



Contents lists available at ScienceDirect

Energy

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

Growth and structural change in China's energy economy

Fredrich Kahrl^a, David Roland-Holst^{b,*}

^a Energy and Resources Group, University of California, Berkeley, CA, USA

^b Department of Agricultural and Resource Economics, University of California, Berkeley, CA, USA

ARTICLE INFO

Article history:

Received 12 September 2007

Received in revised form

20 March 2009

Accepted 21 March 2009

Available online xxx

Keywords:

China

Chinese economy

Chinese energy use

Energy intensity

ABSTRACT

China has been the world's most vibrant economy and its largest source of energy demand growth over the past two decades, accounting for more than one-quarter of net growth in global primary energy consumption from 1980 to 2005. To sustain economic growth and rising living standards, China needs effective policies that anticipate and shape the country's future energy requirements. In this paper, we examine China's national economic and energy accounts over the past decade for insights into changing energy use patterns and their relationship to economic structure. Our results indicate that incipient structural changes in the Chinese energy economy and sustained economic and energy demand growth in China will pose important, and different, challenges for policymakers.

© 2008 Elsevier Ltd. All rights reserved.

1. Growth and structural change in China's energy economy

The Chinese economy's energy needs have increased dramatically since the turn of the millennium. A combination of sustained high rates of economic growth and structural shifts in energy use in the lead up to and following China's accession to the World Trade Organization (WTO) in December 2001 is responsible for this rapid growth in energy demand. From 2002 to 2006 China's primary energy demand growth (27.7 EJ, 13% annual average growth) exceeded the country's primary energy demand growth over the previous two decades (26.8 EJ, 4% annual average growth from 1980 to 2002) (NBS [1]). After declining steadily from 1980 to 2002, the Chinese economy's energy intensity began to increase after 2002 (Fig. 1). The externalities associated with changing energy demand patterns in China are considerable. From 1980 to 2002 China accounted for 30% of the net growth in global energy-related CO₂ emissions; from 2002 to 2005 this share rose to 53% (EIA [2]).

Changes in the Chinese economy's energy use after 2002 have been paralleled by two major changes in economic structure. First, investment increased dramatically after 2001 and overtook household consumption as the largest component of China's GDP in 2004. By 2006, investment had reached 43% of real GDP (1990 yuan) (NBS [1]). Second, trade (both imports and exports) grew substantially, from 43% of GDP in 2002 to 64% of GDP in 2006 (NBS [1]). Export growth was particularly robust, with the real value of

exports rising to near parity with domestic household consumption in 2006 (Fig. 2). In short, a significant portion of China's post-2001 GDP growth has been driven by investment and export growth. Since 2001 investment and exports have grown faster than aggregate GDP (Fig. 3a), while household and government consumption have grown at rates near or slower than overall GDP growth (Fig. 3b). As we demonstrate below, these compositional changes in the Chinese economy are important determinants of energy use and its associated externalities.

Growth and structural change in China have different implications and pose different challenges for policymakers, both in China and abroad. The interplay between growth and intensity is particularly important in the context of international climate negotiations. Rapidly growing countries like China have high uncertainty in economic and attendant energy demand growth. These countries are less likely to commit to binding, absolute reduction targets that do not account for growth uncertainty. Chinese government proposals to reduce CO₂ emissions, to the extent that they have mentioned targets, have indeed focused on CO₂ intensity targets rather than absolute reduction targets.¹ Quite apart from international climate negotiations, in response to the unexpected surge in energy demand during its 10th Five-Year Plan (2001–2005) the Chinese central government set a binding goal of reducing the

¹ The draft of China's First National Climate Change Assessment reportedly includes a goal of reducing the carbon intensity of the Chinese economy by 40% by 2020 and 80% by 2050 (Herzog [3]). The final draft of China's National Climate Change Programme (NDRC [4]) contains no mention of any targets.

* Corresponding author. Tel.: +1 510 643 6362; fax: +1 510 524 4591.
E-mail address: dwrh@are.berkeley.edu (D. Roland-Holst).

