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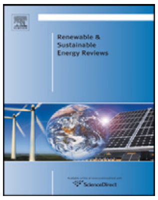

China's energy consumption and sustainable development: Comparative evidence from GDP and genuine savings

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ABSTRACT

This paper employs the structural vector autoregressions framework and the generalized impulse response function to study the long-term dynamic relation between China's energy consumption and sustainable economic growth. In addition to the conventional economic indicators (GDP growth rates), genuine savings rates are particularly examined to indicate sustainable economic development. Results show that the high elasticity of energy consumption dramatically undermines the capacity of China's sustainability in terms of reducing genuine savings rates. We also use variance decomposition to calculate relative variance contribution rates, in order to identify the most important factor affecting GDP growth as well as genuine savings rates. The analysis finds that clean and renewable energy increase the country's genuine savings significantly. That is, renewable energy consumption promotes sustainable development for both natural and economic societies. However, increase in traditional solid energy consumption is more likely to benefit only the growth of GDP.

Contents

1. Introduction

Since the market-oriented reform of 1978, China has been experiencing remarkable economic growth at an average annual growth rate of 9.8%.[1] Its GDP had reached 4985 billion US dollars by the end of 2009 and ranked 3rd in the world following the US and Japan.[2] Data from the State Administration of Foreign Exchange suggests that foreign exchange reserves were 2454 billion US dollars at the end of June 2010. At the same time, despite having the largest population, China's per capita income still increased significantly. An un-neglectable phenomenon is that, compared to EU15 and the OECD countries, China suggests an evident catch-up trend (Fig. 1).

However, along with remarkable economic growth, more than 30 years of rapid industrialization in China has also burned substantial energy and thereby produced a large amount of GHG. The average increase in per capita energy consumption has reached 15% since 2000 and this upward trend is also apparent for solid and liquid fuels (Fig. 2). The elasticity of energy consumption for income is high as shown in Fig. 3.

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[1] Author's calculation based on China Statistical Yearbook 2007.

[2] Data from the World Bank on-line database.

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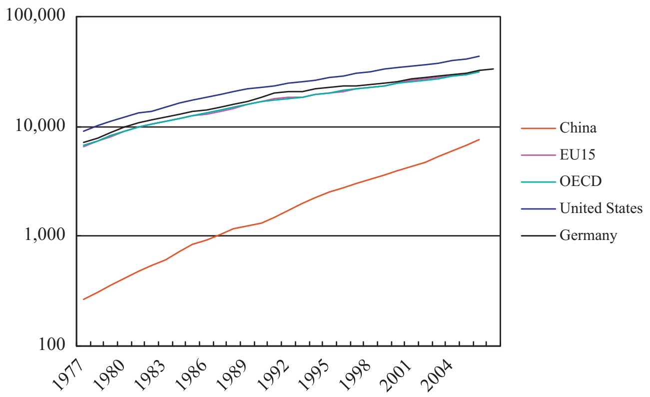

Fig. 1. Log per capita GDP for China and other countries in current PPPs US$, 1977–2006.
Source: Author's calculations. Data of EU15 and OECD countries come from OECD's iLibrary. China's data are the World Bank estimates provided by the UNSD's national account database.

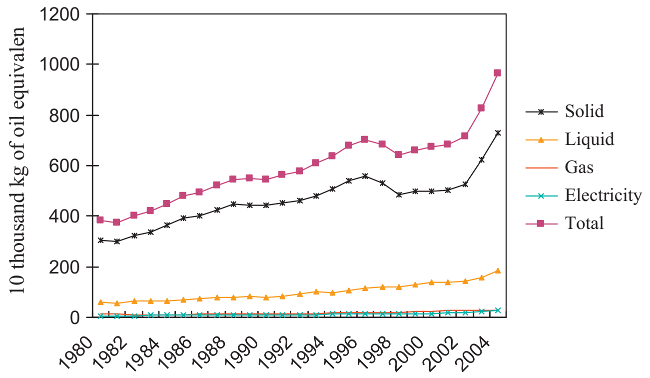

Fig. 2. China's per capita energy consumption by type, 1980–2004.
Source: United Nations Statistical Division (UNSD).

