions. The energy intensity effect had a positive influence on carbon emissions during the pre-reform period, and then became the dominant factor in curbing carbon emissions after 1978. The renewable energy penetration effect and the emission coefficient effect showed important negative but relatively minor effects on carbon emissions. Based on the local realities, a comprehensive suite of mitigation policies are raised by considering all of these influencing factors. Mitigation policies will need to significantly reduce energy intensity and pay more attention to the regional economic development path. Fossil fuel substitution should be considered seriously. Renewable energy should be increased in the energy mix. All of these policy recommendations, if implemented by the central and local government, should make great contributions to energy saving and emission reduction in Xinjiang.

Keywords carbon emissions, Xinjiang, index decomposition analysis, mitigation policy recommendations

1 Introduction

Carbon emissions are the main contributor to anthropogenic climate change (Friedlingstein et al., 2010). The reduction of greenhouse gases (GHG) has raised the awareness of policy makers and government managers around the whole world (Wang et al., 2012, 2013a, b). China has become the world's largest primary energy consumer and carbon emissions emitter after decades of rapid economic growth. Global efforts toward greenhouse gas control have made China feel more international pressure for carbon emissions reduction. Under such a circumstance, ahead of the Copenhagen Climate Change Summit in late 2009, China promised that national carbon dioxide emissions per unit of gross domestic product (GDP) in 2020 would decrease by 40%–45% compared with the 2005 level (Lu et al., 2013; Wang and Liang, 2013). Then, the Chinese government addressed reduction targets in the newly published 12th Five-Year Plan (2011–2015), namely, to reduce the carbon emissions intensity per unit GDP by 17% by 2015, as compared to the 2010 level (Liang and Zhang, 2011b). Meanwhile, China has set a national cap on total energy use, which aims to maintain total energy use at an equivalent to less than 4 billion tonnes of coal by 2015.

China has made great multiple efforts toward carbon emissions mitigation, and has achieved some obvious progress. A lot of researchers have found that economic growth has had a great positive effect on carbon emissions (Wu et al., 2005; Zhang et al., 2009a, b; Xu et al., 2012). Global industry transfer and international trades also have produced great effects on China's carbon emissions (Davis and Caldeira, 2010; Chen and Chen, 2011). China has also achieved a considerable decrease in carbon emissions, mainly due to energy intensity reduction and energy efficiency improvement (Wang et al., 2005; Guan et al., 2008, 2009; Steckel et al., 2011; Xia et al., 2011). Fossil fuel substitution (Ma and Stern, 2008; Zhao et al., 2010), industrial structure optimization (Wu et al., 2005; Liao et al., 2007; Liu et al., 2007; Liang et al., 2013), and

---

Received November 22, 2013; accepted January 14, 2014

E-mail: elephant1987.kevin@gmail.com (Changjian WANG), zhangxl@ms.xjb.ac.cn (Xiaolei ZHANG)

technology improvement (Larson et al., 2003; Glomsrød and Wei, 2005; Chen et al., 2011b; Liang and Zhang, 2011a) have also played important roles in carbon emissions control.

Since the 11th Five-Year Plan (2006–2010), several concrete "low carbon" policies have been enacted (Chen et al., 2011a; Liu et al., 2012), especially the "energy saving and emission reduction" strategy. However, these policies cannot be effectively and efficiently implemented without sufficient understanding of China's emissions status at the regional and sector level (Liu et al., 2012), as well as taking full account of resource endowment, development stage, industrial structure, technological level, human resources, etc. across the different regions in China. Due to provincial or regional diversity, several carbon emissions research projects have been performed at the regional level, such as Beijing (Chen et al., 2013; Tian et al., 2013; Wang et al., 2013c), Shanghai (Zhao et al., 2010), Macao (Li et al., 2013b), Xiamen (Lin et al., 2013), Jiangsu (Liang and Zhang, 2011b), Liaoning (Geng et al., 2013), etc. Some of these carbon emissions research studies paid great attention to carbon accounting of both direct and indirect emissions using input-output analysis (Chen and Zhang, 2010; Chen and Chen, 2011; Chen et al., 2013). These related regional carbon emissions studies and provincial "energy saving and emission reduction" implementation will make great contributions to the realization of China's low-carbon road map in the future. It will also help us to achieve carbon emissions reduction targets and to establish related policy with clear focus and effective operability.

The objectives of this case study in Xinjiang are to analyze energy-related carbon emissions, and to find the most important contributors to increased carbon emissions. Our estimates were based on provincial and national energy statistics. We analyzed the changes in the total carbon emissions and carbon emissions structure from 1952 to 2010. Then, the LMDI I technique based on an extended Kaya identity was applied in order to decompose carbon emissions, and the contribution rates of various factors in different stages were measured quantitatively. The rest of our study is organized as follows. In the next section, we present the method used to calculate the energy-related carbon emissions, and use the proposed complete decomposition approach to decompose carbon emissions over time. Section 3 addresses the data source. Section 4 presents the analysis of the Xinjiang case. The main results and discussion combined with some policy implications are reported in Section 5.

2 Methodology

2.1 Estimation of carbon emissions

Carbon emissions from energy consumption were calculated according to the following method given by the IPCC Guidelines for National Greenhouse Gas Inventories (Chen and Zhang, 2010; Liang and Zhang, 2011b; Geng et al., 2013). Carbon emissions factors and the conversion factor are as follows:

$$C_t = \sum_i E_t^i \times LCV_i \times CF_t^i \times O_i, \tag{1}$$

where the subscript i represents the various fuels in our study, t is the time in years, C_t is total carbon emissions per year t (in million tons, Mt), E_t^i is the total energy consumption of the fuel type i per year t (million tons of standard coal equivalent, Mtce). LCV_i represents the lower calorific value of fuel i. CF_t^i represents the carbon emissions factors of the fuel type i. O_i represents the oxidation rate of fuel i. The conversion factors, lower calorific value, fraction of carbon oxidized, and carbon emission factors of energy sources are listed in Table 1.

2.2 Analysis along Kaya factors

The decomposition of energy-related carbon emissions during the past several decades has been widely performed. Now two major decomposition techniques, index decomposing analysis (IDA) and structure decomposing analysis (SDA), have been widely used in order to find the factors driving the changes in carbon emissions. The SDA model is based on input-output tables, which present decompositions in quantitative economics on the sector scale (Rose and Casler, 1996). Therefore, time series input-output tables and sector energy use data should be collected for the SDA model (Ang et al., 1998; Casler and Rose, 1998; Lee and Lin, 2001). The SDA model uses information from input-output tables, while the IDA model uses aggregate data at the sector level (Hoekstra and van den Bergh, 2003). The IDA model has been applied successfully so far, because the advantage of IDA is that each model can be applied readily to any available data at any level of aggregation in a period-wise or time-series manner (Ma and Stern, 2008; Zhang et al., 2009a, b).

