Global non-fossil fuel consumption: driving factors, disparities, and trends

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Abstract

Purpose – Non-fossil fuels are receiving increasing attention within the context of addressing global climate challenges. Based on a review of non-fossil fuel consumption in major countries worldwide from 1985 to 2015, the purpose of this paper is to analyze trends for global non-fossil fuel consumption, share of fuel consumption and inequality.

Design/methodology/approach – The similarities were obtained between the logarithmic mean divisia index and the mean-rate-of-change index decomposition analysis methods, and a method was proposed for complete decomposition of the incremental Gini coefficient.

Findings – Empirical analysis showed that: global non-fossil fuel consumption accounts for a small share of the total energy consumption, but presents an increasing trend; the level of global non-fossil fuel consumption inequality is high but has gradually declined, which is mainly attributed to the concentration effect; inequality in global non-fossil fuel consumption is mainly due to the difference between nuclear power and hydropower consumption, but the contributions of nuclear power and hydropower to per capita non-fossil fuel consumption are declining; and population has the greatest influence on global non-fossil fuel consumption during the sampling period.

Originality/value – The main contribution of this study is its analysis of global non-fossil fuel consumption trends, disparities and driving factors. In addition, a general formula for complete index decomposition is proposed and the incremental Gini coefficient is wholly decomposed.

Keywords Inequality, Gini coefficient, Index decomposition, Non-fossil fuel consumption

Paper type Research paper

Introduction

Issues surrounding energy are central to many economic and social development problems faced by human society. Energy is key to transportation, industrial development and economic stability, as well as the improvement of living standards. Since the nineteenth century, energy consumption, particularly fossil energy consumption, has increased significantly (Al-mulali, 2016). However, fossil fuels such as coal, oil and natural gas are not only finite but also threaten environmental sustainability (Alper and Oguz, 2016; Wahab, 2017; Zhan *et al.*, 2018). In contrast, renewable energy and nuclear energy not only have huge utilization potential but are also far less harmful to the environment, even producing

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zero carbon emissions. It is claimed that cutting fossil fuel use and developing new and renewable forms of energy is key to achieving a low-carbon society (Sang *et al.*, 2013). In addition, renewable energy is closely connected with the concept of a circular economy, which has gained increasing prominence in academic and policy fields (Gregson *et al.*, 2015; Tseng, Raymond, Anthony, Chien and Kuo, 2018). For example, as one of the most important renewable energy resources, biofuels can be produced from crop straw, animal manure, waste residues, etc., in a harmless and resource-based process, which is consistent with the circular economic model characterized by resource reuse and recycling. Furthermore, the development of renewable energy technologies would greatly promote the realization of a circular economy.

On the whole, the development of non-fossil fuels has received the attention of many countries worldwide, due to numerous factors including the depletion of traditional energy resources, deterioration of the global environment and concerns about energy security and sustainable development in various countries resulting from historical oil crises (Jenkins and Guevara, 2014; Payne *et al.*, 2017; Li *et al.*, 2018). Global non-fossil fuel consumption and share have gradually increased as a consequence. Thus, greater understanding of sustainable consumption is required, especially of non-fossil fuels (Tseng, Chiu and Liang, 2018). According to the BP Statistical Review of World Energy (1965–2016), global non-fossil fuel consumption (including nuclear and renewable energy) accounted for less than 6 percent of total energy consumption in 1965, compared with more than 14 percent in 2015.

The literature on global non-fossil fuel development or consumption can be roughly divided into several categories. The first category explores the potential for using non-fossil to fossil energy consumption in response to global warming. For example, based on panel data from 117 countries worldwide, Liddle and Sadorsky (2017) explored the extent to which improving non-fossil fuel alternatives for electricity production could reduce global greenhouse gas emissions. Their empirical results show that the carbon dioxide emission elasticity of non-fossil fuels in electricity production is −0.75. Trainer (2010) argued that it would be difficult to adequately replace fossil fuels with non-carbon energy resources in order to address global climate change, due to factors such as cost, variability, energy storage requirements and other technical limitations. Brook (2012) further pointed out that relying solely on renewable energy resources would not solve the greenhouse gas problem, but that nuclear fission energy has great potential as an alternative to address global warming. By investigating the drivers of the global decline in carbon intensity between 1850 and 1990, York (2016) pointed out that replacing fossil energy by clean energy remained a challenge for future global policy. In addition, Jarke and Perino (2017) and AlFarra and Abu-Hijleh (2012) also investigated the potential for reducing carbon dioxide emissions by using non-fossil fuel renewable energy and nuclear energy resources, whereas Menegaki and Tsagarakis (2015) and Bilgili *et al.* (2016) explored the impact of non-fossil energy consumption on carbon dioxide emissions based on the environmental Kuznets curve approach.

The second category of literature empirically tests the relationship between non-fossil fuel consumption and economic growth. For example, Asafu-Adjaye *et al.* (2016) discussed the relationship between economic growth, fossil energy consumption and non-fossil fuel consumption for 53 countries worldwide. Their study concluded that relying solely on economic growth was not sufficient to spur the development of cleaner energy, such that governments needed to adopt appropriate incentives to promote investment in renewable energy. Amir (2017) selected a sample of 72 countries worldwide to study the interactions between economic growth, trade and renewable energy consumption. Based on an empirical study of Brazil, Russia, India, China and South Africa economies, Tugcu and Tiwari (2016) found no significant causal relationship between renewable energy consumption and total factor productivity growth. Further related studies were conducted by Bhattacharya *et al.* (2016), Furuoka (2017) and Adewuyi and Awodumi (2017).

The third category of literature studies the development or consumption of non-fossil fuels in a single or several countries. For example, Gozgor (2016) tested whether the growth of renewable energy consumption in Brazil, China and India from 1971 to 2014 was random. Cicia *et al.* (2012) used the Italian national survey to analyze preferences among the general public for fossil, nuclear, wind, solar and bioenergy. Vaona (2012) pointed out that Italy needed diversified types of renewable energy for the public to accept renewable energy resources. Gracia *et al.* (2012) used the data from a 2010 discrete choice experiment in Spain to explore the possibility of supporting the development of renewable energy through raising the electricity price. Foley *et al.* (2013) assessed the technological and market challenges that Ireland faced in improving wind power capacity, and put forward several solutions. Research by Devlin *et al.* (2017) on natural gas and wind power generation in the UK and Ireland indicated that natural gas power generation was of great importance for the sustainable development of renewable energy resources.

