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China's Energy Consumption: a Perspective from Divisia Aggregation Approach

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Abstract:

China's total energy consumption, according to the official data, decreased impressively during 1997-1998 and increased sharply during 2003-2007, which in turn resulted in energy intensity fluctuation. Many literatures explained this "unusual phenomenon" from the perspectives of technical change, economic structure shifting and statistical data quality. They measured aggregate energy in thermal units by using linear summation approaches. In this paper, from the perspectives of heterogeneity and imperfect substitutability among diverse energy types, we further examine China's aggregate energy consumption by using Divisia (Sato-Vartia) approach. The results show that China's aggregate energy consumption and intensity fluctuated *slightly* less than values calculated by using conventional linear approaches, and the "unusual phenomenon" is *partly* explained. It also implies that China's energy intensity changes in 2006-2007 are slightly more optimistic than those officially reported, and the official communiqué of provincial energy intensity reduction achievements are partly bias. Some provincial achievement are underestimated or overestimated on some provinces. Our empirical results are also helpful to further research, such as energy-economic modeling, energy price elasticity, and elasticity of substitution among capital-labor-energy-material (KLEM). The difficulties or defects when using Divisia approach are also discussed in this paper.

Keywords: Divisia; Energy Aggregation; Imperfect Substitutability; China

1. Introduction

It seems there are some puzzles with respect to the interaction of China's energy demand and

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economic growth over the last decade. According to the official data, total energy consumption fluctuated or changed "unusually": decreasing impressively during 1997-1998 and rising sharply during 2003-2007. Furthermore, contrary to most of the earlier predictions, China's energy intensity increased in 2003-2005. Many literatures have explained this "unusual phenomenon" from different perspectives. Most of them focused on industrial structure shifting and technical changes, including Berrah et al. [1], Fisher-Vanden et al.[2], Hofman and Labar [3], IEA [4], Liao et al. [5], Ma and Stern [6], Sinton [7] and Zhang [8]. Liao [9] further investigated it from the perspectives of final demand and national income distribution system. In addition, some scholars, for example, Sinton [10] argued that China's energy statistics were not sufficiently accurate, especially its coal data, which resulted in an underestimation on energy consumption in 1997-1998. The above mentioned studies have contributed much to the explanation on China's "unusual" energy consumption. In this paper, we further examine the issue from the perspective of energy aggregation accounting. In this paper, we try to enrich the explanations, NOT replace the previous.

Most previous studies directly used the aggregate energy data provided by China's National Bureau of Statistics (NBS) or International Energy Agency (IEA). For example, according to NBS [11], China's aggregate energy consumption climbed to 2654.80 millions tons of coal equivalent (Mtce) in 2007, rising by 7.8%. Various energy types, such as oil, coal, natural gas, and hydropower, are linearly aggregated into coal (or oil) equivalent terms according to their thermal conversion factors [11-13][1]. This linear aggregate approach only considers the thermal attributes of different energy types, and implicitly assumes that all energy types are homogeneous and perfect substitutes. However, this approach sometimes may be not scientific when we want to precisely investigate the energy-economy interactions. If energy structure changes significantly (it more specifically saying, if the growth rates of various energy types are different), the linear aggregate results will be bias. Because energy structure information at least is lost. We et al. [14]

[1] In China's official total energy data, hydropower is often converted into coal equivalent based on the coal-power efficiency.

considered the quality difference between fuels when they investigated the energy efficiency of iron-steel sector. Fan et al. [15] noted the imperfect substitutabilities among energy types and employed Divisia approach when they studied substitution elasticity among China's energy-capital-labor. However, they did not describe it in detail, since aggregate issue was not the focus of that paper. To overcome the deficiencies of conventional linear aggregate approaches and evaluate China's energy situation more comprehensively, in this paper we aggregate energy types by using Divisia (Sato-Vartia) index approach, which takes both economic and physical information into account and reflects the imperfect substitutability among various energy types.

To the best of our knowledge, energy aggregation issues can be traced back to the 1960s, but until now, there have been few empirical studies and none in relation to China quantitatively. To reflect the quality differences among energy types, Turvey and Nobay [16] suggested using energy conversion factors in terms of their constant prices rather than their heat contents. Their method considered the quality differences among diverse energy types, but didn't consider the imperfect substitutability as well as their changes over time. Adams and Miovic [17] noted the imperfect substitutability and proposed an alternative aggregation method by adjusting traditional thermal conversion factors. These conversion factors are deflated based on regression analysis. Their alternative method tried to consider both price and physical information. However, this aggregation approach is still linear and fails to deal with the imperfect substitutability.