Even though there were a few shortfalls in the 1990s (below zero), the elasticities of all types of energy input except gas have climbed up to 2 since 2000. The country's economy has become heavily energy-intense. Further increasing fossil-fuel combustion and low energy efficiency jointly produced a great quantity of greenhouse gas (GHG). Table 1 demonstrates that as, the 4th biggest economy, China was the second largest CO_2 emitter in the world at the end of 2004 following the US. An estimation from the International Energy Agency suggested that China's emission was 6.5 billion tons in 2008,[3] rendering it the biggest CO_2 producer in the world.

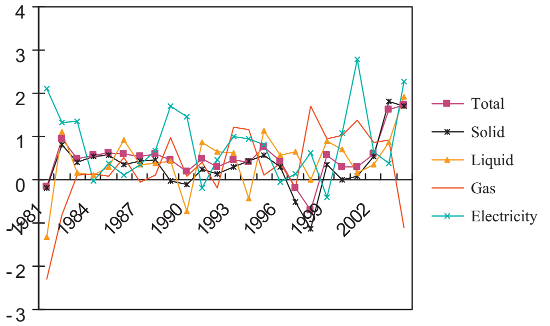

Fig. 3. Elasticities of energy consumption for income in China, 1981–2004.
Source: Author's calculations based on data from UNSD.

In addition to massive aggregate emissions, the growth rate of per capita carbon emissions in China is also significantly higher than that of countries whose economies rank higher than China as well as regions with comparable development level (Fig. 4). More alarmingly, China's annual growth rate of per capita CO_2 has soared to 11.45% since 2003, compared to 2.48% in the period of 1991–2002.[4] Considering that China has not been bound by any GHG emissions cap, this rapid increasing trend is likely to continue at least in the near future.

Even though carbon-use intensity of growth declined during this period, the carbon footprint increased substantially, about 84.2% as shown in Fig. 5. This figure is much higher than the carbon footprint in the US (6.7%), the mean in OECD countries (6.5%) and all developing countries (41.2%) and the world average increase (4.7%). This means that the income growth is faster than the decrease in carbon intensity. By contrast, Germany successfully saw a considerable decrease of carbon footprint by 20.5% as well as a decline in the carbon intensity by 34.5%.

The above energy-intensive growth pattern is worrying for both China and the world. On the one hand, the fast increasing GHG emissions places considerable pressure on the environment and climate. China is increasingly expected to undertake more responsibilities in the World's fight against climate change. On the other hand, it is doubtful that China can maintain its high growth rate in the next 30 years under the current pattern of energy consumption. Nonrenewable fossil fuels (particularly coal) have long dominated the energy needs and low efficiency and lack of clean technologies may undermine the resource and environmental base for future sustainable development. As the government highlights the co-coordinated development between human society and environment, it is worth examining whether China is able to achieve de-carbonized sustainable growth in the long-run.

2. Reviewing greenhouse gas emissions in China

A mass of studies test the relations between GHG, energy consumption and economic growth. Smulders and Nooij [27] find that reducing energy use does not affect economic growth, while plants to reduce the growth rate of energy inputs would depress economic growth in both the long and short term. Dosi and Grazzi [7] discuss the same research question from aspects of the good notion of environment, relative price changes for energy and "discontinuities between different technological paradigms". Nakata [23] reviews a variety of energy-economic models to cast light on the way energy systems change.

Additionally, a large number of studies focus on the relation between energy use and environment [10–12,28–30]. It is widely hypothesized that increasing energy consumption could cause environmental degradation and therefore retard economic growth. The dominant school is the environmental Kuznets curve (EKC)[5] which posits an inverted *U* shape to GHG emission (or energy consumption) as income grows. As regards China, there is no conclusive finding for the existence of EKC between GHG and income growth. The results are very sensitive to the model specifications, measures of indicators and the sample periods of testing. The other line investigating the GHG/energy-income relation focuses on the

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[3] Data come from IEA on-line database at http://data.iea.org.

[4] Author's calculations based on data from Millennium Development Goals Indicators, UNSD.

[5] Many studies have critically reviewed the models of EKC family and their empirical applications for GHG, e.g. Dasgupta et al. [5], Stern [28], Muller-Furstenberger and Wagner [22].

Table 1
Energy-related carbon emissions, 1990–2004.

