Energy 259 (2022) 124948

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

China's energy consumption and economic activity at the regional level

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ARTICLE INFO

Keywords:
China
Economic development
Energy consumption
Decomposition analysis
Regional value chains

ABSTRACT

Since 2013, China's economy has undergone a series of major structural changes under the new normal. This study aimed to research China's plateauing regional-level energy consumption at this stage by analysing socioeconomic factors driving energy consumption changes from 2002 to 2019 through decomposition analysis and regional value chains. The results indicate that the annual growth rate of China's energy consumption dropped from 10% between 2002 and 2013 to 2% between 2013 and 2019, mainly attributable to energy efficiency enhancement offsetting the −27% increase from 2013 to 2019 and structural changes. At the regional level, the three structural drivers were closely related, including the regional structure, industrial structure and energy structure. Under the new normal, the −2.58% contribution of the regional structure to energy consumption growth was mainly made by regions with a high energy efficiency; one way to improve the energy efficiency was to upgrade the regional industrial structure, leading to the slowdown by 0.26%; and industrial transition could be accompanied by adjustment of the energy structure towards relatively clean energy, thereby offsetting growth by −0.13%. The energy consumption required to create value-added outflows along regional value chains varied greatly across regions, sectors and years.

1. Introduction

Energy consumption, which is closely related to economic activity, plays an important role in climate change [1]. Fossil fuel energy consumption currently still dominates, supporting economic development and affecting other economic variables [2]. A pioneering study on the relationship between economic growth and energy consumption found a one-way causal relationship [3]. Studies have indicated that the relationship between energy consumption and economic growth can be divided into four types, including no causal relationship, referred to as the "neutrality hypothesis", a two-way causal relationship, referred to as the "feedback hypothesis", a one-way energy consumption causal relationship with economic growth, referred to as the "growth hypothesis", and a one-way economic growth causal relationship with energy consumption, referred to as the "energy saving hypothesis". In fact, the relationship between energy consumption and economic development is relatively complex on different time scales and among various regional samples [4]. Empirical research covering 119 countries over the past 30 years has demonstrated that the above four types of causal relationships exist in different countries, with 36 countries matching the neutrality hypothesis, 18 countries matching the feedback hypothesis, 25 countries matching the growth hypothesis and 40 countries matching the energy saving hypothesis [5]. The Granger causality test is a widely accepted method to analyse causality [6,7]. The above one-way causality relationship from energy consumption to economic growth could result in an energy-dependent economy [8]. In contrast, if the causality relationship were directed from economic growth to energy consumption [9], environmental regulation implementation, such as energy conservation policies, could hardly restrict economic growth [10]. However, the driving force of economic growth acting on energy consumption is weakening, and a growing body of recent evidence has suggested decoupling. For example, the different sectors and industries of the

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https://doi.org/10.1016/j.energy.2022.124948
Received 20 October 2021; Received in revised form 20 April 2022; Accepted 24 July 2022
Available online 6 August 2022

Chinese economy yield different contributions to this decoupling process [11].

In particular, a high energy consumption exerts great pressure on the energy supply and security, which poses great challenges to environmental governance and climate change in China [12]. Therefore, a notable importance of energy consumption has been attached to sustainable development involving both the economy and environment. At the national level, China has made contributions to the adoption and mitigation of climate change through energy conservation, aiming to attain 16% and 15% decreases in the energy intensity during the Twelfth Five-Year Plan (FYP) period (2011–2015) and Thirteenth FYP period (2016–2020), respectively. In the recent Fourteenth FYP, higher goals were proposed to further reduce the energy consumption per unit GDP by 13.5% and increase the share of non-fossil energy to primary energy to 20%, aligned with the Paris Agreement. At the regional level, provinces have also incorporated total energy consumption control into energy development goals. These policy targets may limit energy consumption to a certain extent [13,14] by targeting the rapid final energy consumption attributed to rapid economic development [15].

To date, existing studies on this topic, namely, how energy consumption and economic activity interact, have not derived a general conclusion [16]. Empirically such a relationship is influenced by the location, time, method and other various factors. In the long run, it has been found that energy consumption trends are closely related to the stage of economic development, while economic growth is usually accompanied by a surge in energy consumption at the early stage of industrialisation with a gradual shift to the service industry upon industrial upgrading [17,18]. Different countries or the different stages of a country's development show different empirical results, which can be classified and compared according to specific stages [19].

However, at present, research on China's energy consumption at the regional level focusing on the new normal stage is relatively limited. Since China's economic development has entered the new normal stage, from high-speed growth to high-quality development, its energy consumption pattern has also changed. Existing studies have analysed China's energy consumption and driving factors under the new normal at the national level, thereby analysing drivers of industrial structure upgrading, energy efficiency improvement and energy structure adjustment [15]. At the regional level, one of the key factors in energy conservation policy formulation entails profound analysis and a comprehensive understanding of the regional economic activity to fully release the potential of regional energy conservation and consumption reduction. Results of the study of the rationality of the energy consumption structure in Chinese provinces have indicated that there exists an energy shortage problem in the eastern regions and a serious energy redundancy problem in the western regions [20]. Analysis through a dynamic panel data econometric model revealed that before the new normal stage, in the case of dramatic energy consumption growth driven by various factors, the industrial structure in 29 provinces in China was gradually shifted from overcapacity heavy industries to technology- and knowledge-intensive industries from 2001 to 2012 [21]. Due to the interrelated effects of regional driving factors, various factors at the regional level should be integrated into the same framework for more comprehensive discussions and enlightening policy implications.

From the value-added perspective, in addition to mere industries, much research has focused on China's carbon emissions along global value chains (GVCs). However, research on value chain analysis at the regional level is limited. The number of growing and transitioning GVCs is closely related to the global energy consumption and carbon emissions [22]. Theoretical [23,24] and empirical studies [25–27] have examined the emission relationship. The role of China in carbon emissions as traced in the global production and trade network among different economies and sectors has been fully explored [28]. Abundant tools and methods have been applied, for example, by using decomposition analysis (DA) to estimate the carbon emission intensity embodied in domestic and foreign demands [29], by further adopting the multi-region structural decomposition analysis technique to quantify the GVC-related intensity from both production and consumption perspectives [30], by employing the GVC position index proposed by Koopman et al. [31] to promote the degree of GVC embedment for energy efficiency optimisation and carbon emission reduction [32], and by researching carbon emissions along GVCs reduced by the intensity effect driven by the labour productivity effect and job creation from a labour market dynamics perspective [33]. At the industrial level, the position of China's industries within GVCs has been measured, revealing a positive feedback loop between the GVC position and environmental efficiency [21], where the rising value chain of the manufacturing industry contributes to energy conservation and emission reduction [34]. Energy consumption along regional value chains (RVCs) remains to be further explored, especially in areas that can achieve coordination and deployment within a certain range, such as the US, the EU and China.

In this study, through a combination of decomposition analysis and RVCs, changes in China's regional energy consumption driven by economic activity from 2002 to 2019 were estimated and analysed, focusing on the characteristics of energy consumption related to economic structure transition under the new normal. This paper aimed to research whether gains in energy efficiency can continue to offset regional energy consumption and whether changes in structural factors can exert a downward pressure on regional energy consumption growth at this stage. To provide theoretical insights and empirical implications, this study focused on the new normal stage at the regional level. The energy efficiency, regional structure, industrial structure and energy structure are closely related, which plays an important role in driving force synergy under the new normal. This study further analysed energy consumption along RVCs, which remains to be explored. By exploring RVCs as an advanced version of the input–output (IO) methodology and application in energy analysis, this paper endeavoured to determine how to mutually benefit regional energy consumption and economic development within the framework of domestic circulation.