In the 1970s, owing to the development of microeconomic and productivity accounting theory, Divisia index theory matured and came into practice. Hudson and Jorgenson [18] used Divisia index approach on energy aggregation when they were constructing econometric general equilibrium models. Berndt [19] carried out an excellent theoretical and methodological research on energy aggregation issues. Thereafter, some empirical studies appeared. For example, Bernard and Cauchaon [20], Bernard and Côté [21], Berndt

[22], Choi and Ang [23], Cleveland [24], Cleveland et al.[25, 26], Hong [27], Nguyen [28], Nguyen and Andrews [29], Patterson [30] Zarnikau [31, 32]. Most of the empirical studies focused on developed countries, especially the United States. Zarnikau et al. [33] derived the energy aggregation approach clearly. A good understanding on aggregate energy is a prerequisite for energy-economy research. Most of the empirical studies above showed that using different aggregation approaches may give rise to different conclusions.

This paper is an empirical study on China. We aim to answer the following questions: i) Do the heterogeneity and imperfect substitutability among various energy types *partly* account for the so-called "unusual" energy consumption in China during the last decade? ii) Do the aggregate energy consumption and intensity curve become smoother when using Divisia approach compared to conventional linear aggregation methods? And iii) what can we learn more about the provincial energy intensity reduction achievements in China? In addition, we will discuss the difficulties or defects when using Divisia aggregate approach.

This paper is organized as follows. Section 2 introduces the disadvantages of conventional energy aggregation approaches, and briefly describes the Divisia aggregate methodology, as well as its discrete expressions. Data description and empirical results are reported in Section 3. Section 4 further discusses China's provincial energy intensity reduction achievements. Finally, we conclude with a summary in Section 5.

2. Divisia aggregation methodology

2.1 Disadvantages of conventional linear aggregations

Before discussing the disadvantages of conventional linear energy aggregation approaches, we briefly introduce their advantages: i) they require less information about various energy types, and the data are relatively easy to collect; ii) they are easy to calculate with less subjectivity; and iii) they make it convenient to compile energy balance tables. These are why they are used widely. However, conventional linear energy aggregation approaches have some disadvantages, which may lead to bias judgments or improper decisions in some cases.

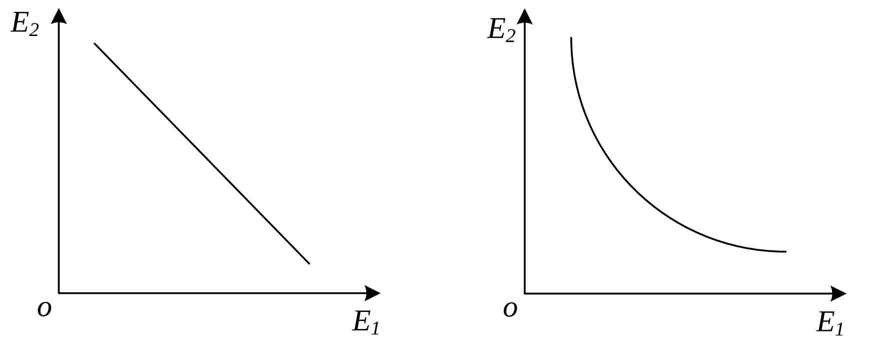
First, from the thermodynamics viewpoint, it is a linear aggregation of different energy types based on their heat content and assumes that all energy types are homogeneous and interconvertible freely. Its theoretical foundation is the first law of thermodynamics, i.e. the law of conservation of energy. For example, 1 kcal of coal is completely equivalent to 1 kcal of oil. In fact, according to the second law of thermodynamics, it is impossible to completely convert one type of energy to another type without any energy loss. That means they are not perfectly interconvertible.

Second, linear aggregation approaches presume that all the energy types are caloric carriers, ignoring the quality differences among various energy types. In this paper, energy quality refers to the relative economic usefulness per heat equivalent unit of different fuels and electricity as Cleveland et al.[26] defined. If we want to *increase* one unit of GDP by using only one type of primary energies, the heat required is different when we use different energy types. If one heat unit of hydropower can generate more useful economic work than one heat unit of coal, we say hydropower have higher quality than coal. Generally, the energy quality can be measured by their marginal products or prices.