	Total emissions ($MtCO_2$)	Annual change of total emissions (%)	Emission share (%)		Population share (%)		Emissions per capita (tCO_2)	
	1990	2004	1990–2004	1990	2004	2004	1990	2004
China	2,398.9	5,007.1	7.8	10.6	17.3	20.2	2.1	3.8
US	4,818.3	6,045.8	1.8	21.2	20.9	4.6	19.3	20.6
Germany	980.4	808.3	−1.3	4.3	2.8	1.3	12.3	9.8
Japan	1,070.7	1,257.2	1.2	4.7	4.3	2.0	8.7	9.9
Least human development countries	74.1	146.3	7.0	0.3	0.5	11.8	0.2	0.2
Low human development countries	77.6	161.7	7.7	0.3	0.6	7.8	0.3	0.3
Medium human development countries	5,944.4	10,215.2	5.1	26.2	35.2	65.1	1.8	2.5
High-income OECD	10,055.4	12,137.5	1.5	44.3	41.9	14.3	12.0	13.2
World	22,702.5	28,982.7	2.0	100.0	100.0	100.0	4.3	4.5

Source: Based on data come from Human Development 2007/2008 Report, UNDP [17].

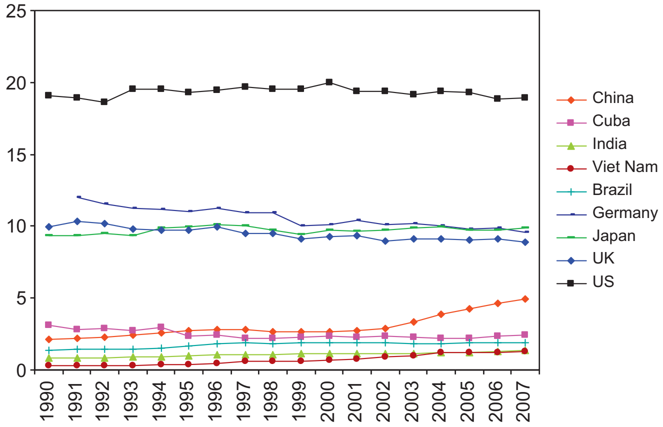

Fig. 4. Metric tons of CO_2 emissions per capita, 1990–2007.
Source: Millennium Development Goals Indicators, UNSD.

causality between energy consumption (and GHG) and economic growth. The most frequently employed models are VAR and VECM based on which Granger causality test, various integration and cointegration tests are implemented to reveal short- and long-run relations between GHG/energy and income. The national aggregate energy use and coal consumption are usually not found to cause GDP growth, while a bi-directional causality runs from electricity and oil consumption to GDP [26,31,33].[6] For different industries, the energy consumption in secondary industry suggests the most salient stimulative effect to the economic growth [16].

There are two underlying imperfections in previous studies. On the one hand, in the empirical view, the long-term dynamics of variables have been investigated extensively under the framework of conventional VAR and VECM. However, the aim of these studies is only to reveal whether there are stationary relations (e.g. cointegrations) or causality links between variables, but is not to suggest how economic development reacts to shocks from changing patterns of energy consumption and increasing GHG emissions.

On the other hand, the overwhelming majority use GDP as the indicator of economic growth [3,7] or a set of human development indicators representing sustainability [10,11]. As Hamilton [14] argued, genuine savings (GS) include all kinds of capital and capture the depreciation of both man-made and natural capital. Based on intertemporal optimization with undeclined social welfare, GS “equate to a modification to the so-called Hartwick rule” [6] and serve as an indicator of weak sustainability. That is, negative GS implies declining utility in the future. In this sense, it is worth directly examining the link between GS and elasticities of energy consumption and GHG emissions to see if current postures of energy use could benefit a country’s sustainability.

This study contributes to current literature in the above two aspects. This paper uses the structural vector autoregressions model and associated generalized impulse response functions to extrapolate how and to what extent shocks from different kinds of elasticities of energy consumption, energy international trade and GHG emissions could impact genuine savings dynamically in the long-run in a range of high-income OECD countries and LDCs, respectively. The rest of this paper is organized as follows: the empirical models are constructed in Section 3; then Section 4 gives the estimation results and discussion; Section 5 concludes.