Thus, this study bridged research gaps in the following three ways: first, this paper focused on the new normal stage at the regional level, expanding findings in the time and space dimensions to provide practical policy implications. Analysis of regional driving forces at the critical stage has indicated that China has systematically designed appropriate energy consumption paths to achieve a sustainable transition. It is of great significance for China to learn from the new normal stage to achieve a sustainable transition and development while reducing energy consumption and addressing environmental issues. Second, the relationship among various structural factors was explored, examining how these factors are correlated and interact to promote regional synergy. Specifically, energy efficiency is an important precondition of the regional structure; the industrial structure is one way to improve the energy efficiency; and the energy structure is closely related to the industrial structure. Third, energy consumption along RVCs still remains to be explored and analysed at the regional level, although China's overall position and role in GVCs has been fully estimated and described at the national level. The paths to high-value-added but low-energy-consumption domestic trade patterns vary among regions, which was clarified in this research.

The remainder of this paper is structured as follows: Section 2 briefly introduces the method and data. The driving factors of changes in energy consumption and regional value chains are analysed in Section 3. Findings with potential policy implications are outlined in detail in Section 4. Section 5 concludes this paper.

2. Method and data

2.1. Decomposition analysis of regional energy consumption and value chains

In decomposition analysis of regional energy consumption, both structural decomposition analysis (SDA) [21] and index decomposition analysis (IDA) [35,36] are used as robustness checks. Based on the IO model, SDA has been widely used in the field of energy and environmental economy to assess the drivers of changes in energy consumption in countries or regions [37,38], which has been further extended to the drivers of changes in greenhouse gas emissions attributed to energy consumption [39]. With the rapid growth of China's energy consumption, an increasing number of studies have focused on the driving factors of China's energy consumption changes [15]. The Logarithmic mean Divisia index (LMDI), as an IDA method with relatively simple data and operations [40], has also been widely used in analysis of the drivers of energy consumption changes [9] in particular regions [41,42] and industries [43,44] in China.

At the national level, the direct and indirect contributions of socio-economic drivers to energy consumption can be estimated and compared through IO-based SDA to quantify the correlation among industries in the national economic system. The classical equation proposed by Wassily Leontief [45] is as follows:

$$X = LY = (I - A)^{-1} Y \tag{1}$$

where X denotes the total output by sectors; Y denotes the matrix of final use, including household and government consumption, fixed capital formation and inventory increase, and exports; L denotes the Leontief inverse matrix calculated as $(I\text{-}A)^{-1}$, with the identity matrix expressed as I; and the coefficient matrix describing intersectoral economic exchanges can be expressed as A [45].

Environmentally-extended input-output analysis (EEIOA), in this study, was applied to quantify the direct and indirect energy consumption in the various industrial sectors, estimated as follows:

$$E = FLY = F(I - A)^{-1} Y \tag{2}$$

where E denotes the final energy consumption by sectors; and F denotes the energy intensity vector calculated by the energy consumption per unit output, representing the energy efficiency [46].

At the national level, this study mainly considered five driving factors, including population, production structure, energy efficiency, consumption volume per capita and consumption patterns. Based on the structure of IO tables, the change in national energy consumption (ΔE) between years t and (t-1) could be decomposed. The decomposition equation is as follows:

$$\Delta E = \Delta P L F Y_v Y_p + P \Delta L F Y_v Y_p + P L \Delta F Y_v Y_p + P L F \Delta Y_v Y_p + P L F Y_v \Delta Y_p \tag{3}$$

where ΔE denotes changes in energy consumption in China; P denotes the national population; L denotes the Leontief inverse matrix in Equation (1); F denotes the energy efficiency measured by the energy intensity; Y_v denotes the consumption volume per capita measured by the final use per unit population (i.e., the GDP per capita); and Y_p denotes the various consumption patterns represented by the final use. Each term in Equation (3) represents the contribution of a given factor to emissions with the other factors maintained unchanged by using the average of all possible first-order decompositions to calculate weights ($5! = 120$).

At the regional level, the LMDI can be used to decompose the impact of the energy mix, industrial structure, regional structure, energy efficiency, economic growth and population on energy consumption by adopting the logarithmic average as the weight. The regional final energy consumption E^t can be decomposed as follows:

$$\begin{aligned} E^t &= \sum_i \sum_j \sum_k \frac{E_{ijk}}{E_{jk}} \times \frac{E_{jk}}{E_k} \times \frac{E_k}{G_k} \times \frac{G_k}{G} \times \frac{G}{P} \times P \\ &= \sum_i \sum_j \sum_k m_{ijk} \times s_{jk} \times e_k \times r_k \times g \times p \end{aligned} \tag{4}$$

where E_{ijk} denotes the energy consumption of energy type i in sector j of province k; G_k denotes the GDP of province k; and P denotes the population. According to Equation (4), E^t can be decomposed into the following six factors: (1) $m = E_{ijk}/E_{jk}$ denotes the proportion of energy type i in sector j and reflects the energy mix; (2) $s = E_{jk}/E_k$ denotes the proportion of the energy consumption of sector j in the total energy consumption and reflects the industrial structure of energy consumption; (3) $e = E_k/G_k$ denotes the energy intensity in province k measured by the energy consumption per unit output and reflects the energy efficiency; (4) $r = G_k/G$ denotes the regional structure represented by the GDP share of provinces in the national GDP; (5) $g = G/P$ denotes the economic growth expressed as the GDP per capita; and (6) p denotes the population.

$L(w_{ijk}^t, w_{ijk}^{t-1})$ is defined as the logarithmic average weight, calculated as follows:

$$L\left(w_{ijk}^t, w_{ijk}^{t-1}\right) = \left(E_{ijk}^t - E_{ijk}^{t-1}\right) \Big/ \left(\ln\left(E_{ijk}^t\right) - \ln\left(E_{ijk}^{t-1}\right)\right) \tag{5}$$

Therefore, the change in energy consumption ΔE^t in year t, compared to year t-1, can be calculated as follows:

$$\begin{aligned} \Delta E^t = &\sum_i \sum_j \sum_k L\left(w_{ijk}^t, w_{ijk}^{t-1}\right) \ln\left(p^t/p^{t-1}\right) + \sum_i \sum_j \sum_k L\left(w_{ijk}^t, w_{ijk}^{t-1}\right) \ln\left(g^t/g^{t-1}\right) \\ &+ \sum_i \sum_j \sum_k L\left(w_{ijk}^t, w_{ijk}^{t-1}\right) \ln\left(r^t/r^{t-1}\right) + \sum_i \sum_j \sum_k L\left(w_{ijk}^t, w_{ijk}^{t-1}\right) \ln\left(e^t/e^{t-1}\right) \\ &+ \sum_i \sum_j \sum_k L\left(w_{ijk}^t, w_{ijk}^{t-1}\right) \ln\left(s^t/s^{t-1}\right) + \sum_i \sum_j \sum_k L\left(w_{ijk}^t, w_{ijk}^{t-1}\right) \ln\left(m^t/m^{t-1}\right) \\ &= \Delta E_p + \Delta E_g + \Delta E_r + \Delta E_e + \Delta E_s + \Delta E_m \end{aligned} \tag{6}$$

where ΔE_p, ΔE_g ΔE_r, ΔE_e, ΔE_s and ΔE_m are changes in energy consumption caused by the population, economic growth, regional structure, energy efficiency, industrial structure and energy mix, respectively.