Although the literature summarized above examines non-fossil fuel development and consumption from multiple perspectives, the overall development characteristics of global non-fossil fuel consumption and several other related problems still need to be further explored. This paper analyzes global non-fossil fuel consumption trends, inequality levels, and proportion of non-fossil fuel consumption with the aim of evaluating non-fossil fuel consumption among major consumers worldwide from 1985 to 2015. In addition, considering related research methods, this paper derives a general expression that can achieve complete index decomposition, and attempts to combine the index decomposition with incremental decomposition of the Gini coefficient, which is rarely seen in the related literature. Overall, this study makes the following three contributions in extending the existing literature: a general formula that can achieve complete index decomposition by means of extending the logarithmic mean divisia index (LMDI) and the mean-rate-of-change index (MRCI) decomposition methods. Complete decomposition of the incremental Gini coefficient by combining the index decomposition analysis with incremental decomposition of the Gini coefficient. It is found that the level of global non-fossil fuel consumption inequality is high but has gradually declined, and is mainly due to the difference between nuclear energy and hydropower consumption. In addition, population size is the principal factor in global non-fossil fuel consumption during the sampling period.

The remainder of this paper is divided into the following sections. The second section documents the methodology, comprising extension of the LMDI and MRCI methods, index decomposition of non-fossil fuel consumption, and decomposition of the Gini coefficient, as well as the data sources. The third section presents empirical analysis of global-scale non-fossil fuel consumption, its degree of convergence and inequality, the proportion of global non-fossil fuel consumption, and LMDI analysis. Finally, the fourth section presents the main conclusions.

Methods and data

Extension of the LMDI and MRCI decomposition methods – complete general index decomposition

Index decomposition analysis is a tool widely used in the fields of energy and environmental policy formulation (Albrecht *et al.*, 2002; Ang, 2004; González *et al.*, 2014). The LMDI method of index decomposition analysis has many advantages, including no residual and simple operation (Ang, 2004; Ang *et al.*, 1998); therefore, the majority of related studies utilize this method (Ang *et al.*, 2003; Baležentis *et al.*, 2011). However, since the LMDI method uses a logarithmic form, it has limitations in dealing with negative numbers. As an alternative, Chung and Rhee (2001) proposed the MRCI decomposition method, which can be completely decomposed and is also able to handle negative numbers. Although the LMDI (note that LMDI in this paper refers to the form of LMDI addition) and MRCI methods are two completely different forms of index decomposition, both can be derived from the same complete general index decomposition expression.

For the sake of brevity, suppose that $X=\sum_i X_i$ and $X_i = x_{i,1},\ x_{i,2},\ \ldots,x_{i,n}$; then, the complete general index decomposition expression is as follows:

$$\Delta X=\sum_i \left(X_i^t - X_i^o\right)$$

$$=\sum_i \left[\Phi_i(*)f_{i,1}+\Phi(*)_i f_{i,2}+\cdots+\Phi(*)_i f_{i,n}\right]=\sum_i \left[\Phi(*)_i \sum_{j=1}^{n} f_{i,j}\right], \tag{1}$$

where $\Phi(*)_i$ represents the distribution coefficient, $\Phi(*)_i=\left(\Delta X_i/\sum_{j=1}^{n} f_{i,j}\right)$; superscripts t and o represent the reporting and base periods, respectively; and $f_{i,j}$ represents the expression related to various effects. The different expressions of $f_{i,j}$ correspond to different decomposition methods; therefore, the difference between the LMDI and MRCI decomposition methods lies in the different expressions of $f_{i,j}$.

For the LMDI decomposition method, if $f_{i,j}=\ \ln(x_{i,j}^t/x_{i,j}^o)$, then:

$$\Phi_i(*)=\frac{\Delta X_i}{\sum_{j=1}^{n}\ln\left(\frac{x_{i,j}^t}{x_{i,j}^o}\right)}=\frac{X_i^t - X_i^o}{\ln\left(\frac{x_{i,1}^t \cdot x_{i,2}^t \cdots x_{i,n}^t}{x_{i,1}^o \cdot x_{i,2}^o \cdots x_{i,n}^o}\right)}=\frac{X_i^t - X_i^o}{\ln X_i^t - \ln X_i^o}. \tag{1a}$$

For the MRCI decomposition method, if $f_{i,j}=((x_{i,j}^t - x_{i,j}^o)/(x_{i,j}^t + x_{i,j}^o/2))$, then:

$$\Phi_i(*)=\frac{\Delta X_i}{\sum_{j=1}^{n}\left(x_{i,j}^t - x_{i,j}^o\right)/\left(\frac{x_{i,j}^t + x_{i,j}^o}{2}\right)}, \tag{1b}$$

where the contribution rate of $f_{i,j}$ to ΔX_i is $\left(\Phi_i(*)f_{i,j}/\Delta X_i\right)$, and $\sum_{j=1}^{n}\left(\Phi_i(*)f_{i,j}\right)/\Delta X_i=1$.

Lenzen (2006) deduced the similarities between the LMDI and MRCI methods from the perspective of complete differentials. However, the present study derives the similarities and differences between them from another perspective. The similarity is that the two methods can be classified as the same complete general index decomposition expression, while the difference lies in the distribution coefficient in the general expression. Furthermore, new complete index decomposition methods can be explored in future, on the premise that the complete general index decomposition formula is satisfied.

Complete decomposition of the incremental Gini coefficient

The Gini coefficient is a common measure of income inequality (Sen, 1997), in which a coefficient of 0 represents perfect equality (everyone has the same income) and 1 represents perfect inequality. Several scholars have used the Gini coefficient to study inequalities in energy consumption (Fernandez *et al.*, 2005; Papathanasopoulou and Jackson, 2009). Other research tools for measuring inequality, such as the Their index, can only be decomposed by grouping. In contrast, one advantage of using the Gini coefficient to measure energy consumption differences is that it can be decomposed by dimensions such as structure, grouping and increment. Two dimensions (structure and increment) were selected to decompose global per capita inequality in non-fossil fuel consumption.

Structural decomposition of the Gini coefficient (Kakwani, 1977; Lerman and Yitzhaki, 1985) can be achieved using the following formula:

$$G^t = \sum_{i=1}^{5} S_i^t \times GG_i^{\,t}, \tag{2}$$

where G is the Gini coefficient of global per capita non-fossil fuel consumption; S_i the proportion of the ith type of non-fossil fuel consumption; and GG_t the concentration ratio of the ith type of non-fossil fuel consumption. The concentration ratio is also termed the pseudo-Gini coefficient, based on sorting total income from low to high, rather than sorting the source of the income itself. If $GG_t > G$, the inequality of income sources widens the overall level of income inequality; conversely, if $GG_t < G$, the inequality in income sources reduces the overall income inequality. Superscripts t and o represent the tth year and the base period, respectively, and the subscript i represents the ith type of non-fossil fuel. Non-fossil fuels can be divided into five categories: nuclear, hydropower, solar, wind and other renewable energies; then, on the basis of Formula (2), the contribution of the difference in the consumption of each non-fossil fuel category to the overall difference can be calculated as $S_i^t \times GG_i^{\,t}/G^t$:

$$\Delta G = G^t - G^0 = \sum_{i=1}^{5} \Delta S_i \times GG_i^0 + \sum_{i=1}^{5} S_i^0 \times \Delta GG_i + \sum_{i=1}^{5} \Delta S_i \times \Delta GG_i. \tag{2a}$$

Decomposition of the incremental Gini coefficient is often achieved in the existing literature by using Formula (2a), the first two terms of which represent the influence of the consumption structure and the influence of the concentration ratio; however, the last term, which is often called the residual term or the interaction term, is determined by the common influence of changes in consumption structure and concentration ratio. Although the interaction terms are influenced by two factors, and thus are economically meaningful, the contributions of the two factors to the interaction terms remain unclear. More importantly, once the value of these interactive items becomes large, then the value of the factor decomposition of the increment will be greatly reduced because, in this case, the individual influence of each factor is significantly reduced (Sun, 1998). Clearly, this will reduce the reliability and accuracy of the decomposition result.