The Kaya identity expresses carbon emissions as a product of four underlying driving factors (Raupach et al., 2007; Mahony, 2013):

$$C = P \times \left(\frac{G}{P}\right) \times \left(\frac{E}{G}\right) \times \left(\frac{C}{E}\right), \tag{2}$$

where C is the total carbon dioxide emissions, P is the total population, G is gross domestic product (GDP), E is the total energy consumption; G/P is the per-capita GDP, E/G is the energy intensity of GDP and C/E is the carbon dioxide emissions coefficient of energy.

2.3 Extended Kaya-decomposition for carbon emissions

In order to get a better understanding of carbon emissions, an extended Kaya identity decomposition analysis

Table 1 Conversion factors, *LCV*, oxidation rate and carbon emission factors of energy sources

Energy sources	Conversion factors [a)]	*LCV* /($\mathrm{MJ \cdot t^{-1}}$ or $\mathrm{MJ \cdot m^{-3}}$) [b)]	Carbon emission factors/ ($\mathrm{t\ C \cdot (TJ)^{-1}}$) [c)]	Oxidation rate [c)]
Raw coal	0.7143 tce/t	20.908	25.80	0.918
Cleaned coal	0.9000 tce/t	26.344	27.68	0.918
Other washed coal	0.2857 tce/t	8.363	25.80	0.918
Coke	0.9714 tce/t	28.435	29.41	0.928
Crude oil	1.4286 tce/t	41.816	20.08	0.979
Gasoline	1.4714 tce/t	43.070	18.90	0.986
Kerosene	1.4714 tce/t	43.070	19.60	0.980
Diesel oil	1.4571 tce/t	42.652	20.17	0.982
Fuel oil	1.4286 tce/t	41.816	21.09	0.985
Other petroleum products	1.4286 tce/t	41.816	20.00	0.980
Nature gas	1.33 tce/10^3 $\mathrm{m^3}$	38.931	17.20	0.990
LPG	1.7143 tce/t	50.179	17.20	0.989
Refinery gas	1.5714 tce/t	46.055	18.20	0.989

a) Data resources: Liang and Zhang, 2011b; b) data resources: Geng et al., 2013; Xi et al., 2011; c) data resources: Geng et al., 2013.

approach has been widely applied in a number of open studies over time (Ma and Stern, 2008; Steckel et al., 2011; Mahony, 2013).

$$C = P \times \left(\frac{G}{P}\right) \times \left(\frac{E}{G}\right) \times \left(\frac{FE}{E}\right) \times \left(\frac{C}{FE}\right) = pgesf, \tag{3}$$

where *FE* is the total fossil energy consumption including coal, oil, and natural gas, and *C*, *P*, *G*, and *E* have the same definitions as in Eq. (2). In addition, *RE* is the total renewable energy consumption. *E* is the sum of *FE* and *RE*.

Within this scheme the variables are defined as follows: $p = P$, population; $g = G/P$, per-capita GDP; $e = E/G$, energy intensity of GDP; $s = FE/E$, share of fossil fuels in the total energy consumption; $f = C/FE$, carbon dioxide emissions coefficient of fossil energy.

Index decomposition analysis (IDA) conducted on an extended Kaya identity, is then applied as the method to decompose Eq. (3). Among various IDA methods, the logarithmic mean Divisia index technique was considered to be the preferred method (Ang et al., 2003; Ang, 2005). The Logarithmic Mean Divisia Index (LMDI I) was adopted due to its advantages for estimating each individual effect through formulations in terms of the weighted average logarithmic changes of the relevant variables (Ang and Liu, 2001; Ang et al., 2003; Ang, 2005). Some important publications were selected to explain the details of the LMDI I method (Ang et al., 1998; Ang and Liu, 2001; Ang et al., 2003; Ang, 2005).

From Eq. (3), the difference in the emission levels between two years can be further decomposed as:

$$\begin{aligned}\Delta C &= C_t - C_0 \\ &= \Delta C_{p-effect} + \Delta C_{g-effect} + \Delta C_{e-effect} \\ &\quad + \Delta C_{s-effect} + \Delta C_{f-effect},\end{aligned} \tag{4}$$

where ΔC is the change of carbon emissions between a base year 0 and a target year *t*, which can be further decomposed to five effects as follows: the population effect ($\Delta C_{p\text{–}effect}$), the affluence effect ($\Delta C_{g\text{–}effect}$), the energy intensity effect ($\Delta C_{e\text{–}effect}$), the renewable energy penetration effect ($\Delta C_{s\text{–}effect}$), and the emission coefficient effect ($\Delta C_{f\text{–}effect}$).

$$\Delta C_{p-effect} = \frac{C_t - C_0}{\ln C_t - \ln C_0} \ln\left(\frac{p_t}{p_0}\right), \tag{5}$$

$$\Delta C_{g-effect} = \frac{C_t - C_0}{\ln C_t - \ln C_0} \ln\left(\frac{g_t}{g_0}\right), \tag{6}$$

$$\Delta C_{e-effect} = \frac{C_t - C_0}{\ln C_t - \ln C_0} \ln\left(\frac{e_t}{e_0}\right), \tag{7}$$

$$\Delta C_{s-effect} = \frac{C_t - C_0}{\ln C_t - \ln C_0} \ln\left(\frac{s_t}{s_0}\right), \tag{8}$$

$$\Delta C_{f-effect} = \frac{C_t - C_0}{\ln C_t - \ln C_0} \ln\left(\frac{f_t}{f_0}\right). \tag{9}$$

3 Data management

Data resources, including the population, gross domestic product (GDP), and total energy consumption (*E*), covering the period from 1952 to 2010, were all available. Economic and population data were collected from various issues of the Xinjiang Statistical Yearbook, China Statistical Yearbook, and Xinjiang Fifty Years (1955–2005). Economic data was measured by GDP in million Chinese yuan in time series, taken in constant prices of 1952 to avoid the impact of the inflation. Energy data were collected from a series of Xinjiang Statistical Yearbooks, China Energy Statistical Yearbooks, and Xinjiang Fifty Years (1955–2005), which were compiled by the National Bureau of Statistics of China and the Xinjiang Statistical Bureau. Energy data includes total energy consumption by fuel types including renewable energy. Energy data used in our research consists of sub-fuel types aggregated as million tonnes of standard coal equivalent (Mtce) in calorific value.