3. Empirical strategies

3.1. Data

The energy consumption-related data from 1980 to 2004 come from the UNSD Common Database. We focus on commercial energy consumption which excludes the use of urban energy consumption and traditional biomass fuels, such as the combustion of straw and fuel wood. The total energy needs are separated into four types: solid, liquid, gas and electrical energy. The economic indicators are also chosen from the UNSD. The values of GDP are measured by 1990 constant USD. Then the elasticities of energy consumption are calculated accordingly based on these data. The genuine savings

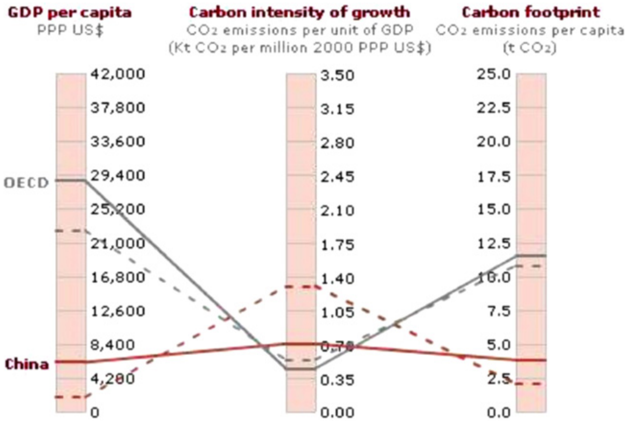

Fig. 5. The process of decarbonising growth, 1990–2004.
Note: The dotted and solid lines represent 1990 and 2004 respectively.
Source: Data in Human Development 2007/2008 Report, UNDP [17].

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[6] The causality from total energy consumption to GDP is also found to hold in some studies [15], but the result is relatively sensitive to what time period the model is built on [33].

rates are drawn from the World Bank Little Green Data Book 2006, calculated according to the following equation:

$$\text{Genuine savings rate} = \frac{\text{Gross national savings} - \text{Natural capital depreciation} - \text{Man-made capital depreciation} - \text{Cost of environmental damage} + \text{Spending on education}}{\text{Gross national savings}}$$

3.2. *Generalized impulse response function for GDP and GS*

Peng and Bao [24] employ generalized impulse response functions based on vector autoregressions model (VAR) to study the long-term dynamic relations between 6 kinds of pollutant and China's economic growth. However, considering that VAR cannot guarantee an orthogonalized impulse response function and therefore gives unreliable results [13], we refer to the form of structural VAR. More specifically, we build a four-variable SVAR(p) for GS rates and possible explanatory variables including energy-related factors and carbon emissions as follows:

$$B_0 y_t = \Gamma_0 + B_1 y_{t-1} + B_2 y_{t-2} + \cdots + B_p y_{t-p} + u_t \tag{1}$$

where

$$B_0 = \begin{bmatrix} 1 & -\beta_{12}^{(0)} & -\beta_{13}^{(0)} & -\beta_{14}^{(0)} \\ -\beta_{21}^{(0)} & 1 & -\beta_{23}^{(0)} & -\beta_{24}^{(0)} \\ -\beta_{31}^{(0)} & -\beta_{32}^{(0)} & 1 & -\beta_{34}^{(0)} \\ -\beta_{41}^{(0)} & -\beta_{42}^{(0)} & -\beta_{43}^{(0)} & 1 \end{bmatrix};$$

$$\Gamma_0 = \begin{bmatrix} \gamma_{10} \\ \gamma_{20} \\ \gamma_{30} \\ \gamma_{40} \end{bmatrix}; \quad y_t = \begin{bmatrix} \ln \mathrm{GS}_t \\ \ln \mathrm{EL}_t \\ \ln \mathrm{IE}_t \\ \ln \mathrm{CO}_{2_t} \end{bmatrix}; \quad u_t = \begin{bmatrix} u_{1t} \\ u_{2t} \\ u_{3t} \\ u_{4t} \end{bmatrix};$$

$$B_i = \begin{bmatrix} \beta_{11}^{(i)} & \beta_{12}^{(i)} & \beta_{13}^{(i)} & \beta_{14}^{(i)} \\ \beta_{21}^{(i)} & \beta_{22}^{(i)} & \beta_{23}^{(i)} & \beta_{24}^{(i)} \\ \beta_{31}^{(i)} & \beta_{32}^{(i)} & \beta_{33}^{(i)} & \beta_{34}^{(i)} \\ \beta_{41}^{(i)} & \beta_{42}^{(i)} & \beta_{43}^{(i)} & \beta_{44}^{(i)} \end{bmatrix}; \quad i = 1, 2, \ldots, p$$