According to the method of Chotikapanich and Griffiths (2001), the per capita energy consumption level, regional order, and population proportion need to be considered in the decomposition of the incremental Gini coefficient. However, this method cannot be combined with structural decomposition. This study decomposes the incremental Gini coefficient using index decomposition analysis, on the basis of structural decomposition of the Gini coefficient. This method can achieve the combination of structural decomposition and decomposition of the incremental Gini coefficient, and can measure the effects of changes in consumption proportion and concentration ratio (termed the proportional effect and concentration effect respectively). As such, it extends the study of decomposition of the Gini coefficient, and complements the incremental decomposition method of Chotikapanich and Griffiths (2001). In addition, since the concentration ratio may be negative, the LMDI method will fail in this case. It is therefore proposed that the Gini coefficient decomposition and the MRCI decomposition method be combined; the specific decomposition results of which are achieved using the following formula:

$$\Delta G = G^t - G^0 = \sum_{i=1}^{5} \left(S_i^t \times GG_i^t - S_i^0 \times GG_i^0 \right) = \sum_{i=1}^{5} \left(\Delta S_i' + \Delta GG_i' \right), \tag{3}$$

where $\Delta S_i'$ and $\Delta GG_i'$ are the proportion effect and concentration effect, respectively, of consuming the ith type of non-fossil fuel:

$$\Delta S_i' = \begin{cases} 0, & \text{if } S_i^t \times GG_i^t - S_i^0 \times GG_i^0 = 0 \\ f\left(S_i^t \times GG_i^t, S_i^0 \times GG_i^0\right)\left[\frac{S_i^t - S_i^0}{(S_i^t + S_i^0)/2}\right], & \text{if } S_i^t \times GG_i^t - S_i^0 \times GG_i^0 \neq 0 \end{cases}, \tag{3a}$$

$$\Delta GG_i' = \begin{cases} 0, & \text{if } S_i^t \times GG_i^t - S_i^0 \times GG_i^0 = 0 \\ f\left(S_i^t \times GG_i^t, S_i^0 \times GG_i^0\right)\left[\frac{GG_i^t - GG_i^0}{(GG_i^t + GG_i^0)/2}\right], & \text{if } S_i^t \times GG_i^t - S_i^0 \times GG_i^0 \neq 0 \end{cases}. \tag{3b}$$

In Formulas (3a)–(3b):

$$f\left(S_i^t \times GG_i^t, S_i^0 \times GG_i^0\right) = \frac{S_i^t \times GG_i^t - S_i^0 \times GG_i^0}{\frac{2\left(S_i^t - S_i^0\right)}{S_i^t + S_i^0} + \frac{2\left(GG_i^t - GG_i^0\right)}{GG_i^t + GG_i^0}}.$$

LMDI and MRCI decomposition of changes in global non-fossil fuel consumption

Non-fossil fuel consumption can be decomposed into the proportions of non-fossil fuels accounted for by total primary energy consumption, per capita primary energy consumption, and population size, termed the structure effect, per capita effect and population effect, respectively (the following formula):

$$NFE_i^t = \frac{NFE_i^t}{E_i^t} \times \frac{E_i^t}{POP_i^t} \times POP_i^t = ES_i^t \times PE_i^t \times POP_i^t, \tag{4}$$

where NFE represents non-fossil fuel consumption; E the primary energy consumption; POP the total population, superscript t represents year t, and subscript i represents country i. ES, PE and POP represent the proportions of non-fossil fuels accounted for by total primary energy consumption, per capita primary energy consumption and population size, respectively.

Furthermore, the change in non-fossil fuel consumption from year o to year t can be decomposed into:

$$\Delta NFE_i = NFE_i^t - NFE_i^0 = \Delta ES_i + \Delta PE_i + \Delta POP_i, \tag{5}$$

where ΔES_i is the structure effect; ΔPE_i the per capita effect; and ΔPOP_i the population effect, and:

$$\Delta ES_i = \begin{cases} 0, & \text{if } \mathrm{NFE}_i^t \times \mathrm{NFE}_i^0 = 0 \\ L\left(NFE_i^t, NFE_i^0\right)\ln\left(\frac{ES_i^t}{ES_i^0}\right), & \text{if } \mathrm{NFE}_i^t \times \mathrm{NFE}_i^0 \neq 0 \end{cases}, \tag{5a}$$

$$\Delta PE_i = \begin{cases} 0, & \text{if } NFE_i^t \times NFE_i^0 = 0 \\ L\left(NFE_i^t, NFE_i^0\right)\ln\left(\frac{PE_i^t}{PE_i^0}\right), & \text{if } NFE_i^t \times NFE_i^0 \neq 0 \end{cases}, \tag{5b}$$

$$\Delta POP_i = \begin{cases} 0, & \text{if } NFE_i^t \times NFE_i^0 = 0 \\ L\left(NFE_i^t, NFE_i^0\right)\ln\left(\frac{POP_i^t}{POP_i^0}\right), & \text{if } NFE_i^t \times NFE_i^0 \neq 0 \end{cases}, \tag{5c}$$

where in (5a)–(5c):

$$L(x,y) = \frac{(x-y)}{(\ln x - \ln y)}.$$

As described in Section 2.1, the MRCI and LMDI methods are two types of decomposition method of the same class. In this study, these two methods are applied separately to the decomposition, in order to improve the reliability of the results. The MRCI decomposition of global non-fossil fuel consumption change is as follows:

$$\Delta NFE_i = NFE_i^t - NFE_i^0 = \Delta ES_i^* + \Delta PE_i^* + \Delta POP_i^*, \tag{6}$$

where ΔES_i^* is the structure effect; ΔPE_i^* the per capita effect; and ΔPOP_i^* the population effect, in which:

$$\Delta ES_i^* = \begin{cases} 0, & \text{if } \mathrm{NF}E_i^t - \mathrm{NF}E_i^0 = 0 \\ f\left(NFE_i^t, NFE_i^0\right)\left[\frac{ES_i^t - ES_i^0}{\left(ES_i^t + ES_i^0\right)/2}\right], & \text{if } \mathrm{NF}E_i^t - \mathrm{NF}E_i^0 \neq 0 \end{cases}, \tag{6a}$$

$$\Delta PE_i^* = \begin{cases} 0, & \text{if } NFE_i^t - NFE_i^0 = 0 \\ f\left(NFE_i^t, NFE_i^0\right)\left[\frac{PE_i^t - PE_i^0}{\left(PE_i^t + PE_i^0\right)/2}\right], & \text{if } NFE_i^t - NFE_i^0 \neq 0 \end{cases}, \tag{6b}$$

$$\Delta POP_i^* = \begin{cases} 0, & \text{if } NFE_i^t - NFE_i^0 = 0 \\ f\left(NFE_i^t, NFE_i^0\right)\left[\frac{POP_i^t - POP_i^0}{\left(POP_i^t + POP_i^0\right)/2}\right], & \text{if } NFE_i^t - NFE_i^0 \neq 0 \end{cases}. \tag{6c}$$