4 Results of case analysis

4.1 Total energy consumption and energy consumption structure

Figure 1 shows the evolution of total energy consumption, including fossil energy and renewable energy, during the period 1952 to 2010. Total energy consumption has increased from 0.393 Mtce in 1952 to 82.902 Mtce in 2010, representing a 210.95-fold increase over these 59 years. A small energy consumption peak was apparent from 1958 to 1960, which was known as the "Great Leap Forward" period. Energy consumption increased rapidly from 3.001 Mtce in 1958 to 5.433 Mtce in 1960. Since then, energy consumption has increased stably, until 2000. "Western Development Strategy" was implemented after 2000, and total energy consumption increased rapidly from 33.160 Mtce in 2000 to 82.902 Mtce in 2010, representing an overall annual growth rate of 9.596%.

Figure 2 illustrates the shares by fuel in total energy consumption over 1952–2010, including fossil energy and renewable energy. Although the share of coal decreased over the whole research period, it still is the leading energy, and has accounted for more than 70% of total energy consumption before 1990, and more than 60% of total energy consumption until 2004. However, an obvious increasing trend occurred after 2005. Only coal and oil were in the energy mix in 1952, accounting for 82.1% and 17.9% of total energy consumption, respectively. The relatively low-carbon fossil fuel, natural gas, was invited into the energy mix in 1954, accounting for only 0.2% of

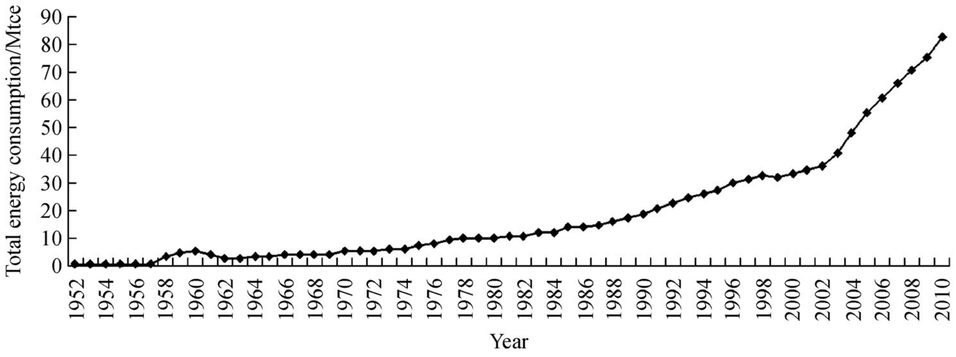

Fig. 1 Total energy consumption in million tonnes of coal equivalent (Mtce) in Xinjiang from 1952 to 2010.

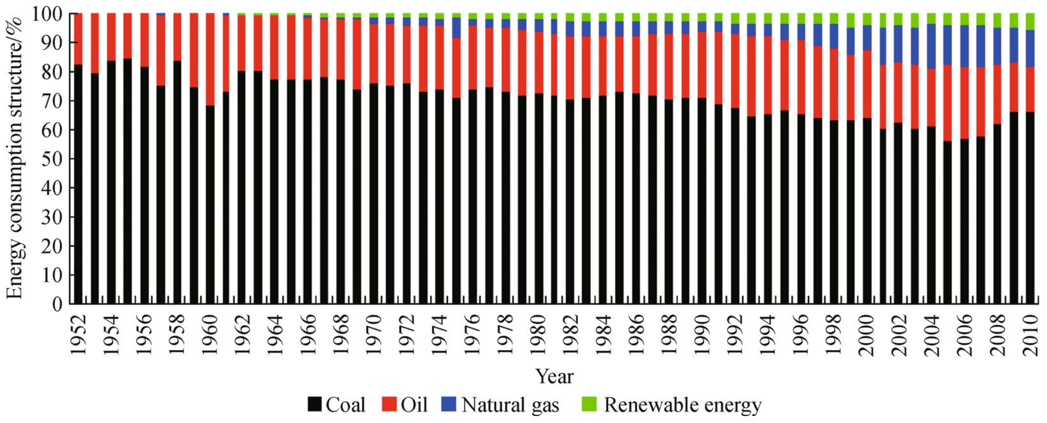

Fig. 2 Changes of energy consumption structure in Xinjiang from 1952 to 2010.

total energy consumption, and then its proportion reached 12.4% in 2010. Renewable energy, mostly consisting of hydro-power and wind power, has been utilized since 1957. Although demands for renewable energy sources have increased obviously, their relative contribution to total energy consumption is still small.

4.2 Carbon emissions evolution

Parallel to the total energy consumption, Figure 3 shows that energy-related carbon emissions in Xinjiang increased from 0.285 Mt in 1952 to 53.662 Mt in 2010, representing a 188.29-fold increase over these 59 years. From 1952 to 1957, the "First Five-Year Plan" period, carbon emissions increased rapidly, representing an overall annual growth rate of 15.67%, largely due to low energy efficiency in the early years of the new China. From 1958 to 1960, the "Great Leap Forward" period, carbon emissions increased dramatically, from 2.183 Mt in 1958 to 3.808 Mt in 1960. After that crazy period, carbon emissions increased slowly during the pre-reform period, representing an overall annual growth rate of 4.97% from 1961 to 1977. Especially during the traumatic "Cultural Revolution" (1966–1976), carbon emissions increased at a painfully slow speed and even decreased. After 1978, the post-reform period, carbon emissions increased rapidly along with economic growth from 6.747 Mt in 1978 to 21.746 Mt in 2000, representing an overall annual growth rate of 5.46%. From 2001 to 2010, "Western Development Strategy" was fully implemented. Rapid economic growth accelerated the increase of carbon emissions from 22.456 Mt in 2001 to 53.663 Mt in 2010 with the annual growth rate reaching 10.16%.

Using the same method, we also calculated the energy-related carbon emissions in China from 1952 to 2010. Figure 4 illustrates the relative contribution of Xinjiang's GDP and carbon emissions to China's total GDP and carbon emissions during the whole research period. It is interesting to find that changes in shares of GDP transformed nearly parallel to carbon emissions before 1990. But then Xinjiang's carbon emissions shares in China keep growing, but Xinjiang's GDP shares in China decrease obviously. Consequently, the most urgent need for Xinjiang will be to re-think the current economic growth mode and energy utilization pattern, in order to make an effective contribution to realize China's obligatory carbon dioxide emissions reduction target at the regional level.

Figure 5 shows that coal consumption is still the biggest contributor to total carbon emissions in Xinjiang. Carbon emissions shares from coal consumption decreased until

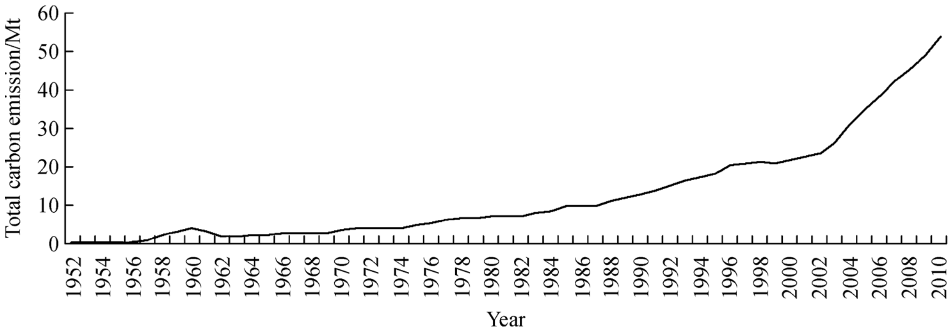

Fig. 3 Total carbon emissions in million tonnes of Xinjiang from 1952 to 2010.