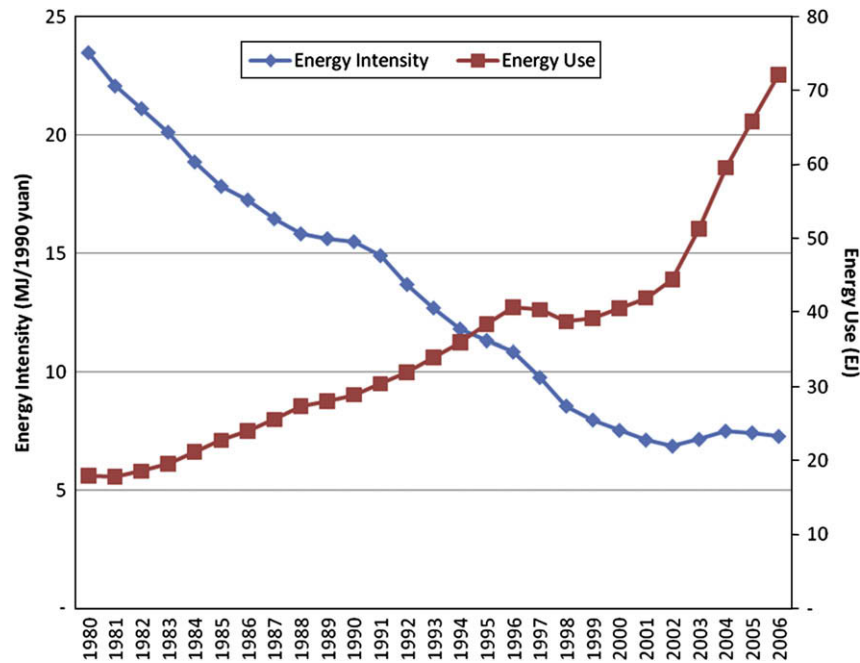


Fig. 1. Energy intensity and energy use in China, 1980–2006. Sources: energy and GDP data are from NBS [1]; GDP data are in 1990 yuan, adjusted using the IMF's deflator for China.

energy intensity of the country's GDP by 20% during its 11th Five-Year Plan (2006–2010), and has made determined efforts to adjust the structure of the country's economy away from energy-intensive production [5]. However, without a clearer understanding of the drivers of rising energy use and intensity in China, it remains unclear what kinds of policies will be most effective for reducing the energy-related impacts of sustained growth in the Chinese economy.

Explanations for the post-2002 shift in the Chinese economy's energy intensity have thus far focused on supply-side forces, including a marked increase in the share of heavy industry in China's economic output since 2002 (Lin et al. [6]; Rosen and Houser [7]). While not disputing heavy industry's role among supply-side forces, attention to demand-side drivers of energy consumption throughout the Chinese economy is equally important for designing forward-looking, macroeconomic policies that reduce the energy intensity of China's economic growth. This paper

examines the domestic energy consumption embodied in China's final demand – the sum of all energy used domestically to create the goods and services used by domestic households, government, businesses (through investment), and foreigners (through exports).

The next two sections explain the data sources and estimation methods used in the paper in considerable detail. Readers who are already familiar with Chinese data sources and input–output (I/O) methods are encouraged to skip to Section 4. Section 4 presents the basic empirical findings, followed by concluding comments in Section 5.

2. Data sources and adjustments

This analysis is based on data from China's national I/O tables and energy input tables, both of which are compiled by the country's National Bureau of Statistics (NBS). Compiling an I/O table is a time- and resource-intensive exercise that normally requires

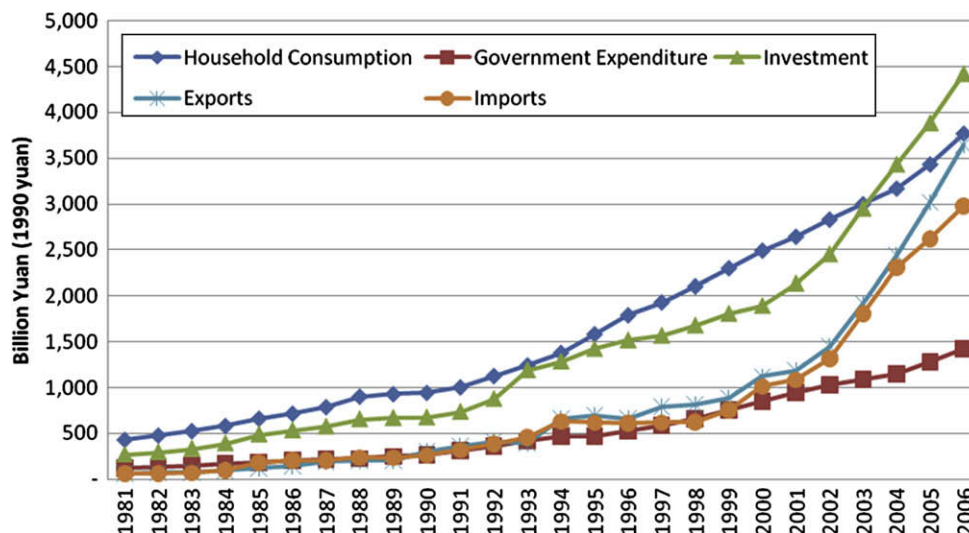


Fig. 2. Household consumption, government expenditure, investment, exports, and imports, China, 1981–2006. Sources: data are based on revised NBS GDP estimates, drawn from China Data Online website, chinadataonline.org. All figures are in 1990 yuan, adjusted using the IMF's deflator for China.