Third and the most important, from the economics viewpoint, conventional linear aggregation approaches implicitly assume that all energy types are perfectly substitutable. For example, if there are n energy types, E_i represents the consumption of i th primary energy type $(i=1,2,\cdots,n)$. According to conventional approaches, the aggregate energy E^{ca} is linearly calculated as follows:

$$E^{ca}=\sum_{i=1}^{n}\lambda_i E_i \tag{1}$$

where λ_i represents the conversion factor based on the calorie content per unit of each energy type and it is usually fixed. The superscript of E^{ca} denotes the conventional aggregation approach. Eq. (1) implicitly assumes that all energy types are perfectly substitutable. That means the elasticities of substitution between them are infinite. If there are two energy types $(i = 1, 2)$, then given E^{ca}, E_1 and E_2 can be freely and linearly combined, i.e. the isoquant curve is linear as shown in Fig.1a. However, in a practical energy-economy system, they are partly substitutable, i.e. the elasticities of substitution between them are limited. Given E^{div} (The superscript of E^{div} denotes " Divisia aggregation approach", and we will explain it later), E_1 and E_2 can be combined freely but not linearly, i.e. the isoquant curve is convex to the origin as shown in Fig. 1b.



a) E_1 and E_2 are perfectly substitutable   b) E_1 and E_2 are partially substitutable

Fig. 1. Explanation of the elasticities of substitution among energy types

In a perfect market economy, the quality differences among various energy types are reflected in their prices (i.e. marginal products); those with high quality usually have a high price. For example, 1 kcal of oil is usually more expensive than 1 kcal of coal. All the elasticities of substitution among energy types are usually limited. They are not constant and will change over time. Therefore, when various energy types are aggregated, not only their physical information (heat content) but also their economic information (such as price and imperfect substitutability) should be taken into account. Divisia aggregation is thus a better approach. In general, when we study the interaction between aggregate energy and the macro economy, Divisia approach is preferable since it covers more information.

2.2 Divisia aggregation methodology

Divisia approach originates from the price index measurement on a bundle of commodities, and is then used in total factor productivity accounting or economic growth research. Berndt [19, 22] and Zarnikau et al. [33] studied the energy aggregation issue in detail. Divisia approach is also widely used in energy intensity decomposition (see good surveys by Ang [34, 35]). Here we will briefly introduce the energy aggregation approach based on Divisia index. The aggregate energy E^{div} is the function of diverse energy types as follows (although we do not know the specific function form):

$$E^{div} = f(E_1, E_2, \cdots E_n) \tag{2}$$

It is assumed that Eq. (2) is linear homogeneous, and satisfies the regularity conditions (positive, limit, twice-differentiable, strictly monotone, and strictly quasi-concave). Then its differential form can be expressed as follows:

$$dE^{div} = \sum_{i=1}^{n} \frac{\partial f}{\partial E_i} dE_i = \sum_{i=1}^{n} (\lambda p_i) dE_i \tag{3}$$

here, p_i and λ represent energy price and Lagrange multiplier, respectively.

$$\lambda = \frac{\partial f / \partial E_i}{p_i} = \frac{E^{div}}{\sum_{i=1}^{n} p_i E_i}, \qquad (i = 1, 2, \cdots, n) \tag{4}$$

Therefore, Eq. (3) can be transformed as follows:

$$E^{div} \cdot d \ln E^{div} = \sum_{i=1}^{n} \lambda p_i E_i \cdot d \ln E_i \tag{5}$$

$$d \ln E^{div} = \sum_{i=1}^{n} \frac{p_i E_i}{\sum_{i=j}^{n} p_i E_i} \cdot d \ln E_i = \sum_{i=1}^{n} s_i \cdot d \ln E_i \tag{6}$$

According to Eq. (6), the aggregate energy growth rate is the weighted sum of growth rates of diverse energy types. And the weights are their cost shares s_i, which include both physical and price information. If and only if the consumption growth rates of all energy types are identical (i.e. the energy consumption structure does not change), the aggregate energy consumption growth rate ($d\ln E^{div}$) will not vary with the energy prices (i.e. it is independent of the prices). Only in this case, $d\ln E^{div}$ is equal to the result based on conventional linear aggregation approaches (i.e. $d\ln E^{ca}$). Divisia approach has many good statistical and economic attributes. For more theoretical details about Divisia approach, see Balk [36], Diewert and Nakamura [37].