The vector y_t includes all variables in the system at time t (y_{it}), i.e. the genuine savings rates, elasticities of energy consumption, the ratio of energy import to export, and per capita CO_2 emissions. The errors u_{it} represent the shocks happening to these four variables respectively and follow the white noise process as:

$$E(u_t u'_\tau) = \begin{cases} D, t = \tau \\ 0, \text{otherwise} \end{cases}$$

The number of lagged terms p is determined by lag exclusion test. After substituting p into Eq. (1), we can derive the GIRF from that SVAR(p).

Specifically, assume that B_0 is a low-triangle matrix, i.e. the model takes a recursive form, Eq. (1) becomes:

$$B_0 y_t = -\Gamma x_t + u_t \tag{2}$$

This can be further re-written in brief as:

$$y_t = \Pi' x_t + \varepsilon_t \tag{3}$$

where $\Pi' = -B_0^{-1}\Gamma$ and $\varepsilon_t = B_0^{-1} u_t$. Thereby the

$$\Omega = E(\varepsilon_t \varepsilon'_t) = B_0^{-1} D (B_0^{-1})'$$

At the same time, Eq. (3) can be expressed by VAM(∞), that is

$$y_t = (I_k + C_1 L + C_2 L^2 + \cdots)\varepsilon_t, \quad t = 1, 2, \ldots, T \tag{4}$$

Therefore we can explain y_{it} by

$$y_{it} = \sum_{j=1}^{k} (c_{ij}^{(0)} \varepsilon_{jt} + c_{ij}^{(1)} \varepsilon_{jt-1} + c_{ij}^{(2)} \varepsilon_{jt-2} + \cdots)$$

From Eqs. (2) and (3), we can derive the relation between disturbance terms as:

$$u_t = B_0 \varepsilon_t \tag{5}$$

Thus, Eq. (4) is further transformed to:

$$y_t = (I_k + C_1 L + C_2 L^2 + \cdots) B_0^{-1} u_t = D(L) u_t, \quad t = 1, 2, \ldots, T$$

in which $D(L) = D_0 + D_1 L + D_2 L^2 + \cdots$ and $D_0 = B_0^{-1}$. The elements in D_s are

$$d_{ij}^{(s)} = \frac{\partial y_{i,t+s}}{\partial u_{jt}}, \quad s = 0, 1, \ldots \quad t = 1, 2, \ldots, T \tag{6}$$

Eq. (6) is thereby the orthogonalized impulse response function. That is, at time period t, the response of $y_{i,t+s}$ facing one unit of shock from y_j. The accumulated IRF of y_i is expressed by $\sum_{s=1}^{\infty} d_{ij}^{(s)}$.

In order to avoid the effects of Cholesky decomposition (making results independent with the order of endogenous variables), we further employ the generalized IRF. According to Koop et al. [19], the above traditional IRF is defined as:

$$\begin{aligned} I_Y(n, \delta, \omega_{t-1}) &= E[Y_{t+n} | V_t = \delta, V_{t+1} = 0, \ldots, V_{t+n} = 0, \omega_{t-1}] \\ &- E[Y_{t+n} | V_t = 0, V_{t+1} = 0, \ldots, V_{t+n} = 0, \omega_{t-1}], \quad n = 1, 2, 3, \ldots \end{aligned}$$

where δ denotes the shock from the kth variable during the period of t and $t+n$, and the scale of shocks V_t equals δ. Thus the conventional IRF not only depends on the signal and scale of δ, but is also relevant to the order of variables ω_{t-1} which is chosen as a priori by researchers. Furthermore, Pesaran and Shin [25] define the generalized IRF by

$$GI_Y(n, V_t, \Omega_{t-1}) = E[Y_{t+n} | \varepsilon_t = \delta, \Omega_{t-1}] - E[Y_{t+n} | \Omega_{t-1}] = A_n \delta$$