In decomposition analysis of regional value chains, value-added outflows to other regions among RVCs can be calculated as follows:

$$\begin{aligned} \mu O_d &= \left(V_d L_{dd} + \sum_{b \neq d}^{K} V_b L_{bd}\right) O_d \\ &= \left(V_d L_{dd} + \sum_{b \neq d}^{K} V_b L_{bd}\right) \sum_{d \neq b}^{K} (A_{db} X_b + Y_{db}) \\ &= V_d \sum_{d \neq b}^{K} L_{dd} A_{db} X_b + V_d \sum_{d \neq b}^{K} L_{dd} Y_{db} + \sum_{d \neq b}^{K} \sum_{b \neq d}^{K} V_b L_{bd} A_{db} X_b + \sum_{d \neq b}^{K} \sum_{b \neq d}^{K} V_b L_{bd} Y_{db} \end{aligned} \tag{7}$$

where O denotes the total outflows of the various sectors, including intermediate and final goods produced for other regions; V denotes the diagonal matrix of value-added coefficients; and the total of VL equals the unit matrix, expressed as μ. In terms of subscripts, d indicates a local province; b indicates a non-local province other than d, thus not equalling d; and K indicates the sum of the provinces as other regions.

2.2. Data sources

This study mainly used the following officially realised datasets: final energy consumption at the national and provincial levels was retrieved from national and provincial energy statistical yearbooks collected in the CEADs database [47]. Cross-sectional data for each year included 20 energy types (Table S2) and 47 social and economic sectors (Table S3), while energy consumption data at the provincial level in physical quantity was converted into the standard quantity of tons of standard coal (tce) based on corresponding unit conversion coefficients (Table S4). National and provincial GDP and population data were obtained from the National Bureau of Statistics of China (NBSC) [48]. Based on the price index, China's single-region input–output (SRIO) tables published by the NBSC (for 2002, 2005, 2007, 2010, 2012, 2015 and 2017) together with China's multi-region input–output (MRIO) tables provided by the CEADs database (for 2012, 2015 and 2017) were converted into the constant price in 2017.

In this paper, the provincial data included 30 provinces except Tibet, Hong Kong, Macao and Taiwan, divided into eight regions (Table S5), including[1] Beijing-Tianjin, North, Northeast, Central Coast, Central, Southern Coast, Southwest, and Northwest.

3. Results

3.1. Driving factors of the changes in China's energy consumption

At the national level, China's energy consumption is rising year by year, but there has occurred a recent slowdown in the growth rate. Choosing 2002 as the base year, the period from 2002 to 2019 could be divided into three stages (Fig. 1a). At the first stage of rapid industrialisation (2002–2007), the total energy consumption increased by 83%. At the second stage of the global financial crisis (2007–2013), the growth rate further increased by 88%. At the third stage of the new normal (2013–2019), the overall growth rate of energy consumption decelerated and gradually plateaued, especially after 2015, with a slight increase of 29% from 210% to 239% in 2019 (Table S6).

By using SDA, the contributions of five driving factors to China's energy consumption were analysed, including economic growth (i.e., consumption volume per capita), population, energy efficiency (i.e., energy intensity measured by the energy consumption per unit output) [46], consumption structure and production structure (Fig. 1a). In addition, through the LMDI, changes in energy consumption attributed to six socioeconomic factors were estimated, similarly covering economic growth, population and energy efficiency (Fig. 1b). Factors related to the structure included the regional structure, industrial structure and energy structure (Fig. 1c).

According to SDA (Fig. 1a), economic growth was the most important cause of energy consumption increase, contributing as much as 141% in 2017 and 175% in 2019 (Table S6). At present, it remains difficult to decouple economic development from energy consumption dominated by fossil fuels and to vigorously develop renewable resources due to technological limitations, especially in the short term. The population is a relatively stable driving factor, leading to a slight increase in energy consumption from 2002 to 2019 at an annual growth rate of 1%. However, the driver that continuously offsets the increase in China's energy consumption is the energy efficiency measured by the energy consumption per unit output, especially at the second and third stages from 2007, with the largest reduction (−88%) in 2015. Under the new normal, supply-side policies promote a gradual reduction in energy consumption per unit GDP by supporting technological progress and eliminating the backward production capacity. Assessed via LMDI, the findings on the contributions of the aforementioned three factors to energy consumption changes are robust (Fig. 1b).

In addition to energy efficiency, structure-related factors contributed to decelerating China's energy consumption growth. Through SDA, it was found that the contributions of the production structure and consumption structure to the increase in energy consumption were less than those of economic growth (Fig. 1a). Despite fluctuations attributed to the ways of accounting for IO tables among the different statistical years, the annual driving rate due to the production structure was 3% on average during the 2002–2019 period. Another structural factor driving the slowdown in energy consumption growth is the consumption structure. The change caused by the consumption structure gradually plateaued at the second and third stages and basically remained stable from 43% to 47% since 2010. The proportions of the energy consumption induced by rural consumption, government consumption and investment (i.e., capital formation & inventory) plateaued at approximately 5%, 7% and 47%, respectively, since 2010. Simultaneously, during the 2007–2019 phases, the main component of energy consumption caused by the final demand gradually shifted from export to urban consumption. The export-induced proportion decreased from 33% to 22%, while that of urban consumption increased from 16% to 19%.

The driving factors related to structure, decomposed via LMDI, included the regional structure, industrial structure and energy structure (Fig. 1c). These three factors revealed favourable trends of their contributions to energy consumption growth deceleration under the new normal (2013–2019), although the changes driven by these factors accounted for relatively lower proportions than that of the energy efficiency. First, the trend of energy consumption changes, caused by the regional structure, began to decline since 2013 from −1%, reaching the lowest value of −8% in 2019. By fully utilising comparative advantages, well-developed regions maintained their advantages in value-added creation with the same energy consumption, while less-developed regions focused on the transition in production capacity by strictly controlling energy-intensive projects with policy support. Second, during the last decade, the industrial structure became another crucial driver offsetting energy consumption growth, ranging from −1% to 1%. Third, the contribution of the energy structure to the increase in energy consumption tended to plateau under the new normal, fluctuating between 3% and 5%.

3.2. Efficiency gains at the regional level

The offset in China's energy consumption could be mainly attributed to gains in energy efficiency, measured by the energy intensity (i.e., energy consumption per unit GDP), at the regional level.

From 2007 to 2019, the contributions of energy efficiency in the eight regions all reduced the energy consumption level at the various stages by −32% (2007–2013) and −27% (2013–2019), caused by gains in energy efficiency at the regional level (Fig. 2a), where the eight regions could be divided into two groups. The first group included the Southwest and the Northwest, whose energy efficiency further contributed to energy consumption reduction after 2013 from −4.92% and −0.98% to −5.79% and −1.53%, respectively. The above energy efficiency improvement was closely related to technological progress; for example, high-tech process innovation, such as the software outsourcing industry in Sichuan province could result in energy system efficiency. Hence, Sichuan in the Southwest, contributed the second highest energy consumption offset (−2.29%) between 2013 and 2019 under the new normal. Compared to the 2007–2013 stage, the second group contributed less when calculating the relative percentage by choosing 2013 and 2007 as the base years for the 2013–2019 stage, while energy consumption was still reduced, including the Central (−7.90%), Central coast (−3.70%), North (−3.12%), South coast (−2.71%), Northeast (−1.40%) and Beijing-Tianjin (−0.92%). The Central, Central coast, South coast and Beijing-Tianjin, as four relatively well-developed regions, could drive energy efficiency improvement via innovative and high-quality development, thus leading to energy consumption reduction. By selecting Guangdong in the South coast as an example, its energy reduction contribution (−1.68%) ranked third in China. Regarding the other two regions, their energy-use efficiency per unit was greatly improved due to steady progress in the elimination of redundant production capacity. The changes in energy intensity in the four relatively underdeveloped regions, including the Southwest, the Northwest, the North and the Northeast, are analysed in detail below.