Eq. (6) is a differential form. Theoretically, we can derive the expression for E^{div} by using a line integral, and it is independent of the integral path since it is linear homogeneous. However, in practice the available data are usually not continuous, but discrete. There are generally two discrete-time approximations to Eq. (6): Törnqvist index and Sato-Vartia index. The difference between these two indices lies in their different approximations to Divisia index. Almost all the previous empirical studies employed Törnqvist index as an approximation. Relatively, Sato-Vartia index is slightly more exact. In this paper, we introduce Sato-Vartia index to the energy aggregation. For more theoretical details about Sato-Vartia index, please see Sato [38] and Vartia [39]. By introducing a period variable t, we can express it as follows:

$$\ln E_t^{div} - \ln E_{t-1}^{div} = \sum_{i=1}^{n} \frac{\left(s_{it} - s_{i,t-1}\right)/\left(\ln s_{it} - \ln s_{i,t-1}\right)}{\sum_{j=1}^{n}\left(s_{jt} - s_{j,t-1}\right)/\left(\ln s_{jt} - \ln s_{j,t-1}\right)} \cdot \left(\ln E_{it} - \ln E_{i,t-1}\right) \tag{7}$$

where $s_{it} = p_{it}E_{it} \Big/ \sum_{i=1}^{n} p_{it}E_{it}$, representing the cost share at period t. To conveniently compare, we index aggregate energy consumption as unity in the initial period. According to Eq. (7), when calculating the cost share, we require not only the physical data of diverse energy types, but also their price data. We can figure out the aggregate energy index at any period cumulatively if the data are available.

Divisia approach takes both the heterogeneity and imperfect substitutability among diverse energy types into account. Their elasticities of substitution can also be derived based on some acceptable assumptions, such as weak separability from other input factors. In addition, these elasticities are not constant but changeable over time. For example, when using computational general equilibrium (CGE) in energy-economic-environment research, factor aggregation issues are usually encountered. And most aggregation function in CGE models use constant elasticity of substitutions (CES). This may not fit the practice. If Divisia aggregate approach is used, the research will be improved substantially. By using Divisia approach, we can also compile a comprehensive primary energy price index [9, 15]. The composite energy price change is equal to the weighted sum of price changes of diverse energy types as showed in Eq.(8). And the weights are also their cost shares s_i . For more details about, please see [36-37].

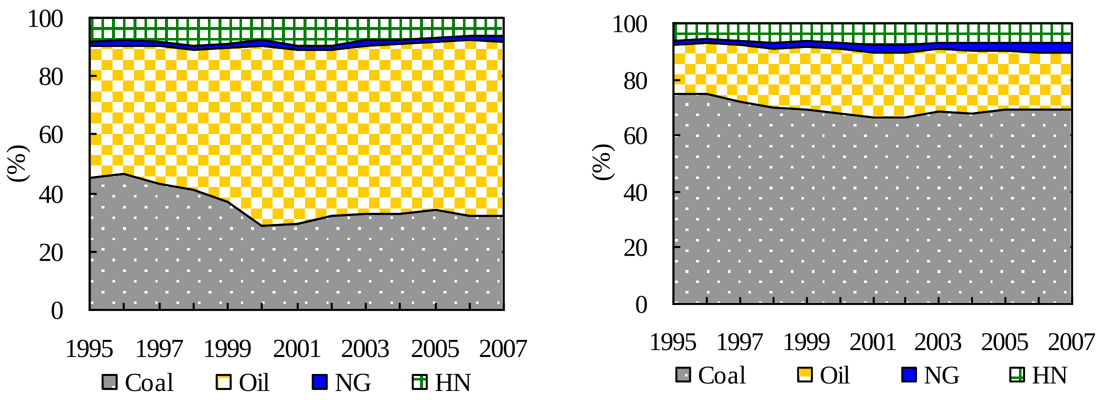
$$d \ln P = \sum_{i=1}^{n} \frac{p_i E_i}{\sum_{i=j}^{n} p_i E_i} \cdot d \ln p_i = \sum_{i=1}^{n} s_i \cdot d \ln p_i \tag{8}$$