Data

The global energy consumption data analyzed in this paper are derived from the BP Statistical Review of World Energy (1965–2016), while the demographic data are derived from The United Nations Statistics Division (1984–2016). In addition to providing worldwide energy consumption data from 1965 to 2015, the BP Statistical Review also lists specific energy consumption data for 67 countries or regions, taking into account the matching of energy consumption data with demographic data, as well as the minimal non-fossil fuel consumption in some countries (annual consumption $< 50{,}000$ toe). A sample of 63 countries was selected to analyze global non-fossil fuel consumption, as follows: Algeria, Argentina, Australia, Austria, Azerbaijan, Bangladesh, Belarus, Belgium, Brazil, Bulgaria, Canada, Chile, China, Colombia, Czech Republic, Denmark, Ecuador, Egypt, Finland, France, Germany, Greece, Hungary, India, Indonesia, Iran, Israel, Italy, Japan, Kazakhstan, Kuwait, Lithuania, Malaysia, Mexico, the Netherlands, New Zealand, Norway, Pakistan, Peru, Philippines, Poland, Portugal, Qatar, Romania, Russian Federation, Saudi Arabia, Singapore, South Africa, South Korea, Spain, Sweden, Switzerland, Thailand, Trinidad and Tobago, Turkey, Turkmenistan, Ukraine, United Arab Emirates, UK, USA, Uzbekistan, Venezuela and Vietnam. This sample is believed to have strong global representativeness; for example, in 2015, the group accounted for >94 percent of global consumption of primary energy and non-fossil fuels. In addition, since non-fossil fuel consumption in many of these countries was minimal or zero during the early years, analysis of that period was not very meaningful and so the study period was revised to 1985–2015.

Empirical results

Global-scale non-fossil fuel consumption (1985–2015)

Figure 1 shows the changes in total global energy consumption, non-fossil fuel consumption, and fossil energy consumption from 1985 to 2015. It can be seen that global energy demand increased continuously during this period. In addition, compared to global fossil energy consumption, non-fossil fuel use remains modest but is increasing both in terms of consumption and proportion, indicating that non-fossil fuels are receiving increasing attention.

In this paper, non-fossil fuels are divided into five categories (nuclear; hydro; solar; wind; geo, biomass, and others), so as to examine the changing trends in global consumption of various non-fossil fuels from the perspective of energy consumption structure. Figure 2 shows that the consumptions of hydro, solar, wind and other non-fossil fuels are increasing; in particular, hydropower consumption is much higher and is growing at the fastest rate.

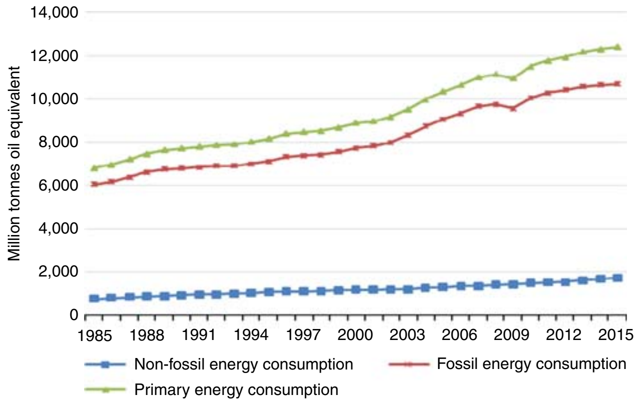

Figure 1. Global non-fossil fuel consumption (1985–2015)

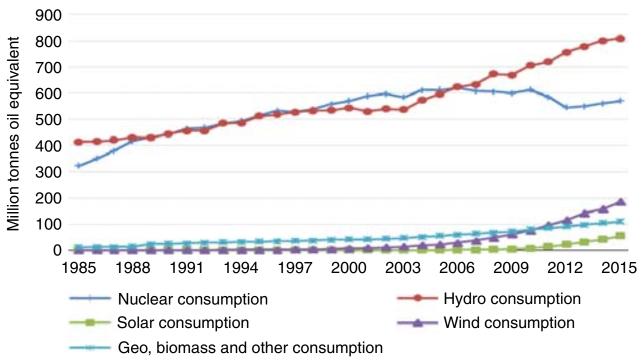

Figure 2. Global consumption of various non-fossil fuels (1985–2015)

However, it should be noted that, although nuclear consumption is also high, its growth has slowed or even declined since 2011, reflecting the large uncertainty remaining in global nuclear consumption.

Since regional difference is a topic of interest in energy consumption studies (Papathanasopoulou and Jackson, 2009; Duro and Padilla, 2011; Lawrence *et al.*, 2013), non-fossil fuel consumption is then studied among the sample countries from a regional perspective (see Figure 3). Note that this paper presents only a comparison of non-fossil fuel consumption in the 63 sample countries in 1985, 1995, 2005 and 2015. Figure 3 shows that there are clear regional differences. For example, non-fossil fuel consumption among the major North American countries was continuously high from 1985 to 2015, while those of Australia, some Eastern Europe countries, and South Africa were lower. It is worth mentioning that several countries, such as Brazil, China, India and Russia, have seen more apparent changes. Specifically, during the survey period, the level of non-fossil fuel consumption in Russia first declined and then increased; in contrast, consumption in Brazil, India, and China increased, most obviously in China. Clearly, global consumption of non-fossil fuels grew rapidly during the sampling period, but the data also show large regional inequalities.

Following the above analysis of global non-fossil fuel consumption from the perspectives of consumption scale, consumption structure, and regional difference, the top 10 consumers of non-fossil fuels are identified in order to better observe the current consumption among the main consumers. As seen in Table I, nine of the ten countries showed rapidly increasing consumption quantities of non-fossil fuel. The exception was Japan, where consumption declined: Following the 2011 Tohoku earthquake and Fukushima nuclear leakage accident, Japan's nuclear consumption has fallen sharply, resulting in a large decrease in the quantity and proportion of non-fossil fuel consumption. The consumption of non-fossil fuel in China, South Korea, and India grew faster during 1985–2015, while the proportion in primary energy consumption in France, Canada, Brazil and German was higher in 2015.