According to the change in energy intensity in each province in further detailed analysis, from 2007 to 2019, all five provinces in the

[1] Eight regions: Beijing-Tianjin region; North region including Hebei and Shandong; Northeast region including Liaoning, Jilin and Heilongjiang; Central Coast region including Shanghai, Jiangsu and Zhejiang; Central region including Shanxi, Anhui, Jiangxi, Henan, Hubei and Hunan; Southern Coast region including Fujian, Guangdong and Hainan; Southwest region including Guangxi, Guizhou, Chongqing, Sichuan and Yunnan; and Northwest region including Inner Mongolia, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang.

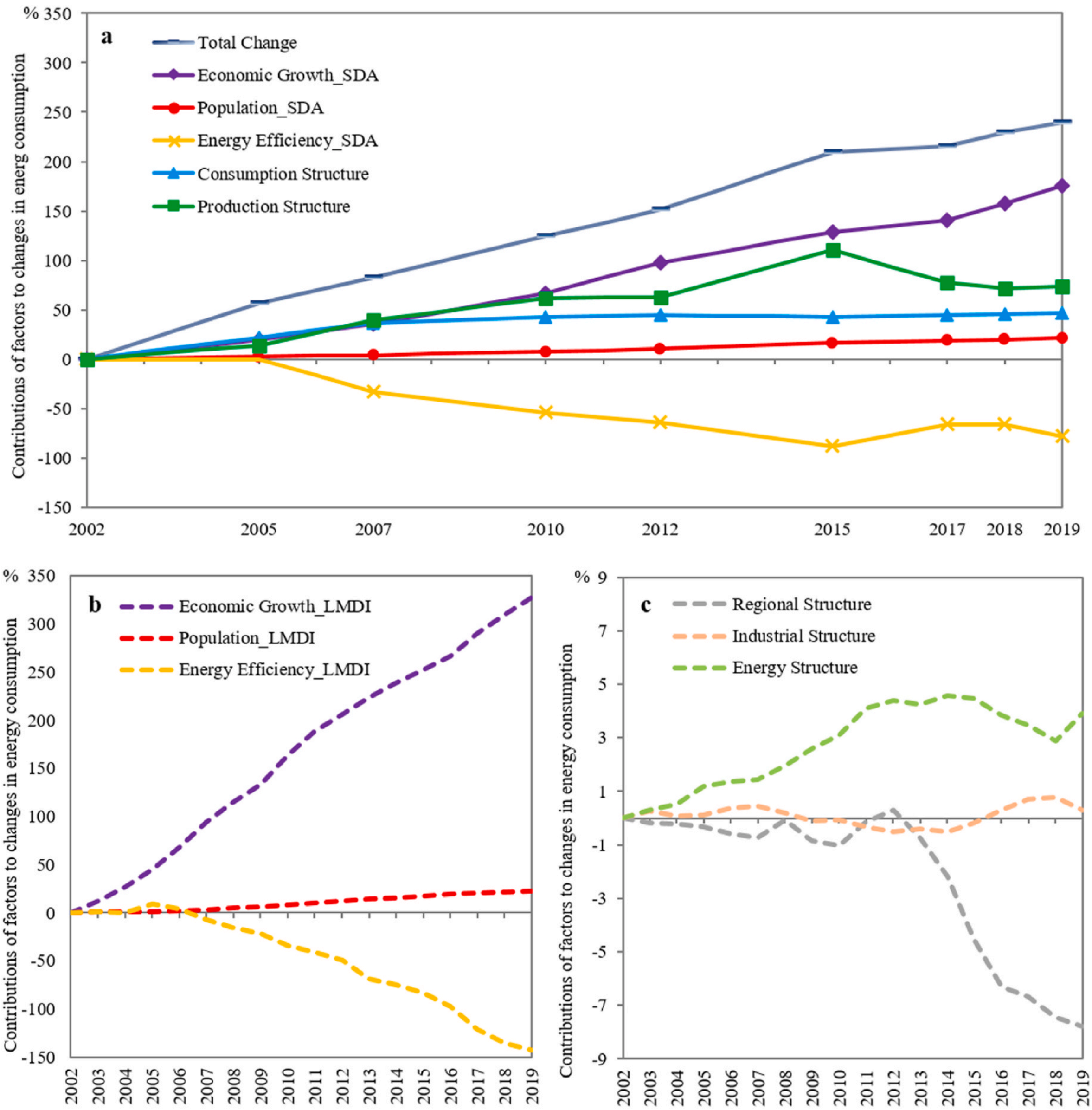

Fig. 1. Driving factors of China's national energy consumption from 2002 to 2019. (a) Contributions of the five driving factors to the percentage changes in energy consumption, decomposed via SDA; (b) contributions of economic growth, population and energy efficiency to the percentage changes in energy consumption, decomposed via LMDI; (c) contributions of structure-related factors to the percentage changes in energy consumption, decomposed via LMDI.

Southwest indicated dramatic downward trends (Fig. 2b). The reason why the five southwest provinces could significantly reduce their energy intensity and achieve energy efficiency improvement is closely related to the fact that each province actively explored its own development model and reasonably planned its development path based on its comparative advantages. The reduction in energy intensity in Guizhou, for example, attributed to digitalisation to improve its energy utilisation efficiency, was the largest among the southwest provinces, with a 66% drop from 1.13 to 0.39 between 2007 and 2019. Digital informatisation, via strong support for cloud computing and rapid development of big data, could promote energy system transformation by actively promoting innovating development and upgrading through technological transformation. In addition, perhaps attributed to the development of the service industry, especially tourism-related industries, the trends and changes in energy intensity in Chongqing (−58%), Yunnan (−49%), Sichuan (−45%) and Guangxi (−39%) were similar, while the energy intensity in Yunnan was relatively higher than that in the other three provinces, affected by their different endowments.

In addition to the Southwest, the energy intensity in the six provinces in the Northwest also decreased to different extents (Fig. 2c). From 2007 to 2019, the energy intensity in Xinjiang (−2%), Ningxia (−5%), Qinghai (−5%) and Inner Mongolia (−7%) slightly decreased by less than 10%, while that in Gansu (−37%) and Shaanxi (−41%) decreased dramatically. The general trend of the energy intensity in Shaanxi province was similar to that in Sichuan province, decreasing from 0.53 to 0.31 and from 0.50 to 0.27, respectively. These two provinces, as key development highlands in Northwest and Southwest China, attracted investment to support high-tech industries with similarities in catering, entertainment and tourism. The abovementioned provinces in the Southwest and Northwest are all inland areas and contain relatively abundant energy resources, including both clean energy and fossil fuels, where the energy intensity exhibited larger reductions at the 2007–2013 stage than those at the 2013–2019 stage by exploring new drivers of economic development.