Therefore, GIRF is independent with previous information set Ω_{t-1}, but only associates with shocks δ. According to the deduction of GIRF, conventional IRF needs to multiply by a coefficient to eliminate the aforementioned effect of Cholesky decomposition. Pesaran and Shin [25] demonstrate that under the setting of GIRF, the effect of y_{t+n} shocks from jth variable is

$$\varphi_j(n) = \delta_j C_n \Sigma e_j, \quad n = 0, 1, 2, \ldots \tag{7}$$

In order to estimate SVAR, we need to impose restrictions on D_0. This study takes the form of short-run restrictions.[7] More specifically, we define $\Sigma = ABA'$, where A is a lower triangular (4×4) matrix and B represents a diagonal (4×4) matrix, and estimate the structural factorization by full-information maximum likelihood (FIML). That is, $A\varepsilon_t = Bu_t$ and ε_t is a combination of all influences of variables. The main purpose of setting such restrictions on A and B is to assume that changes of different energy-related variables at the current time period do not affect GS rates. The maximum likelihood

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[7] There are two forms of restrictions: short- and long-run restrictions. We employ only the former because long-run restrictions presume virtually zero effect that shocks would bring to the system and we will not take this as a priori.

function of SVAR is expressed as:

$$\ell(B_0, D, \hat{\Pi}) = -\frac{Tn}{2}\log(2\pi) + \frac{T}{2}\log\left|B_0\right|^2 - \frac{T}{2}\log\left|D\right| - \frac{T}{2}\text{trace}\left\{(B_0' D^{-1} B_0)\hat{\Omega}\right\}$$

For the unique B_0 and D, FIML can generate $\hat{B}_0$ and $\hat{D}$ making $\hat{B}_0^{-1}\hat{D}(\hat{B}_0^{-1})' = \hat{\Omega}$. Substituting estimates into Eq. (5) gives the structural innovation u_t and the GIRF of genuine savings rates from Eq. (7).

The above procedure is iterated for real GDP growth rates as well. Comparing the results from real GDP growth rates and genuine savings rates tells different responses of economic growth and sustainable development towards the elasticity of energy consumption. Moreover, we replace the overall elasticity of energy consumption, ratio of energy import to export and per capita CO_2 emissions by elasticities of four types of energy consumption (liquid, solid, gas and electricity). Then re-build GIRF between them and real GDP growth and genuine savings rates respectively to investigate how the changes of energy-mix affect economic growth and sustainable development.

3.3. Analysis of variance decomposition

After graphing how genuine savings levels respond to shocks from energy and GHG factors over time by GIRF, the paper also reports the extent to which they would affect the country's GS level. The relevant statistic here is the relative variance contribution (RVC). According to Pesaran and Shin [25], the sum of effects of *j*th disturbance term on y_t equals:

$$\sigma_{ii}^{-1}\sum_{l=0}^{n}(e_i' C_l \sum e_j)^2, \quad n = 0, 1, 2, \ldots \tag{8}$$

The overall variance of y_t is

$$\text{var}\, y_{it} = \sum_{l=0}^{n} e_i' C_l \sum C_l' e_i, \quad n = 0, 1, 2, \ldots \tag{9}$$

In a GIRF, the RVC measures to what extent shocks from the *j*th disturbance term influence y_{it}, i.e.:

$$\text{RVC}_{j\to i}(\infty) = \frac{\sigma_{ii}^{-1}\sum_{l=0}^{n}(e_i' C_l \sum e_j)^2}{\text{var}\, y_{it}} \tag{10}$$

RVC ranges from zero to one and the sum equals one unit. The larger its magnitude is the more significant influence shocks of variable *j* would bring to the economy's sustained growth in the long-run.

4. Empirical results

Figs. A1–A3 attached in the Appendix depict how real GDP growth rate and genuine savings rate respond to the shocks from energy-related variables. First, their responses to overall elasticity of energy consumption and per capita CO_2 emissions take a *U* shape.[8] The accumulated response of real GDP increase is −0.63 for elasticity of energy consumption and −0.6 for per capita CO_2 emissions while the corresponding figures of genuine savings rate are −0.17 and −0.09 respectively. Even though within 2 periods they react positively towards shocks from energy elasticity and GHG emissions, but in the long-run, they would be impaired. The effect of import–export ratio of energy is positive at the beginning and then declines to zero.