3. Data description and empirical results

3.1 Data description

To avoiding double calculations and keeping statistical converge identical, we investigate the primary energy in this paper. Primary energy refers to those that are either extracted or captured directly from natural resource commodities such as crude oil, hard coal, natural gas, or are produced from primary natural resource. The primary energy consumption also includes the net import energy such as oil products from other countries (If we investigate regional energy consumption issues, then it refers to those from other regions). We examine China’s aggregate energy consumption by using Divisia approach, and compare the results to those of conventional approaches. We encounter numerous data challenges when addressing this issue, since it requires not only physical but also price data. In China, the primary commercial energy types mainly include oil (crude oil and net-imported oil products), coal, natural gas (NG), hydropower and nuclear power (HN). The physical data are easily collected or calculated based on China Energy Statistical Yearbook [40-42], Comprehensive Statistical Data and Materials of Industry, Transportation and Energy on 50 Years of New China [43], China Statistical Abstract 2008 [11].

In this paper, we have tried our best to carefully collect and calculate the price data by energy type. The energy prices are the producers' prices (including the sale item for value added tax but excluding transport cost). They are calculated from China Economic Census Yearbook 2004 [44], China Statistical Yearbook 2007 [45], and China Statistical Abstract 2008 [11]. Based on the physical and price data, we can calculate the cost shares of diverse energy types during the period 1995-2007. They are shown in Fig.2a. We also report the heat content shares based on conventional aggregation method (coal equivalent calculation) as shown in Fig. 2b.



a) By cost share
Sources: Authors' calculation

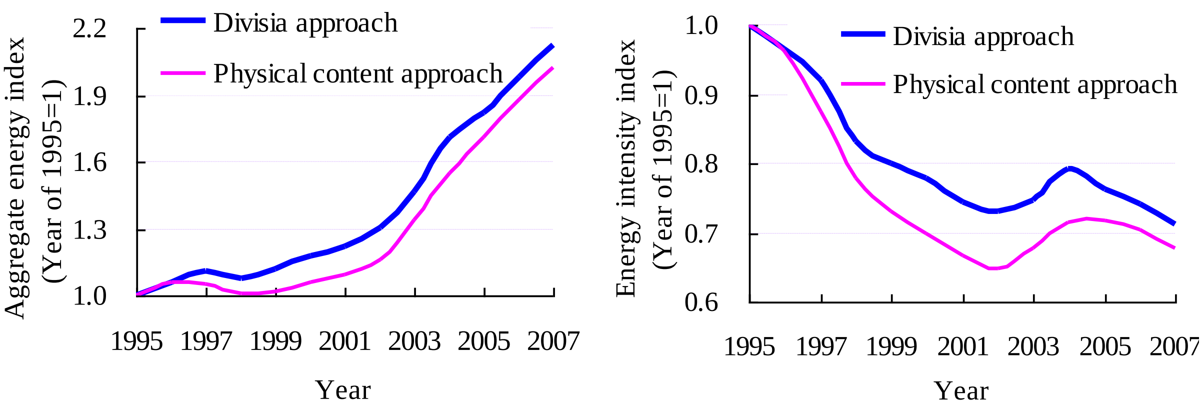
b) By heat content share
Sources: NBS [11]

Fig.2. China's energy consumption structure (NG refers to natural gas and HN refers to hydropower and nuclear power)

According to these two figures, oil and coal have made up about 90% of China's primary energy consumption, whether calculated based on cost or heat content share. Natural gas, hydropower and nuclear power only account for some 10%. If we look at them more disaggregatively, there are different conclusions to be drawn from the two approaches. In terms of heat content, coal is about 66~75% of the aggregate energy consumption, slightly decreasing in 1997-2002 and increasing in 2003-2007, while oil only accounts for 17~24% of the total, slightly increasing in 1997-2000 and decreasing in 2001-2003 and 2005-2007. Almost all the literatures and official documents cite China's energy consumption structure in terms of heat content as above (hydropower is converted to coal equivalent based on thermal power efficiency). However, energy is a commodity. If we look at its structure based on cost share, the judgments may be not the same as for heat share. In terms of cost share, oil has accounted for 44~63% of the energy consumption, rising in the late 1990s; while the coal proportion is only 31~47%, decreasing sharply in the late 1990s. This is because oil price per unit of heat content is much higher than that of coal, especially in recent years. In 2007, oil and coal costs respectively accounted for 6.7% and 3.6% of China's GDP.