Compared to the two western regions, as major provinces of traditional manufacturing, the energy intensity in the two northern

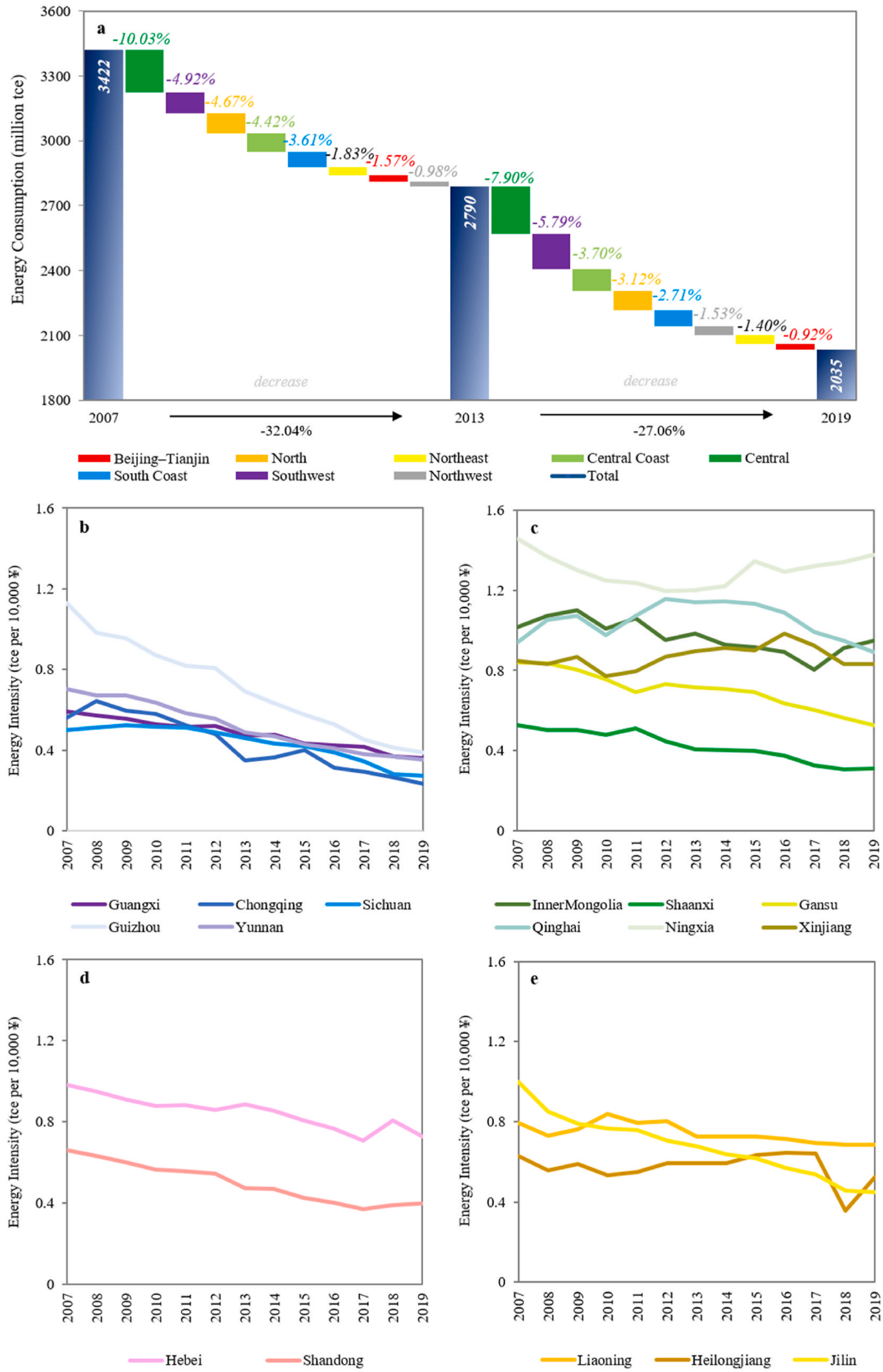

Fig. 2. Changes in China's regional energy consumption caused by gains in energy efficiency from 2007 to 2019. (a) Region-specific contributions of the energy efficiency to changes in energy consumption from 2007 to 2013 and 2013–2019, with the length of the bars reflecting the contribution of each region; (b) trends of the energy intensity in the Southwest from 2007 to 2019; (c) trends of the energy intensity in the Northwest from 2007 to 2019; (d) trends of the energy intensity in the North from 2007 to 2019; (e) trends of the energy intensity in the Northeast from 2007 to 2019.

provinces, Hebei and Shandong, decreased by 26% and 40%, respectively, from 2007 to 2019 (Fig. 2d). Under the new normal, supply-side policies in the North were effectively implemented by strengthening the supervision of energy conservation in key regions and major industrial energy units. Specifically, Hebei promoted the green transformation of manufacturing industries by building a network information platform covering key enterprises in the province and servicing whole-process monitoring of their energy management. By cultivating the market and innovation mechanism, Shandong strictly controlled the increment and optimised the stock. However, the energy intensity in the Northeast (except Jilin) slightly decreased, with that in Liaoning and Heilongjiang dropping by −14% and −17%, respectively (Fig. 2e). Despite similar geographical conditions, the energy efficiency in the North and the Northeast diverged, where the Northeast could learn from the North regarding the detailed policy strength and administrative efficiency.

3.3. Structural changes at the regional level

Attributed to changes in regional development patterns, the regional structure (−2.58%), industrial structure (0.26%) and energy structure (−0.13%) contributed to the slowdown in the growth of energy consumption under the new normal.

In general, China's energy consumption rapidly rose from 1024 million tce in 2002–3111 million tce in 2019, while the growth rate decelerated from 10% (2002–2013) to 2% (2013–2019) with a slight increase of 320 million tce at the third stage (Fig. 3a). From the perspective of the eight regions, this slowdown in growth was similar to the overall national trend.

In terms of the regional structure, high-energy-consuming less-developed regions contributed to a reduction in energy consumption under the new normal, while regions with high economic growth exhibited a certain increase in energy consumption at this stage (Fig. 3b). In relatively well-developed provinces with a high energy efficiency, the increase in the GDP share had limited impact on the energy consumption increment. In contrast, provinces with a relatively low energy efficiency should first adjust their current model of high energy consumption, during which the transition process could shadow their economic growth rate, thus resulting in a relative decrease in the proportion of the corresponding GDP share in the total GDP of China and a subsequent decrease in energy consumption. Specifically, due to adjustment of the regional structure, the energy consumption in the Northeast, North, Northwest, Beijing-Tianjin and Central coast decreased by −2.61%, −1.81%, −0.41%, −0.23% and −0.04%, respectively, whereby Liaoning contributed the largest energy consumption reduction in China (−1.20%). However, the Central, South coast and Southwest, which developed at a relatively high growth rate. In recent years, energy consumption has slightly increased by 0.49%, 0.63% and 1.40%, respectively, among which that in the Southwest was driven by Guizhou, ranking first in China (0.56%), followed by Fujian (0.39%) in South coast and Hubei (0.32%) in Central.

The energy consumption changes of eleven industries also indicated a trend of energy consumption growth slowdown (Fig. 3c). As a pillar industry of the national economy, the annual growth rate of the agriculture sector remained relatively stable, from a 4% growth rate between 2002 and 2013 to a 1% growth rate between 2013 and 2019 under the new normal. The annual growth rates of traditional manufacturing industries, including light industry, chemicals, metal and non-metal products, decreased by approximately 8% at the latter stage below the level at the previous stage. At the new normal stage, the annual growth rates of energy consumption of the other services (4%) and equipment (2%) sectors together with their increasing shares in the total energy consumption (both approximately 1%) possibly indicated that energy consumption increasingly shifted from traditional manufacturing to high-tech equipment and service industries with the upgrading of the industrial structure. Energy consumption in the mining and energy sectors, two sectors closely related to energy consumption, largely decreased from 9% to −3% and from 7% to 1%, respectively, under the new normal.