Table II further shows the consumption structure for various non-fossil fuels among the top 10 consumers in 2015. The main types of non-fossil fuel consumption differ for each country.

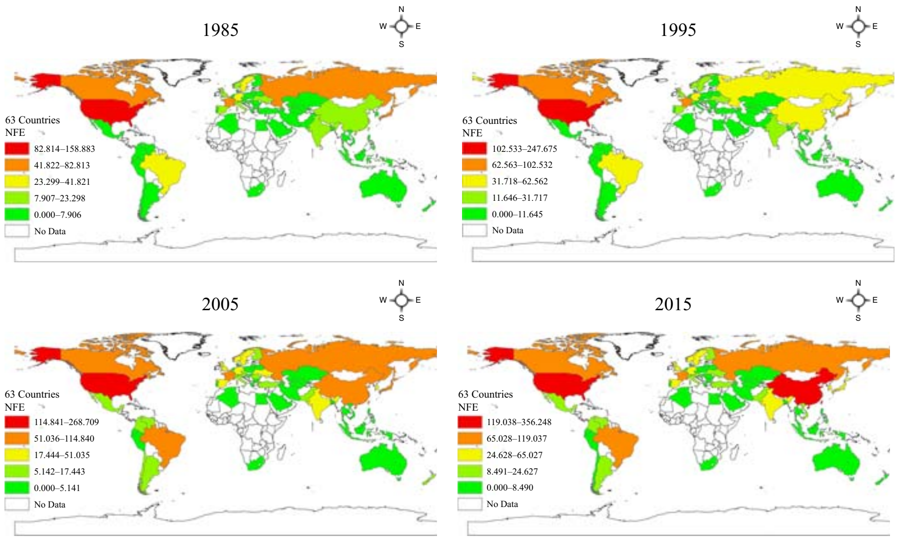

Figure 3. Regional comparison of global non-fossil fuel consumption in different years

Table I.
Non-fossil fuel consumption (mtoe) among global top 10 consumers, 2015

Country	Non-fossil fuel consumption in 1985	Non-fossil fuel consumption in 2015	Proportion of non-fossil fuels in primary energy consumption in 2015 (%)	Average annual geometric rate of growth (1985–2015) (%)
China	20.91	356.25	11.82	109.91
USA	158.88	319.03	13.99	102.35
France	65.18	119.04	49.80	102.03
Canada	82.81	117.62	35.65	101.18
Brazil	41.82	101.26	34.58	102.99
Russian Federation	58.62	82.75	12.41	101.16
Germany	35.69	65.03	20.28	102.02
India	12.74	52.25	7.46	104.82
South Korea	4.62	39.56	14.28	107.42
Japan	55.93	37.36	8.33	98.86

Table II.
Different types of non-fossil fuel consumption (mtoe) among top 10 global consumers, 2015

Country	Nuclear consumption	Hydro consumption	Solar consumption	Wind consumption	Geo, biomass and other energy consumption
China	38.6	254.9	8.9	41.9	12.0
USA	189.9	57.4	8.8	43.6	19.3
France	99.0	12.2	1.7	4.6	1.6
Canada	23.6	86.7	0.6	5.6	1.2
Brazil	3.3	81.7	^[a]	4.9	11.3
Russian Federation	44.2	38.5	^	^	0.1
Germany	20.7	4.4	8.7	19.9	11.3
India	8.6	28.1	1.5	9.4	4.6
South Korea	37.3	0.7	0.9	0.4	0.4
Japan	1.0	21.9	7.0	1.2	6.3

Note: [a]Means less than 0.05

For example, the USA consumed the most nuclear energy (189.9 mtoe), wind, and other non-fossil energy types, whereas China was the largest consumer of hydropower (254.9 mtoe) and solar.

For comparison with the 2015 results presented in Tables I and II, Figure 4 shows the non-fossil fuel consumption quantity and corresponding changes for China, USA, France, India, and Japan during the sampling period (1985–2015). The five countries were selected for the following reasons. First, the USA and China were the largest primary energy consumers, with China overtaking the USA. Second, although India had the lowest proportion of non-fossil fuel consumption among the top 10 countries in 2015, the quantity

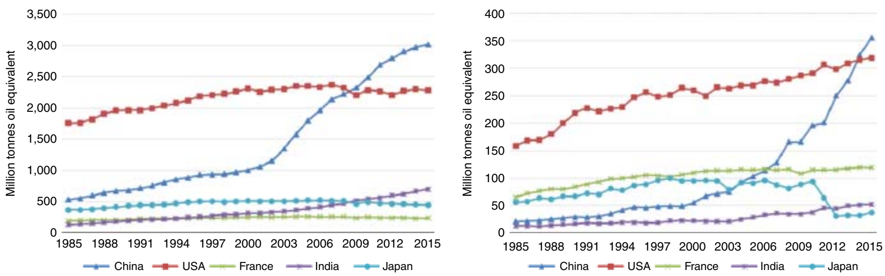

Figure 4.
Primary energy consumption (left) and non-fossil fuel consumption (right) for China, USA, France, India and Japan, 1985–2015

has increased rapidly at 4.84 percent annually, which although lower than China (9.91 percent) and South Korea (7.42 percent) is higher the growth rates for the USA (2.35 percent) and France (2.03 percent) during 1985–2015. Third, as ones of the world's top 10 non-fossil fuel consumers, France had the highest proportion of non-fossil fuel consumption in 2015, and Japan, as the exception, has experienced decreasing non-fossil fuel consumption.

Figure 4 shows that China has overtaken the USA to become not only the world's largest energy consumer overall, but also the largest consumer of non-fossil energy. The rapid growth of primary energy consumption in China has been mainly driven by its booming economy in recent years (Chen *et al.*, 2016, 2017), while its increasing consumption of non-fossil fuels has been contributed to the development of green technologies and policies supporting circulating economy and cleaner energy (Wu, 2017; Song and Wang, 2018). In addition, although India has experienced relatively rapid growth in primary energy consumption, and its energy consumption now exceeds that of France, it has still seriously lagged behind France in terms of non-fossil fuel consumption. This means that India should pay greater attention to the technological development of clean energy.

Inequality analysis of global per capita non-fossil fuel consumption

Formula (2) is used to analyze the degree of inequality in global per capita non-fossil fuel consumption, and the contributions of various non-fossil fuels to this inequality. Based on Table III, Figure 5 presents the changing trends in the contributions to per capita inequality in non-fossil fuel consumption. It should be noted that, since there is no obvious regularity in year-on-year growth, Formula (4) adopts a fixed base to decompose from the perspective of cumulative change, in order to eliminate annual fluctuations.