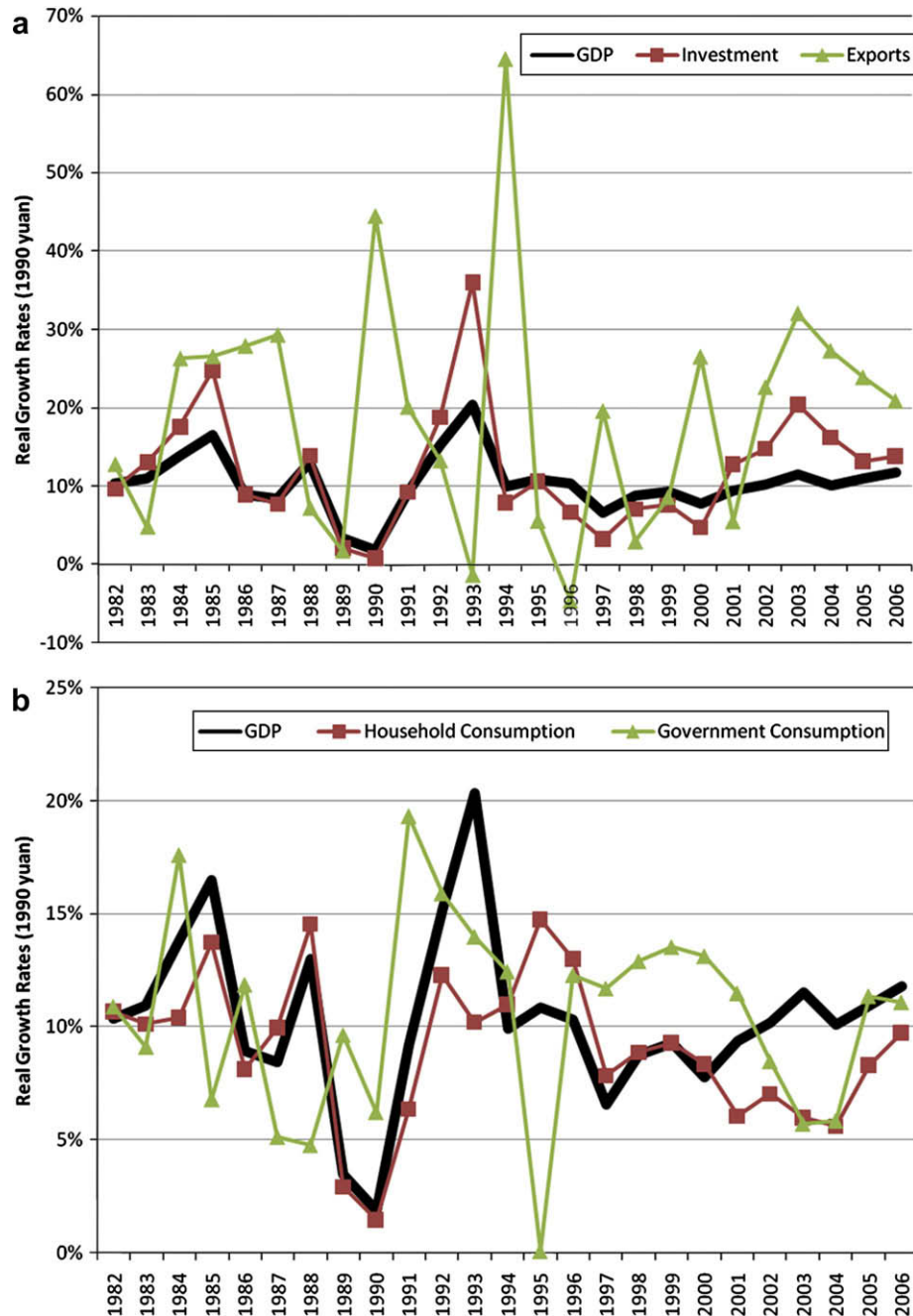


Fig. 3. (a) Real GDP, investment, and export growth rates, 1981–2006. (b) Real GDP, household consumption, and government consumption growth rates, 1981–2006. Sources: data are based on revised NBS GDP estimates, drawn from China Data Online website, chinadataonline.org. All figures are in 1990 yuan, adjusted using the IMF's deflator for China.