From the perspective of the industrial structure, the overall industrial structure resulted in a slight increase in energy consumption at the new normal stage. Although regions have transferred and upgraded to high-tech and tertiary industries under the new normal, the total effect of industrial restructuring on energy consumption is also affected by the added value and energy use (Fig. 3d). It is ideal to transfer from industries with a high energy consumption but a low added value to those with a low energy consumption but a high added value. Specifically, the areas where industrial structure upgrading could reduce energy consumption included the Central coast (−0.05%) and Central (−0.01%), choosing Jiangsu province in the Central coast with the second largest contribution (−0.04%) as an example. Its energy consumption in the light industry sector and chemicals sector exhibited declines of −1.50 million tce and −2.91 million tce, respectively, while the energy consumption in the equipment sector and other services sector increased by 0.16 million tce and 1.36 million tce, respectively. Industrial upgrading could reduce energy consumption, while energy consumption could be differentiated at the high end of the value chain. The energy consumption in the other six regions, including the Northeast, Southern coast, Northwest, North, Beijing-Tianjin, and Southwest, slightly increased by 0.01%, 0.01%, 0.02%, 0.06%, 0.09% and 0.13%, respectively. For example, there was an overall increase in energy consumption in Chongqing province (0.09%) in the Southwest, who, which vigorously developed tourism during its industrial upgrading process, with increases in the transport sector (0.52 million tce) and wholesale, retail, and catering sector (1.00 million tce).

The energy mix, including six types of energy, indicated a trend of deceleration similar to that of the total energy consumption (Fig. 3e). The annual change rate of coal consumption shifted from an increase (9%) at the 2002–2013 stage to a decrease (−1%) at the 2013–2019 new normal stage. Although coal still accounted for the largest share of consumption (40% in 2019), its share sharply dropped by 13% below the 2002 level, representing the largest decline. The annual growth rate of gas consumption ranked first (8%) under the new normal, with its share increasing by 4% in 2019 over the 2002 level. This indicates that the structure of the energy system was improved by using relatively clean energy instead of traditional fossil fuels under the new normal. The annual growth rates of energy consumption for oil and electricity exhibited the same change level from the previous stage to the new normal stage, decreasing by 6%. The share of oil consumption remained basically unchanged (21%) under the new normal.

From the perspective of the energy structure, the shift in most regions from coal to other clean energy contributed to a reduction in energy consumption under the new normal (Fig. 3f). Under the new normal, the energy structure was directly adjusted by reducing coal and increasing gas, as well as indirectly through industrial upgrading. The increase in the share of clean energy further reduced the energy intensity, thus improving the energy efficiency. Specifically, optimisation of the energy structure led to a reduction in energy consumption in four regions, including the Southwest (−0.17%), Northeast (−0.10%), Beijing-Tianjin (−0.03%) and North (−0.05%). Chongqing province ranked first (−0.11%) and benefited from abundant gas reserves in the Southwest, with a decline of −1.50 million tce in chemicals sector followed by a decline of −1.44 million tce in the metal and non-metal products sector. Conditions varied among the other four regions, including the South coast (0.02%), Central (0.02%), Central coast (0.03%) and Northwest (0.09%). The main cause was the increase in sectors with a high energy intensity in the Northwest, represented by the value of −0.86 million tce in the metal and non-metal products sector in Xinjiang (0.06%). However, the increase in energy consumption caused by the energy structure in the Central coast, Jiangsu (0.05%), for example, was mainly concentrated in the construction sector in the tertiary industry, with an increase of 1.06 million tce.

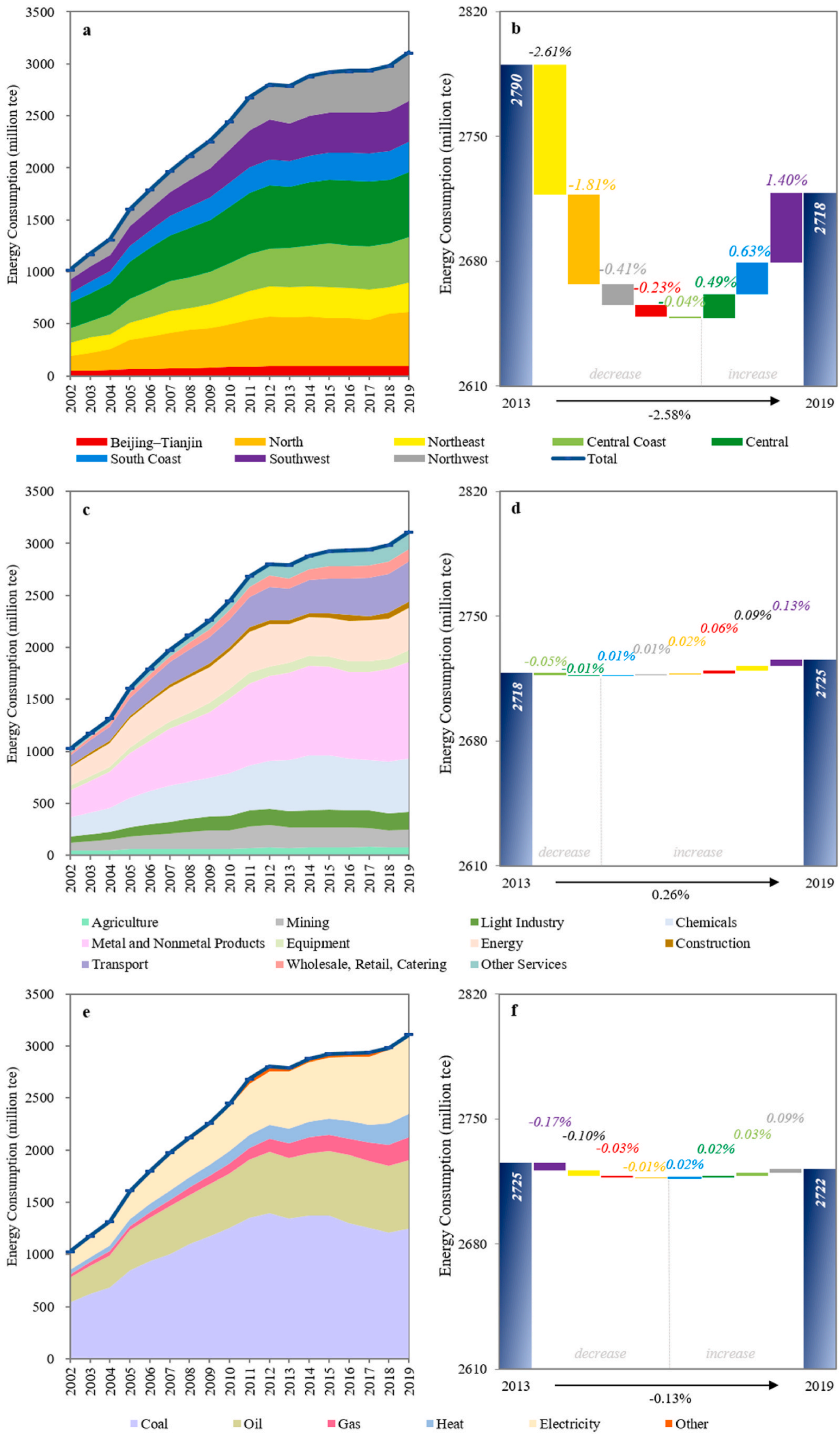

Fig. 3. Structural changes in China's energy consumption. (a) Total energy consumption in the eight regions in China from 2002 to 2019; (b) region-specific contributions of the regional structure to changes in energy consumption from 2013 to 2019, with the length of the bars reflecting the contribution of each region; (c) total energy consumption of eleven industries in China from 2002 to 2019; (d) region-specific contributions of the industrial structure to changes in energy consumption from 2013 to 2019; (e) total energy consumption of six energy types in China from 2002 to 2019; (f) region-specific contributions of the energy structure to changes in energy consumption from 2013 to 2019.

3.4. Energy consumption along regional value chains

Energy consumption at the regional level was further explored by analysing local energy consumption to produce intermediate and final goods for other regions (Table S7) along regional value chains (Fig. 4).