Table III and Figure 5 show that during the sampling period inequality in global per capita non-fossil fuel consumption has decreased. That is, among the main energy consumers, the Gini coefficient of inequality decreased by 0.1392, from 0.7412 in 1985 to 0.6020 in 2015. In addition, decomposition of the Gini coefficient shows that 80 percent of the inequality in global per capita non-fossil fuel consumption among the main energy consumers was contributed by nuclear and hydropower; whereas, the contributions of solar, wind, and other renewable energy resources were less than 20 percent. However, over time, the contributions of nuclear and hydropower decreased whereas those of other non-fossil fuels increased. It is concluded that the larger contributions of nuclear and hydropower are attributable to their higher shares of primary energy consumption, according to Formula (2).

Although the consumption of nuclear and hydropower far exceeds that of other non-fossil energies, the worldwide development of nuclear and hydropower has been somewhat restricted by some adverse factors. For example, changes in hydrological conditions, such as droughts and floods, have significant influence on electricity generation by hydroelectric power plants; and security is an important issue influencing nuclear development. China's nuclear development is expected to decrease to 60–70 GW by the year 2020 due to the negative influence of the Fukushima nuclear accident (Zhou *et al.*, 2012). Many countries have developed types of new energy other than nuclear and hydropower. For instance, as the country with greatest wind energy consumption, China's installed capacity increased from 11.26 GW in 2005 to 44.73 GW in 2010, and its solar energy capacity increased from 70 MW to 700 MW (Zhou *et al.*, 2012). The UK and Iceland also vigorously developed wind energy, and the UK became the global leader in offshore wind installation, with more than 1200 MW of offshore wind power in 2012 (Devlin *et al.*, 2017).

The convergence theory is an important part of modern economic growth theory, and several scholars have applied it to the fields of carbon emission and energy consumption (Strazicich and List, 2003; Anoruo and DiPietro, 2014). β-convergence, proposed by Baumol (1986), represents absolute convergence. If β-convergence exists, individuals with lower

Year	Gini coefficient	Contributions Nuclear consumption (%)	Hydro consumption (%)	Solar consumption (%)	Wind consumption (%)	Geo, biomass, and other consumption (%)
1985	0.7412	47.49	51.06	0.00	0.00	1.45
1986	0.7445	49.48	49.01	0.00	0.00	1.51
1987	0.7468	51.18	47.32	0.00	0.00	1.52
1988	0.7416	53.52	45.00	0.00	0.00	1.49
1989	0.7403	53.93	43.25	0.01	0.07	2.75
1990	0.741	53.75	43.24	0.01	0.09	2.91
1991	0.7413	54.48	42.46	0.01	0.09	2.95
1992	0.741	54.45	42.29	0.01	0.10	3.14
1993	0.7383	54.19	42.56	0.01	0.12	3.13
1994	0.7315	55.09	41.54	0.02	0.14	3.21
1995	0.7304	54.57	42.15	0.02	0.14	3.12
1996	0.7311	55.27	41.40	0.02	0.15	3.16
1997	0.7313	54.25	42.20	0.02	0.19	3.33
1998	0.7238	55.06	41.27	0.02	0.26	3.38
1999	0.7289	55.25	40.96	0.02	0.34	3.43
2000	0.7272	55.24	40.78	0.02	0.52	3.43
2001	0.7169	57.64	38.46	0.03	0.64	3.23
2002	0.717	57.07	38.58	0.03	0.90	3.42
2003	0.7103	56.61	38.59	0.04	1.11	3.66
2004	0.7011	56.75	38.08	0.05	1.37	3.75
2005	0.6943	55.65	38.67	0.07	1.64	3.96
2006	0.6829	55.39	38.43	0.10	2.00	4.08
2007	0.6759	54.33	38.68	0.13	2.59	4.26
2008	0.6651	52.90	39.29	0.22	3.31	4.29
2009	0.6637	51.78	39.47	0.36	3.99	4.40
2010	0.6503	51.06	38.81	0.56	4.88	4.68
2011	0.6419	47.85	40.18	1.00	6.03	4.93
2012	0.6305	45.16	41.02	1.56	7.14	5.11
2013	0.6198	44.07	40.34	2.01	8.31	5.29
2014	0.6109	43.98	39.12	2.55	8.91	5.45
2015	0.6020	43.09	37.92	3.16	10.22	5.62

Table III.
Global per capita non-fossil fuel consumption Gini coefficient and contributions of various non-fossil fuels (1985–2015)

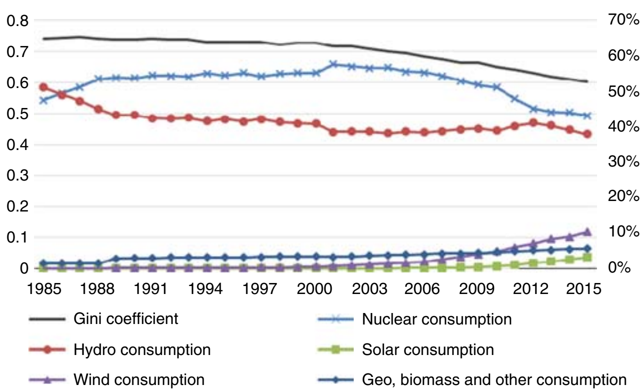

Figure 5.
Global per capita non-fossil fuel consumption, and contributions of various non-fossil fuels to Gini coefficient (1985–2015)

initial values have higher growth rates (Payne *et al.*, 2017). The results of the above analysis show that large inequality exists in global per capita non-fossil fuel consumption; thus, absolute β-convergence is used here to further test whether the global per capita non-fossil fuel gap is narrowing. Table IV lists the absolute convergence of global per capita non-fossil fuel consumption over different time spans. On the whole, during 1985–2015, there was significant absolute convergence; however, absolute convergence during the periods 1985–1995 and 1995–2005 was not significant. Significant convergence occurred during the last ten years (2005–2015). Other studies have shown similar results. For example, Payne *et al.* (2017) found the presence of β-convergence when analyzing the USA's per capita renewable energy consumption. The present analysis indicates that, at the global scale, non-fossil fuel consumption also showed convergence, i.e., during the sampling period, and particularly during the last ten years (2005–2015); since countries with lower primary per capita non-fossil fuel consumption showed higher per capita growth rates, the disparity gradually narrowed.

According to Formula (3), the impact of each non-fossil fuel on the inequality of per capita non-fossil fuel consumption depends on two factors: the proportion and concentration of per capita non-fossil fuel consumption. Therefore, Formula (3) is further applied to achieve decomposition of the incremental Gini coefficient, so as to calculate the effects of these two factors. The results are shown in Table V, based on which Figure 6 describes the trends of the two factors.

From Table V and Figure 6, it can be seen that, during the sampling period, the decreasing inequality in global per capita non-fossil fuel consumption was mainly attributed to the concentration effect, and less to the proportion effect.