several years, which means that I/O tables are not compiled on an annual basis and often have a several year lag between the date of the data and the date it is published. China's I/O tables are assembled every five years (1992, 1997, 2002), and are updated periodically after (e.g., 1995, 2000, 2004) based on the underlying structure of the five-year tables. We use the official 1997 and 2002 tables in this paper, as well as an unofficial NBS update for 2004. Energy input tables for China are compiled every year for major energy consuming sectors and published online in China's main statistical yearbook, with a two-year lag between the date of release and the date of the data (i.e., 1997 data are available in the 1999 statistical yearbook). To match I/O tables, we use the 1997, 2002, and 2004 energy input tables from the 1999, 2004, and 2006 statistical yearbooks.

Two major recent data revisions by the NBS – corrections to GDP and energy use estimates – have implications for both I/O and energy input tables. In addition, the NBS I/O tables are in current prices and the intermediate use portions of the tables do not account for the fact that, over the past decade, prices for primary and secondary energy sources in China have risen significantly faster than prices elsewhere in the economy. The remainder of this section describes our approach to addressing these issues in our economic and energy data.

In 2006 the NBS undertook a significant revision to national GDP estimates to correct a long-standing bias against the small business and the services sector in economic data collection (Naughton [8]). Both the 2002 and 2004 tables account for this revision; the discrepancy between 2002 and 2004 I/O tables and 2006 statistical

yearbook data for 2002 and 2004 consumption and investment is infinitesimal. Discrepancies between the 1997 I/O table and 2006 NBS data for 1997 GDP are substantial. The I/O table underestimates GDP by roughly 12%, household consumption by 6%, government consumption by 22%, and investment by 11% relative to 2006 estimates (NBS [1]). Correcting this GDP underestimate in the 1997 table requires scaling both the final expenditure and value added portions of the table to reflect NBS revisions. While scaling final expenditure is relatively straightforward using an assumption of homothetic preferences, because revised statistics for value added at a sectoral level are not available, scaling value added for each sector by an averaged GDP correction coefficient likely introduces a non-trivial source of error into the I/O coefficients matrix. Additionally, revising the 1997 I/O table to account for NBS GDP revisions does not significantly affect our results. For these reasons we use the original 1997 table throughout this analysis.

A second major revision, this time to energy data, was undertaken in 2006 to reflect a more accurate estimate of coal consumption, primarily during the period from 1999 to 2001, when it is believed that provincial governments were significantly underreporting coal consumption [9,10]. This revision included a 9% and 8% increase in coal consumption in 2000 and 2001, respectively. The correction for 2002 and 2004 is more modest at 4% [11]. These revisions affect only the accuracy of data in the 2002 energy input table, published in 2004. The 2006 *Statistical Yearbook's* energy input tables include revised statistics for coal use; data before 1998 were not revised. Because the 2006 *Statistical Yearbook* only publishes revised coal use data at a detailed sectoral level beginning in 2003, the only two options for correcting 2002 sectoral coal use data are to assume that coal use was systemically underreported across sectors or years, both of which are likely to introduce new uncertainty into sectoral coal use estimates. Given that the revision to 2002 coal use data was not large to begin with, we argue that correcting the 2002 energy input tables based on either of these options would not necessarily produce more accurate results. We use 2002 energy input data from the 2004 *Statistical Yearbook's* energy input tables in our analysis.

China's energy prices have risen considerably over the past decade, while wholesale price rises for other industrial goods have

reportedly been more stable (Fig. 4). Because we use energy intensity measures to convert between monetary transactions in the I/O table and physical energy use, accounting for higher relative energy prices is important for ensuring consistency across different years. This is particularly true because, over the past decade, China's energy prices have often not moved in tandem. During the period from 1997 to 2002, for instance, coal and oil prices were almost perfectly out of step. To account for changing relative energy prices in the intermediate economy, we use a relative energy price index based on NBS data on inter-annual changes in ex-factory prices for coal, oil, and electricity [11], normalizing these prices to both a base year (1990) and the general price index. Changing relative prices for energy sectors disrupts the symmetry of the I/O tables, which requires rebalancing them (see below). Correcting for disproportionate changes in relative energy prices does not ultimately have a significant effect on either the shares or intensities of embodied energy in final demand, and the results we report below are based on uncorrected prices.