Local energy consumption supplying outflows in the North and Central coast increased from 2012 to 2017, while that in the remaining six regions decreased. Hebei, in the North, was the province with the highest energy consumption for outflows, reaching 69 million tce in 2017, while the increase in Central coast was mainly due to the sharp rise in Shanghai (191%) from 2012 to 2017. In terms of regions with a decreasing trend, the sharp decline in energy consumption for outflows in Southwest was mainly attributed to Sichuan (−55%) and Chongqing (−44%), as two energy supply source provinces, from 2012 to 2017. At the sectoral level, the increasing energy consumption for outflows to other regions in the various sectors and corresponding regions was relatively scattered. For example, local energy consumption to produce outflows in the equipment (39%), construction (417%) and other services (59%) sectors—represented by regions Northwest, Southwest and Northeast, respectively—at least doubled between 2012 and 2017. However, the decreasing trends were relatively centralised. In the energy sector (−77%), the energy consumption fell in each region, especially the Southwest and Northwest as energy supply source regions exporting fossil fuels. These two regions also indicated opposite trends between the proportions of energy consumption and outflows (Table S7), which should be closely related to the RVC analysis below.

From a cross-sectional perspective, the distribution of RVCs was analysed based on the regional endowment. The eight regions could be divided into three groups (Fig. 4). The first group was represented by relatively well-developed regions, including the Beijing-Tianjin, Central coast, Central and South coast, whose local or non-local value-added intermediate outflows were slightly higher than the final outflows. The second group included two energy-supply regions, the Southwest and Northwest, whose local value-added terms were obviously higher than the non-local value-added terms for either intermediate or final outflows. The third group, the North and Northeast, combined the

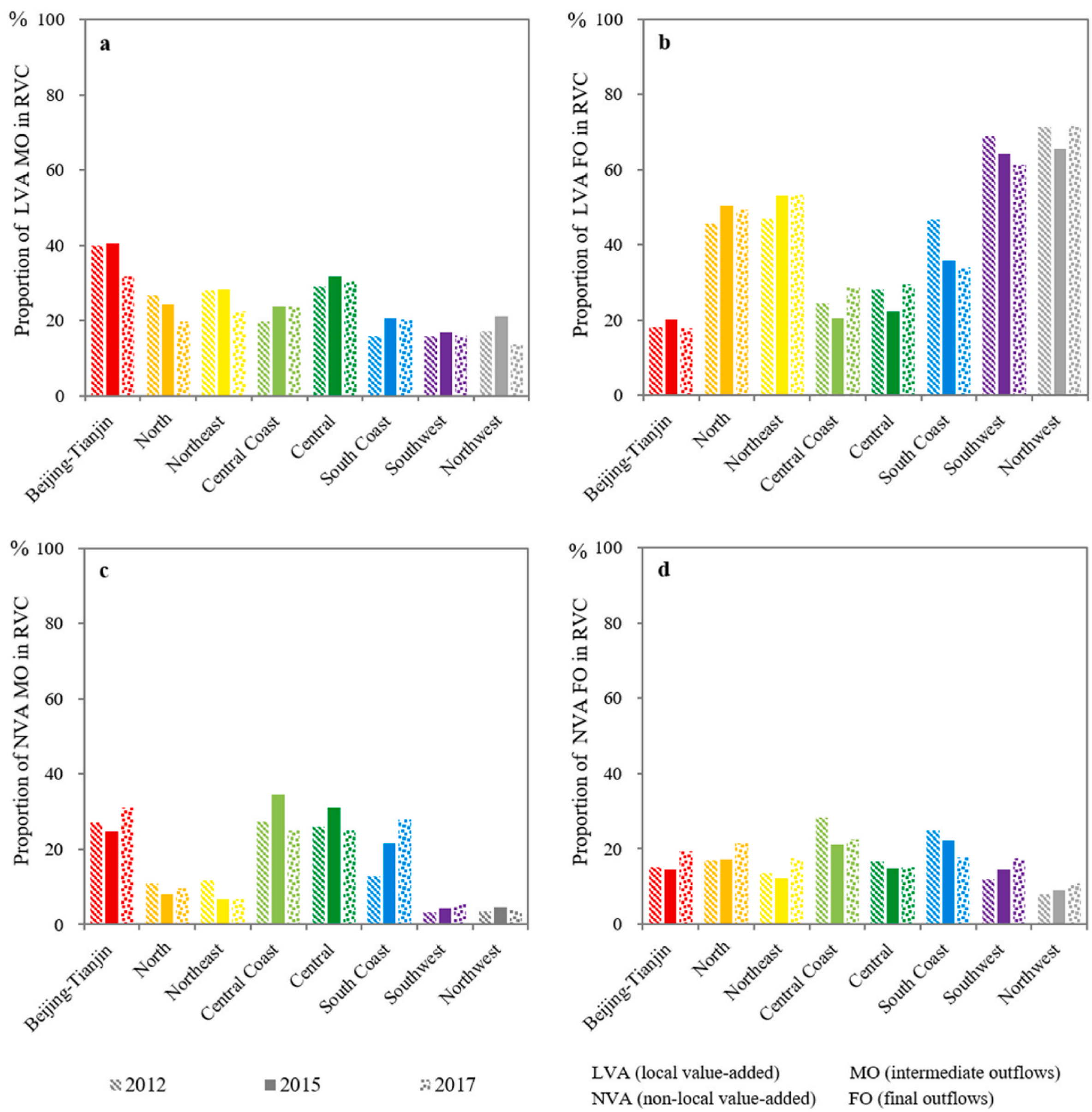

Fig. 4. Proportion of value-added outflows among RVCs in the eight regions in 2012, 2015 and 2017. (a) Proportion of local value-added intermediate outflows among RVCs; (b) proportion of local value-added final outflows among RVCs; (c) proportion of non-local value-added intermediate outflows among RVCs; (d) proportion of non-local value-added final outflows among RVCs.

characteristics of the first two groups, with higher local value-added terms than non-local value-added terms and higher intermediate outflows than the final outflows. In general, local value-added intermediate outflows in RVCs occupied the largest proportion, with the lower boundary of 25%; while non-local value-added final outflows in RVCs occupied the smallest proportion, with an upper boundary of 25%.

From a time-series perspective, the trend of RVCs was explored according to regional development. On the basis of the above grouping, the first group was further differentiated. There was a trend shift from local value-added intermediate outflows to non-local value-added final outflows in the Beijing-Tianjin, Central and South coast, while the Central coast exhibited the opposite tendency. In the second group, represented by the Southwest and Northwest the proportion of local value-added intermediate outflows was distributed to the other three items. Therefore, their local or non-local value-added final outflows increased from 2012 to 2017, while their non-local value-added intermediate outflows slightly rose. The North and Northeast in the third group roughly indicated an increase in final outflows and a decrease in intermediate outflows.

4. Discussion

During the period from 2002 to 2019, China's economic growth was one of the main factors driving the dramatic increase in national energy consumption. However, during the phase of the new normal (2013–2019), China experienced an economic transition with a shift from a focus on aggregate growth at a high speed to a pattern of sustainable development with a high quality, leading to a notable slowdown in China's energy consumption growth. In addition, gains in energy efficiency greatly offset energy consumption growth. Simultaneously, changes due to structure-related factors, including production structure, consumption structure, regional structure, industrial structure and energy structure, exhibited favourable trends of the national energy consumption under the new normal. At the regional level, the contributions of gains in energy efficiency and structural improvement, i.e., regional structure, industrial structure and energy structure, varied among the eight regions. The aforementioned four regional factors were closely related, thereby driving regional interaction and cooperation to yield synergistic effects.