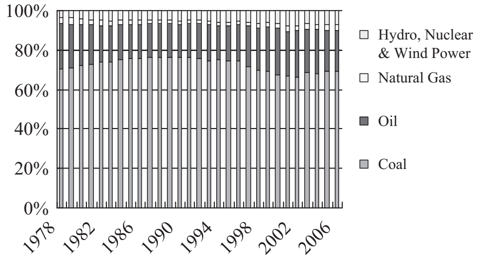

Fig. 6. The composition of energy consumption, 1978–2006.
Source: Author's calculations based on various issues of China Energy Statistical Yearbook.

Second, while looking at different types of energy use, the shocks of elasticities in all four kinds of energy input would have negative influence on real GDP growth. Nevertheless, liquid energy consumption would benefit the real GDP in the long-run. Similar things also happen to the genuine savings rate, however this time electricity becomes the only exception. The shocks from elasticity of electricity requirement would benefit the increase of genuine savings rate, and such effect is always positive. The possible explanation for this phenomenon may be that, compared with coal, oil and natural gas, the expanding requirement for electricity would not necessarily bring about massive exploration of natural resources (hydropower, wind and solar power generation). Therefore, the natural capital depreciation in the GS calculation would not increase so much. Consequently, the decrease in genuine savings rate would be slowed down, although the GS rate may rise due to the immense increment in national savings. In general, using cleaner energy is a better choice for enhancing sustainability but more liquid energy consumption would be selected if the government insists on rapid economic growth.

Figs. A4–A6 describe the relative variance decomposition. Fig. A4 suggests that the overall energy elasticity contributes most to real GDP growth and genuine savings rate. Following is the import–export ratio of energy for real GDP, while for GS rates, CO_2 emissions are the second most important factor. This indicates that if China wants to achieve its goal of constructing "harmonious development", controlling expanding low efficient energy use and curbing GHG emissions are essential steps. Specifically for four kinds of energy needs, solid energy serves as the greatest driving force for real GDP increase. This also echoes the structure of China's energy consumption (Fig. 6): coal has long dominated total energy needs since 1978. In contrast, for the GS rate, liquid and gas energy suggest the most significant influences. In particular, with respect to the elasticity of gas energy use, its degree of importance in promoting growth of genuine savings rates rises dramatically over time.

5. Concluding remarks

Although that China has seen an economic miracle in the past 30 years, the country's future development may face potential pressure from increasing elasticity of energy consumption and GHG emissions. The capacity for sustainable development in terms of genuine savings rates is largely limited by higher elasticities of energy input. Although consuming more energy, especially from solid energy sources like coal, can boost real GDP, it is detrimental to raising the GS rates. By comparison, clean energy sources such as gas and electricity would benefit GS. In this sense, there may

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[8] The response of GS rates to CO_2 emissions is positive and increasing after the period 8. It is inconsistent with the widely held belief that GHG is detrimental to sustainable development. We cannot point to a clear reason for this. It may be the result of data imperfection, but further careful investigation is needed. The same shape of curve also happens to the response of GS rates to the overall elasticity of energy consumption. We suspect that this may be due to the increasing proportion of clean and renewable energy sources. Therefore, even though the elasticity grows, the capability for sustainable development would not be hurt.

be some trade-off between continuously rapid economic growth and sustainable development. The Chinese government has set up a plan to raise gradually the use of electricity and oil and control coal consumption to achieve a less energy-intensive and decarbonized growth. However, as many forecasts suggest [1,2,8,9,18,21], coal would still be the mainstay for energy use and China's total energy requirement and GHG emissions would continue to expand fast until at least 2010. In addition, as the main policy maker, National Development and Reform Commission claims, China will "enhance the proportion of oil in the total energy consumption, in an attempt to support further economic growth in the future" [33]. The elasticities of energy consumption may stay at a high level. Therefore, it could be argued that the recent increasing trend of genuine savings rates may not be sustained. Instead, the country's capability of sustainable development may deteriorate, at least to some extent, in the future. This requires more efficient and forward-looking decision-making by the national energy strategy and management. Polices should encourage diversified energy supply, especially renewable energy, as suggested by [32]. Ma et al. [20] and Chen and Wang [4] provide the most recent comprehensive review for laws, prosperities and difficulties in utilising carbon-free renewable energy sources. Another useful complement to it could be calculating and using "green GDP" as another yardstick besides the conventional growth-oriented economic planning. Composing statistics and evaluation of environment and the natural resources may be the main difficulties in doing so, and this will demand future research.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.rser.2011.03.026.

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