We close our discussion of data sources with a few thoughts on the accuracy of NBS data. China's economic and energy statistics have come under greater scrutiny in recent years, often in tandem [8,12,13]. The afore-mentioned NBS data revisions indeed reflect the difficulties of maintaining data accuracy in a rapidly changing, increasingly decentralized economy where information remains highly politicized. That said, there are indications that NBS economic and energy data is not without grounding in reality. For instance, NBS data on exports comport with data from other countries; if GDP estimates were grossly underestimated, exports would now comprise an even larger share of China's GDP than they do currently [8]. The dramatic shock to China's energy and commodity markets after 2002 [14] also suggests that the country's resource use has indeed greatly accelerated over the past five years, a fact that accords with official economic and energy data. Finally, as Naughton [8] notes the NBS is the only source of comprehensive data on the Chinese economy. As this data plays a role in Chinese policymaking, analyses based on NBS data are important for improving its accuracy and for providing common ground for policy research. By maintaining a critical eye and comparing a range of data sources, in this article we attempt to do both.

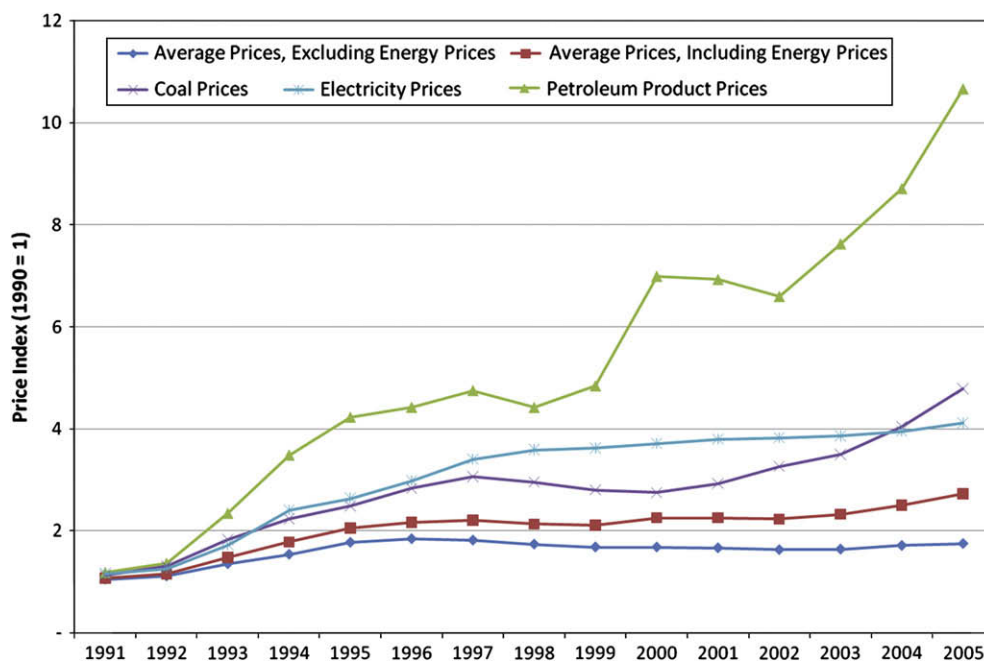


Fig. 4. Ex-factory coal, oil, electricity, and average prices in China, 1991–2005 (1990 = 1). Sources: based on NBS [11].

3. Methods

In tandem, China's I/O and energy input tables provide insight into the flows of energy throughout its economy, as these extend over long supply chains from extraction and processing to intermediate use and eventually into final goods and services. Combining the two tables integrates the economic structure of I/O tables with the energy consumption patterns characteristic of different sectors. To integrate the tables, we use a sectoral intensity technique common in energy and environmental I/O analysis [15–17].

3.1. Input–output tables

An I/O table is a double entry accounting matrix that records income and expenditure transactions within an economy. “Open loop” tables, which do not “close” the flow of income from factors of production to institutions, typically include inter-industry transactions (intermediate use), industry payments to factors (value added), and institutions' payments to industries for goods and services (final demand). All of the tables that we examine here are open loop tables. In this open accounting framework, final users purchase goods and services, which increases demand for intermediate inputs and factors to produce these goods and services. Demand for intermediate inputs further increases output from other sectors to produce these inputs, which requires still further outputs to produce that output, and so on. In this way, I/O tables capture the relationship between final demand and total inputs and outputs in an economy.