First, energy efficiency was an important premise of the regional structure. The increase in the regional GDP share with a relatively high energy efficiency caused a smaller increment in energy consumption growth. Second, upgrading of the industrial structure was one way to improve the energy efficiency. In addition to technological progress, by shifting from primary and manufacturing industries to high-tech and value-added industries, the energy consumption per unit output was reduced. Third, the energy structure was closely related to the industrial structure. In the absence of consideration of the differences in regional resource endowment, upgrading and transformation from sectors producing goods with a high carbon intensity to sectors providing services with a lower energy use were usually accompanied by restructuring and adjustment from coal or oil fuels to cleaner primary energy such as natural gas or secondary energy such as electricity. Here, represented by the Northwest region with further gains in energy efficiency under the new normal, its linkage-optimising effect of driving factors at the regional level provided a typical example as an appropriate path and cost-effective pattern to design sustainable transition for regional development. Shaanxi province in the Northwest, as a reference, has performed effectively and efficiently by setting enhanced targets to achieve energy-saving, emission-reducing and green-developing goals simultaneously. Shaanxi sets goals of 12% for the energy intensity and 15% for the carbon intensity among the policy goals of the provincial 14th Five-Year Plan (FYP), which are stricter than the national requirements of 13.5% and 18%, respectively (Table S8). Therefore, it is suggested that provinces without specific plans at present for their comprehensive energy production capacity in 2025, including Beijing, Tianjin, Zhejiang, Jiangxi and Yunnan, should follow a similar approach to force sustainable transition.

In terms of the regional structure, the Southwest, a rapidly developing region, still maintained a relatively high speed of economic growth and required corresponding support and guarantees of the energy system. For example, Guizhou indicated a moderate increase in the regional structure contribution. However, the contribution of the regional structure was premised on the energy efficiency. Analysis of the regional energy efficiency indicated that the energy intensity in the Southwest dramatically dropped under the new normal, especially in Guizhou. Its reduction in energy consumption was largely caused by its energy efficiency (−1.26%), mainly because the energy intensity in Guizhou fell sharply, which offset the energy consumption growth driven by its increasing GDP share. Going a step further, the considerable gains in energy efficiency were attributable to great improvements in industrial structures. The Southwest development pattern indicated that, even with rapid economic growth, the increase in energy consumption due to industrial structure upgrading could be limited, especially in Guizhou (0.01%), which turned to emerging industries, including big data and cloud computing. Under the new normal, Guizhou promoted a rapid development of the digital economy under the new round of technological revolution and industrial transformation, especially new technology integration and innovation represented by artificial intelligence, which increasingly highlighted the driving role of new momentum for economic growth. Guizhou further improved the efficiency of resource allocation by implementing infrastructure required for digital transfer of industries and re-industrialisation. On the basis of existing achievements, Guizhou is seeking a deeper level of industrial upgrading and transformation through its provincial capital Guiyang. Guizhou-Cloud Big Data Industry Development Co., Ltd. (GCBD) took over iCloud, as an example, adding another benchmark case for successful industrial upgrading and landing in Guiyang, which achieved mutual benefits for both enterprises and the industry. Simultaneously, the energy structure contributed to a reduction in energy consumption in Guizhou (−0.01%), attributed to industry transition where energy use was dominated by electricity. In addition, the Southwest, with abundant gas reserves, could easily access clean energy sources such as natural gas, thereby basically achieving full gasification. With an increased use of clean energy, the Southwest optimised its energy structure by improving fuel types. In addition, Shanghai provided a good example here with contributions to energy consumption reduction driven by energy efficiency (−0.98%), regional structure (−0.09%) and industrial structure (−0.01%) factors. According to the experience in these regions and provinces [49,50], it is recommended that all regions should specifically set their own precise goals by systematically and simultaneously considering the internal characteristics of each province and even cities within the same province at the regional level.

The results for RVCs demonstrate that the energy consumption required to create a unit of value-added term in RVCs varies greatly among the different regions, sectors and years. For example, the Southwest and Northwest, as energy supply source regions, adjusted their own energy supply patterns towards outlands through product outflows so that more non-local value-added terms could be created via sectoral interaction with flows and cycles in the economic system. China's movement along GVCs could avoid the transfer of emission-intensive production to other regions, indicating a shift to less emission-intensive trade patterns rather than pure outsourcing [51]. Similarly, domestic trade and circulation via RVCs could also rebalance local or non-local as well as value-added terms or energy-intensive outputs and outflows. For example, coastal regions should carefully select trade sectors in inland regions from RVCs with green products using renewables.

This study explored China's energy consumption path and economic development model at the regional level on multiple scales, focusing on the driving forces and RVCs at the new normal stage of sustainable transition. However, limitations still exist, e.g., the update of IO tables in databases in a timely manner.

5. Conclusions

In conclusion, this study mainly analysed the change trend of China's energy consumption from 2002 to 2019 at the national and regional levels. Based on decomposition analysis and regional value chains, the contributions of social and economic drivers to energy consumption were estimated and examined. The results indicate that China's energy consumption has risen. However, the growth rate has decelerated in recent years. As China's economy has shifted from high-speed growth to the new normal stage of sustainable development, its energy consumption pattern has also changed. As a result of the improvement in energy efficiency and structural upgrading, the annual growth rate of China's energy consumption declined from 10% between 2002 and 2013 to 2% between 2013 and 2019. Under the new normal, energy efficiency gains have continuously offset the increase in energy consumption in China, indicating efficiency gains due to technological progress in previous economic development. In addition to energy efficiency enhancement, structure-related factors contributed to decelerating energy consumption growth in China.

At the regional level, efficiency gains and structural changes, including changes in the regional structure, industrial structure and energy structure, have contributed to the slowdown of the increase in energy consumption under the new normal, despite variations among regions. In terms of the regional structure, the transition from extensive to intensive development patterns in less-developed regions with a high energy intensity has reduced energy consumption. In terms of the industrial structure, regions with appropriate paths involving new momentum for economic growth have decreased energy consumption via transfer to industries with a low energy consumption but a high value-added mode. In terms of the energy structure, the shift from coal to relatively clean energy use in the majority of regions has further contributed to a reduction in energy consumption. These factors at the regional level are closely related, thus promoting synergy between regions. Specifically, the pressure exerted by the regional structure on energy consumption growth can be mainly attributable to well-developed regions with a high energy efficiency. Energy efficiency gains can be realised through the upgrading of the regional industrial structure, and the proportion of clean energy in the energy structure should be considered during industrial restructuring.

Accordingly, systematic policy-making is suggested for the above eight regions with their provinces and even cities. Regarding national and provincial policy goals, if aiming at strengthened carbon-intensity targets over energy-intensity targets, this study indicates that the proportion of clean energy should be greatly increased. With the improvement in the comprehensive energy production capacity, to simultaneously achieve the energy efficiency target (i.e., without increasing the energy intensity), it is necessary to achieve technological progress, industrial upgrading, and value-chain restructuring, thereby creating high-speed economic development. In addition, energy-supply regions may individualise their transition process by restructuring local and non-local value-added outflows per unit energy consumption along regional value chains, while in terms of domestic value chain, regions should also take cooperative and synergetic actions in domestic trade and circulation via policy combinations for coordinated development.

Credit Author Statement

Jiali Zheng: Conceptualization, Methodology, Software, Visualization, Formal analysis, Writing – original draft, reviewing and editing; Gengzhong Feng: Project administration, Funding acquisition, writing-reviewing and editing; Zhuanzhuan Ren: Data curation, Investigation, Visualization, Writing – original draft; Nengxi Qi: Formal analysis, Software, Data curation, Writing – original draft; D'Maris Coffman: Validation, Formal analysis, Investigation, writing-reviewing and editing; Yunlai Zhou: Visualization, Validation, Software, writing-reviewing and editing; Shouyang Wang: Supervision, Resources, writing-reviewing and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was supported by the National Social Science Foundation of China (20&ZD053). We thank the Royal Society for its support of J.Z. as a Royal Society Newton International Fellow.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2022.124948.

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