Table IV. Cross-sectional absolute β-test

Period	β coefficient	t-statistic	Adj R^2
1985–2015	−0.2968	−3.61[a]	0.1741
1985–1995	−0.0659	−1.11	0.0041
1995–2005	−0.0293	−1.47	0.0195
2005–2015	−0.1382	−3.25[a]	0.1415

Note: [a]Denotes significance at the 1 percent level

Table V. Concentration effect and proportion effect of global per capita consumption of non-fossil fuel on Gini coefficient (1985–2015)

Year	Concentration effect	Proportion effect	Year	Concentration effect	Proportion effect
1986	0.0010	0.0022	2001	−0.0127	0.0025
1987	0.0002	0.0022	2002	0.0006	−0.0005
1988	−0.0076	0.0024	2003	−0.0057	−0.0010
1989	−0.0022	0.0009	2004	−0.0079	−0.0013
1990	0.0009	−0.0002	2005	−0.0044	−0.0024
1991	−0.0007	0.0009	2006	−0.0093	−0.0020
1992	−0.0007	0.0004	2007	−0.0043	−0.0027
1993	−0.0015	−0.0012	2008	−0.0064	−0.0043
1994	−0.0075	0.0007	2009	−0.0007	−0.0007
1995	−0.0006	−0.0005	2010	−0.0108	−0.0026
1996	−0.0003	0.0010	2011	−0.0042	−0.0043
1997	0.0013	−0.0012	2012	−0.0040	−0.0074
1998	−0.0077	0.0002	2013	−0.0087	−0.0019
1999	0.0038	0.0014	2014	−0.0079	−0.0010
2000	−0.0018	0.0000	2015	−0.0086	−0.0003

Proportion and LMDI – MRCI analyses of global non-fossil fuel consumption

The previous sections analyzed two aspects of global non-fossil fuel consumption: the scale and development trends, and the inequality and influencing factors. As York (2016) identified, ensuring the substitution of fossil fuel by clean fuels is an important challenge for future global climate and environmental governance. Therefore, quantitative analysis of this substitution process is key to addressing global environmental governance issues such as global warming and environmental change.

Figure 7 compares non-fossil fuel consumption as a proportion of primary energy consumption in 2015 among the six geographic regions of the world (North America; South and Central America; Europe and Eurasia; Middle East; Africa; East Asia and Pacific). Generally, the proportion of non-fossil fuel consumption was lowest in the Middle East and Africa, while their role as alternatives to fossil fuels is more significant in Europe and Eurasia. In 2015, the countries in North America; South and Central America; Europe and Eurasia; and Asia Pacific with higher proportion of non-fossil fuel consumption were Canada, Brazil, Sweden, and New Zealand, respectively.

The increment in non-fossil fuels consumption could be decomposed into structure effect (the proportion of non-fossil fuels to total primary energy consumption), per capita effect (per capita primary energy consumption), and population effect (population size), according to Equations (5) and (6).

Figure 8 clearly shows that the decomposition results obtained using the MRCI (right) and LMDI (left) methods are similar, since these two methods are derived from the same

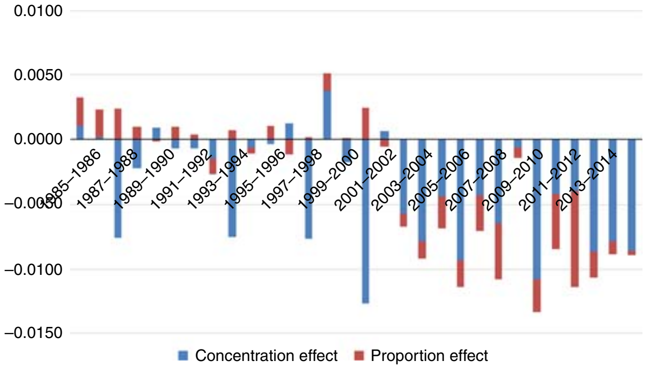

Figure 6.
Decomposition of the incremental Gini coefficient for global per capita consumption of non-fossil fuel (1985–2015)

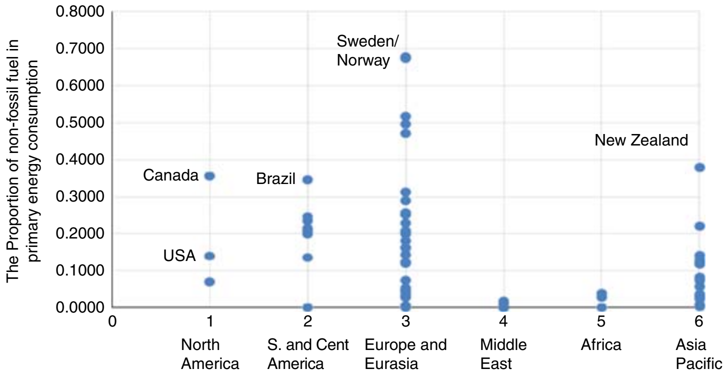

Figure 7.
Proportion of global non-fossil fuel consumption to primary energy consumption in 2015

general decomposition expression. The population effect was the main factor in increased non-fossil fuel consumption worldwide; per capita effect become significant after the year 2002; and structure effect was less important than per capita effect and fluctuated slightly after the year 2004.

In addition, representative counties from Figure 7 (Brazil, Canada, New Zealand, Norway, Sweden and USA), which consumed a higher proportion of non-fossil fuels, were selected for incremental decomposition analysis of their non-fossil fuel consumption. In addition, emerging economies such as Brazil, China and India have been extensively studied when considering sustainable economic development (Gozgor, 2016; Jabbour, 2010; Jabbour and Jabbour, 2016). Therefore, these three emerging economies are also considered as representative countries. As the LMDI method is more commonly used, only the decomposing results based on Formula (5) are presented in Figure 9.

One main feature of Figure 9 is that although New Zealand, Norway and Sweden consumed higher proportions of non-fossil fuels during 1985–2015, these shares fluctuated greatly, whereas that of China grew stably and continuously.

As for the causes of the increase in non-fossil fuels consumption, the population effect presented steady growth, and was the main factor in Canada and China. Furthermore, the per capita effect showed consistent growth in Brazil, China and India, whereas it declined slightly in New Zealand, Sweden and the USA in recent years.

All other factors being equal, per capita energy consumption is positively associated with economic development yet negatively associated with technical progress; consequently, developed countries such as New Zealand, Sweden and the USA tend to enhance energy utilization efficiency with the help of green technology, whereas people in emerging countries such as Brazil, China and India consume more energy in line with development of economy.

Finally, although the structure effect was the main factor for the increase in Sweden and the USA, it had minimal importance or even negative influence in driving the increases observed in many countries such as Brazil, Canada, China, India, Norway and New Zealand. In fact, the USA has implemented more aggressive policies to promote the development of non-fossil fuels since the 1990s, such as the Energy Policy Act of 1992, the Energy Independence and Security Act of 2005, and policies encouraging sustainable expansion of renewable energy resources in 2007 (Payne *et al.*, 2017). Furthermore, China, as the largest developing country, has made great efforts to develop renewable energy since 2013 (Peggy and Kenneth, 2014). However, in general, much more progress is required toward effectively replacing fossil energy with non-fossil fuels worldwide.