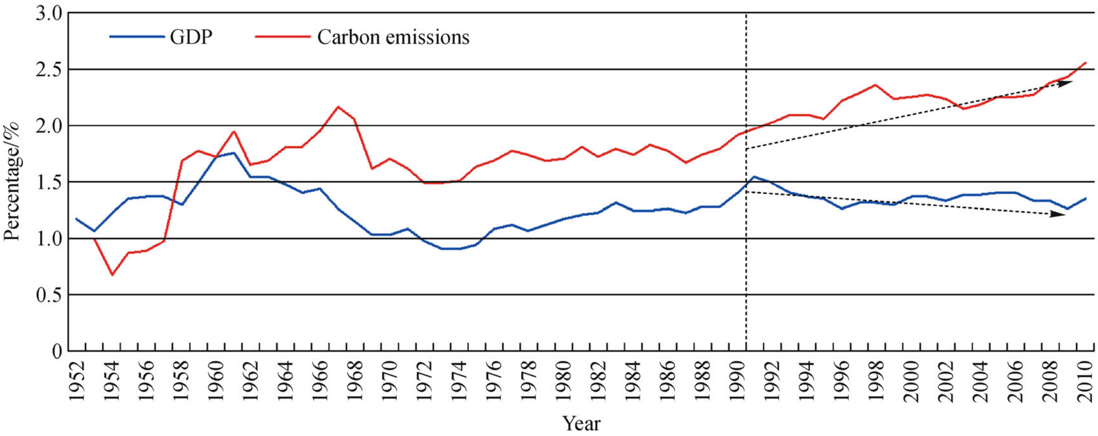

Fig. 4 Contributions of Xinjiang's GDP and carbon emissions to China from 1952 to 2010.

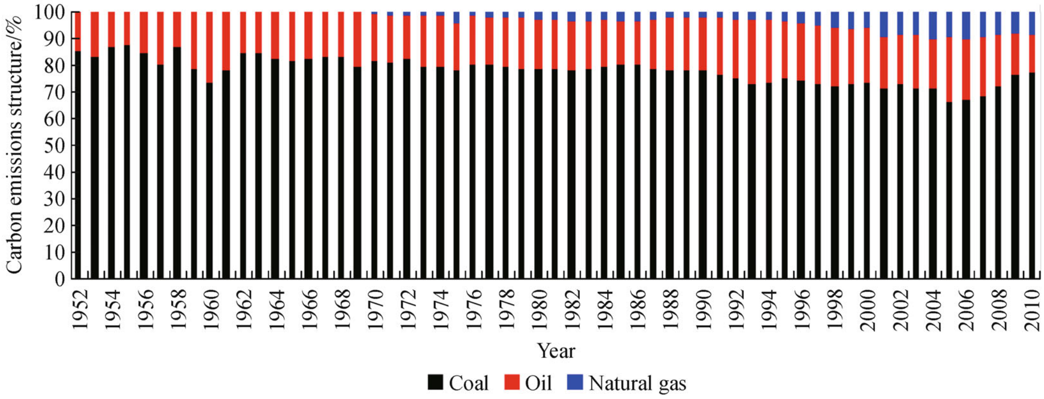

Fig. 5 Share changes of carbon emissions from the consumption of coal, oil, and natural gas from 1952 to 2010.

2004, but then it increased. Carbon emissions shares from natural gas increased steadily from 0.12% in 1954 to 8.66% in 2010.

4.3 Decomposition of carbon emissions

First we used the method, LMDI I based on an extended Kaya identity, presented in section 2 to decompose carbon dioxide emissions yearly. Yearly decomposition results are presented in Table 2.

In order to have the best understanding of influencing factors on carbon emissions in long time series, we divided the carbon emissions process into 6 stages, according to socio-economic development status and carbon emissions

Table 2 Complete decomposition of carbon emission change in million tones (1952–2010)

Year	*p-effect*	*g-effect*	*e-effect*	*s-effect*	*f-effect*	ΔC
1952–1953	0.0094	0.0344	0.0675	0.0000	–0.0021	**0.1093**
1953–1954	0.0155	0.0429	–0.1468	0.0000	0.0033	**–0.0850**
1954–1955	0.0086	0.0546	0.0722	0.0000	0.0004	**0.1359**
1955–1956	0.0207	0.0795	0.0269	0.0000	–0.0034	**0.1236**
1956–1957	0.0284	0.0050	0.0908	–0.0019	–0.0082	**0.1141**
1957–1958	0.0551	0.1462	1.2711	0.0026	0.0245	**1.4995**
1958–1959	0.2847	0.3173	0.4030	0.0000	–0.0578	**0.9471**
1959–1960	0.1935	0.3420	0.1945	0.0000	–0.0517	**0.6783**
1960–1961	0.1134	–1.3811	0.3311	–0.0067	0.0398	**–0.9035**
1961–1962	–0.0378	–0.3789	–0.5674	–0.0048	0.0427	**–0.9462**
1962–1963	0.0384	0.1977	–0.3130	–0.0039	0.0004	**–0.0804**
1963–1964	0.0857	0.2465	–0.0495	0.0000	–0.0120	**0.2706**
1964–1965	0.1344	0.2077	–0.0428	–0.0023	–0.0029	**0.2942**
1965–1966	0.1583	0.1796	0.0563	–0.0053	0.0022	**0.3911**
1966–1967	0.1116	–0.5515	0.4123	–0.0114	0.0066	**–0.0326**
1967–1968	0.1124	–0.4559	0.2186	–0.0028	–0.0028	**–0.1304**
1968–1969	0.0995	–0.0689	–0.1033	0.0000	–0.0227	**–0.0953**
1969–1970	0.1040	0.3630	0.4713	–0.0031	0.0074	**0.9426**
1970–1971	0.1239	0.3358	–0.1005	0.0038	–0.0089	**0.3540**
1971–1972	0.1495	–0.4194	0.2684	–0.0079	0.0066	**–0.0026**
1972–1973	0.1450	–0.0984	0.1157	0.0000	–0.0295	**0.1328**
1973–1974	0.1344	–0.0725	0.0363	–0.0041	0.0037	**0.0978**
1974–1975	0.1148	0.4173	0.4773	0.0093	–0.0662	**0.9524**
1975–1976	0.1401	0.5128	–0.3323	–0.0107	0.0756	**0.3856**
1976–1977	0.1135	0.5701	0.1915	–0.0060	0.0059	**0.8750**