3.2 Empirical results

According to Eq. (7) and the prepared data, we can determine China's aggregate energy consumption and energy intensity from the perspectives of heterogeneity and imperfect substitutability among diverse energy types. We index them to 1.0 at Year 1995. The results are shown in Fig. 3. For conveniently comparing, we also report the results based on conventional approaches (heat content E^{ca}).



a) Aggregate energy consumption in China

b) Energy intensity in China

Fig. 3. Aggregate energy consumption and energy intensity in China (*Sources*: authors' calculation

and NBS [11])

As shown in Fig. 3, on the whole, the differences between results are not very obvious when using Divisia and conventional heat content aggregation approaches. During 1995-2007, China's aggregate energy consumption increased by 1.13 and 1.05 times in terms of E^{div} and E^{ca}, respectively; and its energy intensity was reduced by 28.8% and 32.2% in terms of E^{div} and E^{ca}, respectively. The cumulated energy growth rate of E^{div} was slightly higher than that of E^{ca}, and the energy intensity of E^{div} decreased slightly more slowly than that of E^{ca}.

At first glance, the curve in terms of E^{div} is smoother than that measured in E^{ca}. This can be further quantitatively verified through regression analysis, as shown in Table 1. According to the determination coefficient (R^2), Model II in terms of E^{div} satisfies the energy-economy relationship with a better fit than Model I in terms of E^{ca}. This is because E^{div} takes not only energy physical but also economic attributes into consideration, and can reflect the economy more exactly.

Table 1

OLS estimates of aggregate energy consumption and GDP

Model	Intercept	$\ln E^{ca}$	$\ln E^{div}$	R^2
I	0.228 [0.023]	1.253 [0.000]		0.868
II	0.127 [0.060]		1.296 [0.000]	0.948

Note: The dependent variable is log (GDP) in the two regression models (OLS, Newey-West adjusted). The figures in square brackets are *p*-values. Sample period: years 1995-2007.

If examining some years in detail, we can find more information about China's energy situation. E^{ca} declined by 0.83% and 4.05% in 1997 and 1998 respectively. These data have been cited in most previous literatures and government documents, and have been described as "unusual". However, as shown in Table 2, if measured by Divisia approach, aggregate energy consumption E^{div} increased by 4.34% and fell by only 2.54% in those two years, respectively. It means the "unusual" phenomenon is partly reduced. The reasons lie in the energy structure changes and substitutions among various energy types. Oil has generally higher quality than coal, i.e. the marginal product of oil is higher than that of coal. In 1997 and 1998, coal consumption dropped by 3.79% and 7.01%, respectively, while oil consumption grew by 1.94% and 0.64% respectively. As a result, the aggregate energy consumption in terms of E^{div} was not so "unusual". Similarly, we can explain why the energy intensity declined so quickly in 1997-1998 in terms of E^{ca}.

In 2003-2007, China's aggregate energy consumption increased sharply. Many previous literatures emphasized the industrial structure shifting, i.e. the energy intensive sectors expanded rapidly. This is a fact. If we further turn to the Divisia approach, the sharpness of the increase can also be partly reduced. Since 2003 (except for 2004), coal consumption has increased more rapidly than oil. Therefore, E^{ca} rose more rapidly than E^{div} as shown in Fig.3.

Table 2

Aggregate energy-economy indicators growth rate in China (unit: %)

Year	$d\ln E^{div}$	$d\ln E^{ca}$	$d\ln GDP$	$d\ln \frac{E^{div}}{GDP}$	$d\ln \frac{E^{ca}}{GDP}$	$d\ln Oil$	$d\ln Coal$
1995	7.48	6.88	10.9	-3.11	-3.66	7.41	7.11
1996	6.16	5.92	10.0	-3.50	-3.72	8.54	5.13
1997	4.34	-0.83	9.3	-4.53	-9.25	12.94	-3.79
1998	-2.54	-4.05	7.8	-9.62	-11.02	0.64	-7.01
1999	3.32	1.22	7.6	-4.01	-5.95	6.33	0.39
2000	5.49	3.53	8.4	-2.70	-4.51	6.48	1.54