Conclusions

This study selected 63 countries to review the global trends, inequalities, and drivers of increased non-fossil fuel consumption from 1985 to 2015, based on BP statistical data.

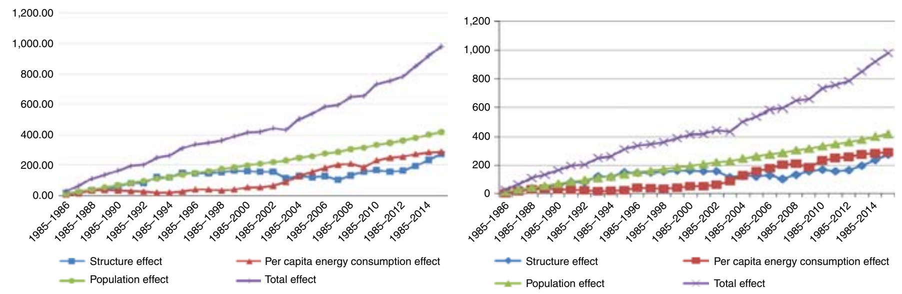

Figure 8.
Decomposition of change in global non-fossil energy consumption obtained by LMDI (left) and MRCI (right) methods (1985–2015)

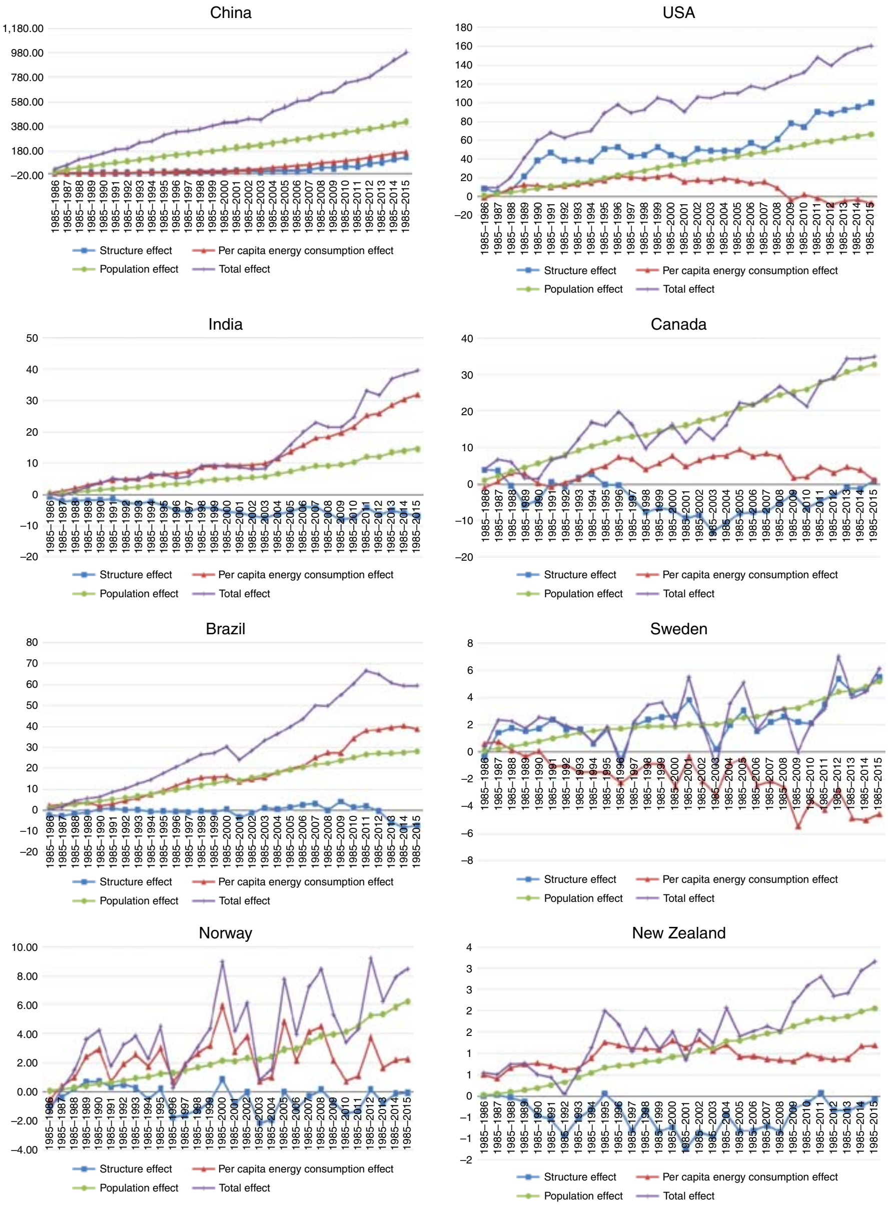

Figure 9.
Additive decomposition of changes in non-fossil energy consumption in representative countries (1985–2015)

Similarities were derived between the LMDI and MRCI decomposition methods, and a complete general index decomposition expression was provided in addition to a method for complete decomposition of the incremental Gini coefficient. The conclusions are as follows.

First, on the one hand, global consumption of non-fossil fuels remains limited compared with fossil energy consumption, but has shown a consistently increasing trend from 1985 to 2015. On the other hand, consumption of nuclear and hydropower has been much greater than that of other non-fossil fuels such as solar, wind, etc.

Second, there remains inequality in non-fossil fuel consumption per capita, although this declined from 0.7412 in 1985 to 0.6020 in 2015. However, there was a significant absolute convergence trend in global per capital non-fossil fuel consumption during 1985–2015, with non-fossil fuel consumption growing fastest in countries with lower initial values. Structural decomposition of the Gini coefficient showed that differences in nuclear and hydropower consumption contributed most to the global disparity in non-fossil fuel consumption per capita; and – based on the incremental decomposition – that the concentration effect played a significant role.

Finally, in terms of the driving factors for the increase in non-fossil consumption: according to the LMDI and MRCI decomposition methods, it is concluded that global population growth was the most important factor promoting the increase in non-fossil consumption, and that this differed between countries. For example, the increasing structure effect drove the growth of non-fossil fuel consumption in the USA during 1985–2015, whereas the increase in per capita energy consumption effect pushed the growth of non-fossil fuel consumption in Brazil and India during most years.

Generally, under conditions of increasing environmental pressure, such as global warming, resource depletion, and constant pressure on population growth, more and more countries have made great efforts to promote the development of non-fossil energy. Moreover, technical advances in the utilization of renewable energy benefit the development of a circular economy, which has attracted increasing attention. Renewable energy could be deployed in agricultural, industrial, and residential sectors by following the principles of a circular economy (reduce, reuse and recycle). It should be noted that although there is vast space for technological development in non-fossil fuel utilization in the future, replacing fossil energy with non-fossil fuels remains challenging, especially for developing countries.

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