(*Continued*)

Year	*p-effect*	*g-effect*	*e-effect*	*s-effect*	*f-effect*	Δ*C*
1977–1978	0.1285	0.3737	–0.0439	0.0000	–0.0243	**0.4340**
1978–1979	0.1243	0.6929	–0.8006	–0.0137	–0.0242	**–0.0213**
1979–1980	0.1476	0.6316	–0.4832	0.0000	–0.0062	**0.2898**
1980–1981	0.1096	0.5612	–0.3740	–0.0146	–0.0060	**0.2761**
1981–1982	0.0716	0.5972	–0.6030	–0.0224	–0.0308	**0.0125**
1982–1983	0.1007	1.2027	–0.5945	0.0000	0.0225	**0.7315**
1983–1984	0.0662	0.7794	–0.4750	–0.0084	0.0190	**0.3812**
1984–1985	0.1134	1.1999	–0.1619	0.0185	0.0093	**1.1792**
1985–1986	0.1590	0.5662	–0.5026	–0.0199	–0.0010	**0.2017**
1986–1987	0.1599	0.5486	–0.6153	–0.0304	0.0039	**0.0668**
1987–1988	0.1487	1.1489	–0.0147	0.0000	–0.0245	**1.2585**
1988–1989	0.2213	–0.6171	1.1406	–0.0119	0.0106	**0.7436**
1989–1990	0.6239	1.1737	–0.7072	0.0000	0.0044	**1.0948**
1990–1991	0.2217	2.1186	–1.3041	0.0277	–0.0745	**0.9894**
1991–1992	0.2418	1.2442	–0.1767	–0.0450	–0.0592	**1.2051**
1992–1993	0.2450	1.1721	0.1129	–0.0164	–0.1130	**1.4007**
1993–1994	0.2878	0.7592	–0.2201	–0.0176	0.0415	**0.8509**
1994–1995	0.3094	0.6344	–0.1780	–0.0184	0.0206	**0.7680**
1995–1996	0.3200	–0.0115	1.7952	0.0397	–0.0843	**2.0591**
1996–1997	0.3458	2.2195	–1.8630	–0.0636	–0.1806	**0.4581**
1997–1998	0.3555	1.0251	–0.6030	–0.0218	–0.0479	**0.7078**
1998–1999	0.3325	1.5412	–2.0698	–0.2433	0.0008	**–0.4386**
1999–2000	0.8768	2.8783	–3.0945	0.0672	0.0560	**0.7838**
2000–2001	0.3177	1.1216	–0.2686	–0.0695	–0.3910	**0.7102**
2001–2002	0.3520	1.9290	–1.4688	0.0482	0.1270	**0.9873**
2002–2003	0.3706	3.7018	–1.2243	–0.0779	–0.1348	**2.6355**
2003–2004	0.4254	3.8639	0.3494	0.2974	–0.1014	**4.8347**
2004–2005	0.7848	4.8416	–0.9903	–0.0344	–0.3324	**4.2693**
2005–2006	0.7195	4.3898	–1.6584	–0.1153	0.0252	**3.3609**
2006–2007	0.8785	2.9901	–0.4919	0.0421	0.1303	**3.5492**
2007–2008	0.7382	3.2343	–0.8040	–0.3211	0.5879	**3.4353**
2008–2009	0.6127	0.2001	2.1409	–0.1492	0.6528	**3.4573**
2009–2010	0.5365	8.9143	–4.4877	–0.2712	–0.0144	**4.6774**

change trend, combined with a certain historical background. A brief description of the six division stages is shown in Table 3. Results of the complete decomposition of carbon emissions are presented in Table 4 and Fig. 6.

Stage 1 (1952–1957): During the early years of the new China, Xinjiang's economic scale was small, accounting for 1.16% of China's total GDP during the same period, but grew fast, representing an annual growth rate of 15.45%. The "First Five-Year Plan" was implemented with the national development slogan-"take steel as the key link". Rapid economic growth was driven by a large amount of energy consumption due to low energy efficiency. Carbon emissions accounted for 0.88% of China's total carbon emissions during the same period, but grew rapidly, with an annual growth rate of 15.67%.

Decomposition results from Table 4 and Fig. 6 show that the affluence effect (*g-effect*) is the dominant positive effect in driving increases in carbon emissions over stage 1, bringing in a 0.244 Mt increase, accounting for 61.43% of the total changes (Δ*C*) in absolute value. The population effect (*p-effect*) and the energy intensity effect (*e-effect*) also had positive effects on carbon emissions, representing

Table 3 Brief description of six division stages

Stage	Historical backgrounds	Population growth rate per year/%	GDP growth rate per year/%	Carbon emissions growth rate per year/%	Carbon emissions per GDP growth rate per year/%	Carbon emissions per capita growth rate per year/%
Stage 1 (1952–1957)	First Five-Year Plan	3.71	15.45	15.67	5.25	14.84
Stage 2 (1958–1960)	Great Leap Forward	8.56	21.16	32.09	8.17	21.67
Stage 3 (1961–1977)	Cultural Revolution	3.38	4.89	4.97	1.69	1.54
Stage 4 (1978–1990)	Reform and Opening up	1.81	10.7	5.59	–10.96	3.71
Stage 5 (1991–2000)	Advantageous Resources Transformation Strategy	1.95	9.03	5.06	–11.22	3.05
Stage 6 (2001–2010)	Western Development	1.69	13.28	10.16	–4.80	9.33

Table 4 Complete decomposition of carbon emission changes in million tones in six stages

Stage	*p-effect*	*g-effect*	*e-effect*	*s-effect*	*f-effect*	ΔC
Stage 1 (1952–1957)	0.0829	0.2444	0.0790	–0.0014	–0.0070	0.3979
Stage 2 (1958–1960)	0.4798	0.6414	0.6121	0.0000	–0.1079	1.6254
Stage 3 (1961–1977)	2.3365	0.8093	0.3326	–0.0710	0.0014	3.4087
Stage 4 (1978–1990)	2.0490	9.5653	–5.2444	–0.1172	–0.0384	6.2143
Stage 5 (1991–2000)	3.0497	10.6074	–5.2116	–0.2918	–0.3588	7.7949
Stage 6 (2001–2010)	5.3981	34.4471	–8.9191	–0.3403	0.6209	31.2067