Year	$d\ln E^{div}$	$d\ln E^{ca}$	$d\ln GDP$	$d\ln \frac{E^{div}}{GDP}$	$d\ln \frac{E^{ca}}{GDP}$	$d\ln Oil$	$d\ln Coal$
2001	3.78	3.35	8.3	-4.18	-4.57	1.78	2.27
2002	7.12	6.00	9.1	-1.80	-2.83	8.50	4.89
2003	12.29	15.28	10.0	2.06	4.78	9.47	19.51
2004	16.55	16.14	10.1	5.87	5.50	16.86	14.40
2005	6.52	10.56	10.4	-3.54	0.12	2.64	11.95
2006	8.56	9.61	11.6	-2.73	-1.79	7.19	10.38
2007	7.33	7.84	11.9	-4.08	-3.66	6.30	7.90

Note: $d\ln E^{div}$ and $d\ln E^{ca}$ refer to the energy growth rate in terms of E^{div} and E^{ca}, respectively, $d\ln GDP$ refers to GDP growth rate, $d\ln \frac{E^{div}}{GDP}$ and $d\ln \frac{E^{ca}}{GDP}$ refer to energy intensity growth rate in terms of $\frac{E^{div}}{GDP}$ and $\frac{E^{ca}}{GDP}$, respectively, $d\ln Oil$ and $d\ln Coal$ refer to oil and coal consumption growth rates.

To turn down the trend that energy consumption sharply increased in 2003-2005, China's central government set a target to reduce its energy intensity by 20% in 2006-2010, which means a 4.4% reduction annually. Unfortunately, the energy intensity in terms of E^{ca} only declined by 1.79% and 3.66% in 2006 and 2007, respectively [11]. The result seems rather pessimistic. However, as shown in Table 2, if we measure it in terms of E^{div}, the performance in these two years is slightly more optimistic. In 2007, the energy intensity was reduced by 4.08% in terms of E^{div}.

4. Discussion

In economic activities, diverse energy types are not only heat carrier, but also production factors with heterogeneity. The empirical results show that different energy aggregation approaches may give rise to different judgments or decisions. Divisia aggregate approach is preferable since it takes into account both the heterogeneity and imperfect substitutability among diverse energy types. If Divisia approach is employed, the "unusual" phenomenon of China's energy consumption and intensity changes in the past decade are partly explained. In a perfect market economy, Divisia aggregate approach reflects the energy-economy interaction more comprehensively than conventional linear aggregate approaches.

The aggregation issue has been widely recognized in microeconomics, but it is rarely noted in energy-economy empirical studies. Most of the energy-macroeconomy research use aggregate energy calculated by linear summation approach. If we further study the energy-economy interaction by using E^{div} data, the results or conclusions may not be the same as some previous empirical results, such as the aggregate energy-macroeconomy causality effect [46] and energy price elasticity [3, 47]. In the following section, we will review China's provincial energy saving performance evaluation results based on Divisia idea. We will discuss it qualitatively due to data limitations.

To incentivize local authorities to attach more importance to energy saving, Chinese central government has assigned an energy saving target to every local province. Their energy intensity should be reduced by 12-30% in 2006-2010, varying between provinces, and the subsequent achievements will be evaluated every year. Therefore, it is crucial to scientifically and comprehensively evaluate their achievements since it will determine the incentive efficiency. If aggregate energy consumption is measured in terms of E^{ca}, to reduce the aggregate energy growth rate as far as possible, some local authorities may try to substitute some coal with oil, natural gas, or electricity (on a net basis, moved in from other provinces) since the latter three have higher quality. If aggregate energy consumption is measured in E^{div}, the evaluation results may be independent of the energy structure changes. Here, we will take Beijing and Shandong as illustrations since they are typical energy consumer and producer respectively in China.

The energy saving achievements communiqué of Year 2006 was released by the central government [48]. According to the communiqué, Beijing ranked the best among the 30 provinces reported. Its energy intensity fell by 5.25% in terms of E^{ca}. Most literatures attributed Beijing's achievements to its efforts on technical progress and industrial structure shifting. However, in addition to those efforts, energy structure shifting also contributed to the "5.25%" reduction. Aggregate energy consumption measured in E^{ca} grew by 7.3% in Beijing, while the oil and natural gas consumption (excluding final energy produced in Beijing) increased by 8.9%, 26.9%, respectively, far above the growth rate of E^{ca}, and coal consumption declined by 0.9%, far below the growth rate of E^{ca} [49, 50]. Oil and natural gas have higher quality than coal. Therefore, to some extent, the energy intensity reduction achievement in Beijing was relatively overestimated. If we consider the heterogeneity and imperfect substitutability among diverse energy types and evaluate the provincial energy intensity reduction achievements by using Divisia aggregate approach, the evaluation results will not be the same as the current ones (unfortunately, due to the unavailability of provincial energy prices, we cannot accurately calculate it).