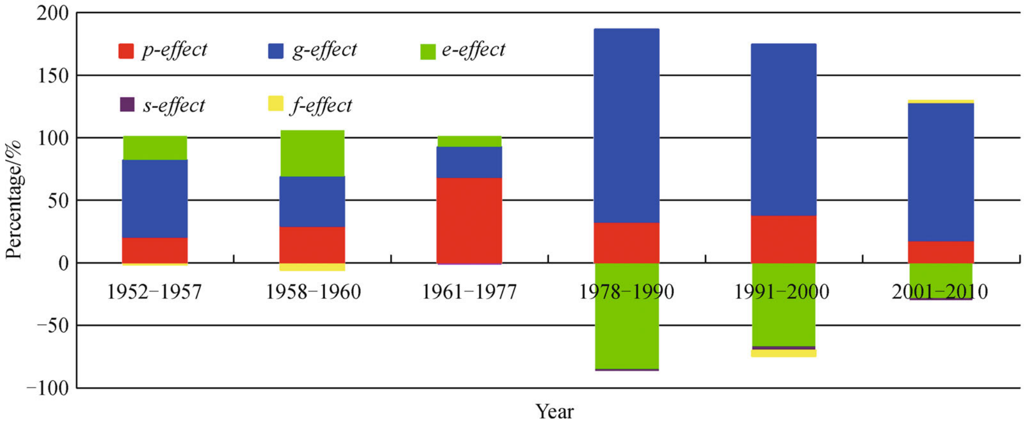

Fig. 6 The comparison of decomposition results for the six periods.

contribution rates of 20.83% and 19.86% in absolute value, respectively. The emission coefficient effect (*f-effect*) and the renewable energy penetration effect (*s-effect*) are important negative but relatively minor effects on carbon emissions, representing a decrease of 0.001 Mt and 0.007 Mt, respectively.

Stage 2 (1958–1960): During the special period known as the "Great Leap Forward", people all over the country shouted loudly with slogans such as "the whole nation and the whole party as a giant steel furnace", etc., in order to produce a large amount of steel. Outdated manufacturing techniques and low energy efficiency led to the unthinkable waste of resources and increased carbon emissions. Carbon emissions increased dramatically, and an annual growth rate reached 32.09%.

The affluence effect (*g-effect*) is still the dominant positive effect in driving carbon emissions, bringing about a 0.641 Mt increase. The energy intensity effect (*e-effect*) exceeded the population effect (*p-effect*), and became the second contributor to the increase of carbon emissions, bringing about a 0.612 Mt increase. The emission coefficient effect (*f-effect*) is the only negative effect on carbon emission, resulting in a 0.108 Mt decrease. The renewable energy penetration effect (*s-effect*) has no observable effect, because there is no transformation in the share of fossil fuels in total fuels.

Stage 3 (1961–1977): During the pre-reform period, economic growth speed was slow. Especially during the traumatic "Cultural Revolution" period (1966–1976), economic development was seriously affected. The annual growth rate of GDP and carbon emissions was 4.89% and 4.97%, respectively.

The population effect (*p-effect*) became the dominant positive effect in driving carbon emissions increases over this stage; a 2.337 Mt carbon emissions increase was attributable to population growth, accounting for 68.54% of the total changes (ΔC) in absolute value. The affluence effect (*g-effect*) is the second positive effect, resulting in a 0.809 Mt increase. The renewable energy penetration effect (*s-effect*) is the only important negative but still relatively minor effect on carbon emissions. The shares of renewable energy in total energy consumption increased from 0.3% in 1961 to 1.9% in 1977, representing a decrease of 0.071 Mt carbon emissions.

Stage 4 (1978–1990): During this special and important period after 1978, China fully carried out "reform and opening up" policy. The economic development mode was transformed from a planned economy to a market oriented economy. Xinjiang's economic development resumed rapid growth, representing an overall annual growth rate of 10.70%. Compared with the rapid economic growth, synchronized high-speed growth has not appeared in terms of carbon emissions increase, representing an overall annual growth rate of 5.59%, the most important reason is that energy consumption intensity decreased after 1978.

The affluence effect (*g-effect*) is the dominant positive effect in driving carbon emissions increase, bringing in a 9.565 Mt increase, accounting for 153.92% of the total changes (ΔC) in absolute value. A great discovery was found during this stage, the energy intensity effect (*e-effect*) changed from positive to negative. The energy intensity effect plays a most important role in curbing carbon emissions growth, resulting in a 5.244 Mt decrease, accounting for 84.39% of the total changes (ΔC) in absolute value. The renewable energy penetration effect (*s-effect*) and the emission coefficient effect (*f-effect*) also play important negative but relatively minor effects on carbon emissions.

Stage 5 (1991–2000): After more than ten years of reform and opening up, Xinjiang began to pay more attention to its own economic development strategy. The "Advantageous resources transformation" strategy was introduced into Xinjiang's "Eighth Five-Year Plan", in order to open the "new-type industrialization" process, optimize energy consumption structure, and improve energy efficiency. Carbon emissions per unit GDP decreased rapidly, representing an overall annual decrease rate of 11.22%.

The scale effects consisting of the affluence effect (*g-effect*) and the population effect (*p-effect*) are still the dominant positive drivers in Xinjiang. The energy intensity effect (*e-effect*) still plays the most important role in curbing carbon emissions growth. The emission coefficient effect (*f-effect*) and the renewable energy penetration effect (*s-effect*) have relatively minor negative effects on carbon emissions, but their contribution rates increased obviously, accounting for 4.60% and 3.74% of the total changes (ΔC) in absolute value, respectively.

Stage 6 (2001–2010): In January 2000, the State Council set up a leading group for western development. The "Western Development Strategy" was fully implemented in order to comprehensively improve social and economic development in Xinjiang. In order to speed up economic growth, energy-intensive sectors, mostly consisting of power generation, the coal chemical industry, and the petro-chemical industry, etc., were largely expanded based on their own abundant mineral resources. Economic development grew fast with a high annual growth rate of 13.28%. Meanwhile, the shares of heavy industry increased from 74.64% in 2001 to 86.34% in 2010. Consequently, carbon emissions increased dramatically along with the rapid economic growth, representing an overall annual growth rate of 10.16%.

The affluence effect (*g-effect*) is the dominant positive effect in driving carbon emissions increase over stage 6, accounting for 110.38% of the total changes (ΔC) in absolute value. The energy intensity effect (*e-effect*) plays a most important role in curbing carbon emissions growth. Unfortunately, a relatively minor negative effect attributed to the emission coefficient effect (*f-effect*) has disappeared, and it has a slightly positive effect on carbon emissions, resulting in a 0.621 Mt decrease, accounting for 1.99% of the total changes (ΔC) in absolute value. The shares of the second industry in the total economic output increased from 38.5% in 2001 to 47.7% in 2010. The shares of coal in total energy consumption did not constantly decrease, and even increased until reaching 65.8% in 2010. The adjustment of industrial structure and energy consumption structure failed to curb carbon emissions during this stage.

5 Concluding remarks and policy recommendations

5.1 Concluding remarks

A complete decomposition analysis, the LMDI I technique based on an extended Kaya identity, has been conducted in order to analyze the main factors influencing the changes in energy-related carbon emissions in Xinjiang during the long-time period from 1952 to 2010. This method includes a measure of the population effect, the affluence effect, the energy intensity effect, the renewable energy penetration effect, and the emission coefficient effect in six different divided stages. The main conclusions drawn from the current research may be summarized as follows:

1) The affluence effect and the population effect are the two most important contributors to the increased carbon emissions during the whole research period. However, their contributions are different in the special development period. The population effect is largely dwarfed by the affluence effect during the last three stages, owing to the rapid economic growth and the "family planning policy" controlling population growth after 1978.

2) The energy intensity effect had a positive effect on carbon emissions during the first three stages before 1978, largely due to low energy efficiency and outdated manufacturing technique technologies. After the "reform and opening up", the energy intensity effect assumed the dominant role in curbing carbon emissions until now.

3) The renewable energy penetration effect and the emission coefficient effect have important negative but relatively minor effects on carbon emissions. The relatively minor effect of renewable energy penetration is largely attributed to the still small shares of renewable energy, less than 6% of total energy consumption. The emission coefficient effect plays a minor role in curbing carbon emissions, because the coal-dominated energy consumption structure has not been changed fundamentally. Even the emission coefficient effect plays a slightly positive effect on carbon emissions during the nearest stage, largely due to increased coal shares in total energy consumption.

5.2 Policy recommendations

As for Xinjiang, a western less developed area in China, how to slow down carbon emissions without jeopardizing social-economic development is a big dilemma faced by the local government at present. Another dilemma faced by Xinjiang is that of how to improve its economic role in China, and to make an effective contribution to the realization of China's obligatory carbon mitigation targets in 2020 at regional levels.

The affluence effect resulted from economic development, which will keep growing and also speed up in the future. In view of its dominant positive effect in driving carbon emissions, economic development modes should be re-thought and transformed by upgrading economic structure. Emerging low carbon industries, energy saving, and environmental protection industries should be paid more attention during the process of economic structure adjustment.

The energy intensity effect should be paid more attention. Although energy intensity continued to decrease after 1978, there is still much potential for it to decline further compared to the national average level. Production processes and the energy efficiency of energy intensive sectors should be improved, especially the power generation industry, the coal chemical industry, and heating in winter.

Considering the emission coefficient effect, fossil fuel substitution should be transformed from high-carbon coal to relatively low-carbon oil and natural gas. Although Xinjiang has abundant oil and natural gas resources, these resources are mainly allocated and controlled by state-owned companies, such as Petro China and Sinopec. Consequently, coal will be easily selected as the main fuel to drive its rapid economic growth because of the rich coal resources and the lower coal price in Xinjiang. Unfortunately, resource tax reform in Xinjiang merely on oil and gas without taking full account of the coal-dominated energy consumption structure, not only cannot change the unreasonable energy consumption structure, but also further exacerbates it. Current reforms on oil and gas have no contribution to carbon emissions reduction, even leading to higher energy intensities (Zhang et al., 2013).

Another important thing is that we cannot ignore the abundant renewable energy in Xinjiang, especially wind power and solar PV energy (Li et al., 2013a; Ma et al., 2013). Wind power not only has considerable economic benefit in Xinjiang, but also has co-benefits, such as the mitigation of carbon emissions and air pollutant emissions (SO_2, NO_X and $PM_{2.5}$), and conservation of water resources (Ma et al., 2013). The shares of renewable energy in total energy consumption should be increased obviously and effectively.

Solving these problems effectively will be of great help for Xinjiang in harmonizing economic growth and carbon emissions reduction, even environmental damage reduction.

Acknowledgements The authors would like to thank the anonymous reviewers for their thoughtful, insightful, and constructive comments. The current work is supported by the Western Action Plan Project of the Chinese Academy of Sciences (KZCX2-XB3-01).

References

Ang B W (2005). The LMDI approach to decomposition analysis: a practical guide. Energy Policy, 33(7): 867–871

Ang B W, Liu F L (2001). A new energy decomposition method: perfect in decomposition and consistent in aggregation. Energy, 26(6): 537–548

Ang B W, Liu F L, Chew E P (2003). Perfect decomposition techniques in energy and environmental analysis. Energy Policy, 31(14): 1561–1566

Ang B W, Zhang F Q, Choi K H (1998). Factorizing changes in energy and environmental indicators through decomposition. Energy, 23(6): 489–495

Casler S, Rose A (1998). Carbon dioxide emissions in the U.S. economy: a structural decomposition analysis. Environ Resour Econ, 11(3/4): 349–363

Chen G Q, Guo S, Shao L, Li J S, Chen Z M (2013). Three-scale input-output modeling for urban economy: carbon emission by Beijing 2007. Commun Nonlinear Sci Numer Simul, 18(9): 2493–2506

Chen G Q, Shao L, Chen Z M, Li Z, Zhang B, Chen H, Wu Z (2011a). Low-carbon assessment for ecological wastewater treatment by a constructed wetland in Beijing. Ecol Eng, 37(4): 622–628

Chen G Q, Zhang B (2010). Greenhouse gas emissions in China 2007: inventory and input-output analysis. Energy Policy, 38(10): 6180–6193

Chen Q, Kang C, Xia Q, Guan D (2011b). Preliminary exploration on low-carbon technology roadmap of China's power sector. Energy, 36 (3): 1500–1512

Chen Z M, Chen G Q (2011). Embodied carbon dioxide emission at supra-national scale: a coalition analysis for G7, BRIC, and the rest of the world. Energy Policy, 39(5): 2899–2909

Davis S J, Caldeira K (2010). Consumption-based accounting of CO_2 emissions. Proc Natl Acad Sci USA, 107(12): 5687–5692

Friedlingstein P, Houghton R A, Marland G, Hackler J, Boden T A, Conway T J, Canadell J G, Raupach M R, Ciais P, Le Quéré C (2010). Update on CO_2 emissions. Nat Geosci, 3(12): 811–812

Geng Y, Zhao H, Liu Z, Xue B, Fujita T, Xi F (2013). Exploring driving factors of energy-related CO_2 emissions in Chinese provinces: a case of Liaoning. Energy Policy, 60: 820–826

Glomsrød S, Wei T Y (2005). Coal cleaning: a viable strategy for reduced carbon emissions and improved environment in China? Energy Policy, 33(4): 525–542

Guan D, Hubacek K, Weber C L, Peters G P, Reiner D M (2008). The drivers of Chinese CO_2 emissions from 1980 to 2030. Glob Environ Change, 18(4): 626–634