Shandong province, a large coal and oil producer in East China, had results that are contrary to those of Beijing. Shandong's energy intensity declined by 3.46% measured in E^{ca}. Its aggregate energy consumption measured in E^{ca} increased by 10.8%, in which coal and oil increased 14.7% and 5.0%, respectively (hydropower and electricity moved in from other provinces on a net basis, and natural gas consumption in Shandong were very lower) [51, 52]. If measured in E^{div}, the energy intensity reduction in Shandong will be slightly higher than 3.46%, which means its energy saving achievement was underestimated in the released communiqué. The above calculations for Beijing and Shandong imply that when evaluating provincial energy intensity reduction achievements, we should also pay attention to energy structure shifting; otherwise, judgments or decisions may be bias or inequitable. Although the data are not available, Divisia idea can also help us to analysis the energy intensity more comprehensively.

Divisia index approach has many advantages when it is used in energy aggregation. It should be noticed that it also has some disadvantages. Divisia index theory is based on the assumptions of neoclassic economics. In an imperfect market, not all factor prices are equal to their marginal products, and some prices are only account records, not reflecting the relationship between supply and demand. There are some distortions in the price system more or less, especially in the government regulated market. As a result, to some extent the price function of incentive and constraint become weak. In China, energy prices are strictly regulated by government before 1993. Since then they have been deregulated gradually due to its market oriented economic reforms (except for the natural gas price), and the price mechanism has become more functional. Natural gas has accounted for a small part of the total energy consumption. Therefore, in our current empirical study, though the price data are not very accurate, they can reflect the relationship between energy supply and demand in general terms. This will not affect our additional explanations on the "usual" energy consumption in the last decade.

5. Conclusions

To explain China's "unusual" energy-economy interaction during the last decade, earlier literatures were mainly focused on technical changes and industrial structure shifting. In this paper, we further investigate it from the perspective of energy aggregation accounting. It should be noted that we only try to enrich the explanations, NOT replace the previous. This is helpful for us to analysis energy-economy issues more comprehensively. By using Divisia aggregation approach, we consider both the heterogeneity and imperfect substitutability among various energy types, while conventional linear aggregation approaches implicitly assume all energy types are homogeneous. To more accurately calculate the Divisia index under discrete conditions, we introduced the Sato-Vartia index approximation rather than using Törnqvist index.

Our empirical results show that when using Divisia approach (compared with conventional linear aggregation approaches): i) the heterogeneity and imperfect substitutability among various energy types *partly* account for the so-called "unusual" energy consumption during the last decade; ii) China's aggregate energy consumption and intensity curves become smoother; iii) China's energy intensity declined by 2.73% and 4.08% in 2006 and 2007, respectively, which is slightly more optimistic; iv) the provincial energy saving achievements communiqué released by the central government may be bias or inequitable, underestimating the performance in some provinces, such as Shandong, and overestimating it in some others, such as Beijing.

As mentioned in Section 2, Divisia index approach implicitly assumes a perfect market economy and requires energy price data. Energy is a special commodity and almost all governments in the world have regulated it more or less, especially the final energy products such as electricity and heating. This means that some energy prices do not exactly reflect the supply-demand relationship. If the cost of resource non-renewability and environmental pollution externality are fully included in the energy price, and the economic system is less regulated, the results based on the Divisia aggregation approach may be more accurate and useful as a basis for decision making.

In 2010, at the end of China's 11th Five Year Development Plan, the central government will evaluate whether provincial energy intensity reduction targets are realized. We suggest that the evaluation should not only take the aggregate energy intensity reduction into consideration (since the official aggregate data are linear summations of various energy types), but also take the energy structure changes into accounts.

Our empirical results are also helpful to advance some aspects of research, such as energy-economy modeling, energy price elasticity, and elasticity of substitution among capital-labor-energy-material (KLEM). If these issues are re-examined, the results may not be the same as some previous research results based on conventional linear aggregate energy.

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