Guan D, Peters G P, Weber C L, Hubacek K (2009). Journey to world top emitter—An analysis of the driving forces of China's recent CO_2 emissions surge. Geophys Res Lett, 36(4): L04709

Hoekstra R, van den Bergh J C J M (2003). Comparing structural decomposition analysis and index. Energy Econ, 25(1): 39–64

Larson E D, Wu Z X, DeLaquil P, Chen W Y, Gao P F (2003). Future implications of China's energy-technology choices. Energy Policy, 31(12): 1189–1204

Lee C F, Lin S J (2001). Structural decomposition of CO_2 emissions from Taiwan's petrochemical industries. Energy Policy, 29(3): 237–244

Li C, Ge X, Zheng Y, Xu C, Ren Y, Song C, Yang C (2013a). Techno-economic feasibility study of autonomous hybrid wind/PV/battery power system for a household in Urumqi, China. Energy, 55: 263–272

Li J S, Chen G Q, Lai T M, Ahmad B, Chen Z M, Shao L, Ji X (2013b). Embodied greenhouse gas emission by Macao. Energy Policy, 59: 819–833

Liang S, Xu M, Suh S, Tan R R (2013). Unintended environmental consequences and co-benefits of economic restructuring. Environ Sci Technol, 47(22): 12894–12902

Liang S, Zhang T (2011a). Interactions of energy technology development and new energy exploitation with water technology development in China. Energy, 36(12): 6960–6966

Liang S, Zhang T (2011b). What is driving CO_2 emissions in a typical manufacturing center of South China? The case of Jiangsu Province. Energy Policy, 39(11): 7078–7083

Liao H, Fan Y, Wei Y M (2007). What induced China's energy intensity to fluctuate: 1997–2006? Energy Policy, 35(9): 4640–4649

Lin J, Liu Y, Meng F, Cui S, Xu L (2013). Using hybrid method to evaluate carbon footprint of Xiamen City, China. Energy Policy, 58: 220–227

Liu L C, Fan Y, Wu G, Wei Y M (2007). Using LMDI method to analyzed the change of China's industrial CO_2 emissions from final fuel use: an empirical analysis. Energy Policy, 35(11): 5892–5900

Liu Z, Geng Y, Lindner S, Guan D (2012). Uncovering China's greenhouse gas emission from regional and sectoral perspectives. Energy, 45(1): 1059–1068

Lu Y, Stegman A, Cai Y (2013). Emissions intensity targeting: from China's 12th Five Year Plan to its Copenhagen commitment. Energy Policy, 61: 1164–1177

Ma C, Stern D I (2008). Biomass and China's carbon emissions: a missing piece of carbon decomposition. Energy Policy, 36(7): 2517–2526

Ma Z, Xue B, Geng Y, Ren W, Fujita T, Zhang Z, Puppim de Oliveira J A, Jacques D A, Xi F (2013). Co-benefits analysis on climate change and environmental effects of wind-power: a case study from Xinjiang, China. Renew Energy, 57: 35–42

Mahony T O (2013). Decomposition of Ireland's carbon emissions from 1990 to 2010: an extended Kaya identity. Energy Policy, 59: 573–581

Raupach M R, Marland G, Ciais P, Le Quéré C, Canadell J G, Klepper G, Field C B (2007). Global and regional drivers of accelerating CO_2 emissions. Proc Natl Acad Sci USA, 104(24): 10288–10293

Rose A, Casler S (1996). Input-output structural decomposition analysis: a critical appraisal. Econ Syst Res, 8(1): 33–62

Steckel J C, Jakob M, Marschinski R, Luderer G (2011). From carbonization to decarbonization? Past trends and future scenarios for China's CO_2 emissions. Energy Policy, 39(6): 3443–3455

Tian X, Chang M, Tanikawa H, Shi F, Imura H (2013). Structural decomposition analysis of the carbonization process in Beijing: a regional explanation of rapid increasing carbon dioxide emission in China. Energy Policy, 53: 279–286

Wang C, Chen J N, Zou J (2005). Decomposition of energy-related CO_2 emission in China: 1957–2000. Energy, 30(1): 73–83

Wang C, Wang F, Li L, Zhang X (2013a). Wake-up call for China to re-evaluate its shale-gas ambition. Environ Sci Technol, 47(21): 11920–11921

Wang C, Wang F, Wang Q, Yang D, Li L, Zhang X (2013b). Preparing for Myanmar's environment-friendly reform. Environ Sci Policy, 25: 229–233

Wang C, Wang Q, Wang F (2012). Is Vietnam ready for nuclear power? Environ Sci Technol, 46(10): 5269–5270

Wang Y, Liang S (2013). Carbon dioxide mitigation target of China in 2020 and key economic sectors. Energy Policy, 58: 90–96

Wang Y, Zhao H, Li L, Liu Z, Liang S (2013c). Carbon dioxide emission drivers for a typical metropolis using input-output structural decomposition analysis. Energy Policy, 58: 312–318

Wu L B, Kaneko S, Matsuoka S (2005). Driving forces behind the stagnancy of China's energy-related CO_2 emissions from 1996 to 1999: the relative importance of structural change, intensity change and scale change. Energy Policy, 33(3): 319–335

Xi F, Geng Y, Chen X, Zhang Y, Wang X, Xue B, Dong H, Liu Z, Ren W, Fujita T, Zhu Q (2011). Contributing to local policy making on GHG emission reduction through inventorying and attribution: a case study of Shenyang, China. Energy Policy, 39(10): 5999–6010

Xia X H, Huang G T, Chen G Q, Zhang B, Chen Z M, Yang Q (2011). Energy security, efficiency and carbon emission of Chinese industry. Energy Policy, 39(6): 3520–3528

Xu J H, Fleiter T, Eichhammer W, Fan Y (2012). Energy consumption and CO_2 emissions in China's cement industry: a perspective from LMDI decomposition analysis. Energy Policy, 50: 821–832

Zhang M, Mu H, Ning Y (2009a). Accounting for energy-related CO_2 emission in China, 1991–2006. Energy Policy, 37(3): 767–773

Zhang M, Mu H, Ning Y, Song Y (2009b). Decomposition of energy-related CO_2 emission over 1991–2006 in China. Ecol Econ, 68(7): 2122–2128

Zhang Z, Guo J, Qian D, Xue Y, Cai L (2013). Effects and mechanism of influence of China's resource tax reform: a regional perspective. Energy Econ, 36: 676–685

Zhao M, Tan L, Zhang W, Ji M, Liu Y, Yu L (2010). Decomposing the influencing factors of industrial carbon emissions in Shanghai using the LMDI method. Energy, 35(6): 2505–2510