An I/O table represents a snapshot of the economy at equilibrium, where the total income received by industries for their outputs is equal to their total outlays for inputs. I/O tables thus capture the inner workings of all sectors in an economy, at different levels of sectoral disaggregation. The NBS compiles its national I/O table at 122-sector resolution, although in many cases a more aggregated version is more readily available and widely used. NBS tables have slightly different sectoring schemes to account for, *inter alia*, the arrival of new sectors. Comparisons across I/O tables require a common sectoring scheme, which typically involves aggregating individual tables to reach a shared number and classification of sectors. I/O tables are easily aggregated by combining rows and columns according to

$$T^* = R'TC \quad (1)$$

where T is the original table, R is a matrix of 1's and 0's indicating the desired row sectoring scheme, C is a matrix of 1's and 0's indicating the desired column sectoring scheme, and T^* is the new table. Because the R and C include value added and final demand, respectively, T^* is not square and R and C are generally not of equal size. We use a 39-sector aggregation scheme in this analysis.

3.2. Input–output multipliers

Analyses of open form I/O tables are based on the interrelationship among intermediate use, value added, and final demand. In the I/O table, these three components form the partitioned matrix

$$\begin{bmatrix} T & Y \\ V & O \end{bmatrix} \quad (2)$$

where T is an $n \times n$ matrix of inter-industry transactions for n industries, V is a $k \times n$ matrix of k value added accounts, and Y is an $n \times m$ matrix of m final demand sources. Y includes the four

principle components of final demand: household consumption, government expenditure, investment, and net exports.

By convention, the columns (j) in the I/O table represent expenditures, while the rows (i) represent income. Each x_{ij} element of the I/O table thus represents a payment from sector j to sector i , or conversely the income received by sector i from sector j . For each sector i , summing across intermediate income (x_{ij}) and aggregate final demand (Y_i) gives gross output (X_i) for that sector

$$\sum_j x_{ij} + Y_i = X_i \quad (3)$$

Each column sum (X_j) in the I/O table represents the total inputs required to produce a given level of output (X_i), where, in symmetric I/O tables, X_j and X_i are equal. Similarly, each quantity x_{ij} normalized by its column sum X_j represents the quantity of sector i required to produce one unit of sector j , or a_{ij} . Mathematically, this is represented by

$$x_{ij} = a_{ij}\hat{X}_j = AX \quad (4)$$

where A is normally referred to as the input–output coefficient matrix, or the technical coefficient matrix. This technical coefficient matrix shows the inputs to production across the entire economy, and thus its technical structure.

Substituting Eq. (3), Eq. (2) can be rewritten as

$$AX + Y = X \quad (5)$$

X has the solution

$$X = (I - A)^{-1}Y = M_L Y \quad (6)$$

where M_L is the Leontief inverse, also referred to as the multiplier matrix. Each element m_{ij} in the multiplier matrix reflects the total output induced in sector i by a one unit change in final demand for sector j .

3.3. Energy multipliers

Energy flows can be integrated into I/O tables based on an assumed proportionality between inter-industry transactions and sectoral energy inputs, which are linked through sectoral energy intensities. In other words, if an increase in the demand for processed food increases the demand for agriculture, the demand for energy in the economy increases by a proportional amount that is determined by the energy intensity (e.g., in joules/unit) of agriculture. The primary energy intensity (α_i) of each sector i is that sector's total primary energy input (E_i) divided by its total output, or, in matrix notation

$$\alpha = \hat{X}^{-1}E \quad (7)$$

where \hat{X} is the diagonalized matrix of sector outputs.

The embodied energy in each sector is the transpose of α multiplied by the multiplier matrix, or

$$\epsilon = \alpha'(I - A)^{-1} = \alpha'M_L \quad (8)$$

where ϵ is a row vector of embodied energy intensity values (here in MJ/yuan) that reflects the embodied energy induced by a unit change in final demand in that sector. The total embodied energy in each final demand activity can be calculated as

$$EE_{ik} = \epsilon_j Y_{ik} \quad (9)$$

where EE_{ik} is the energy embodied in final demand activity k 's final demand for sector i , ϵ_j is the embodied energy intensity for sector i ,

and Y_{ik} is activity k 's demand for sector i . In this analysis, $k = 4$ and includes household consumption (C), government spending (G), gross capital formation (I), and exports (EX).

It is important to emphasize that α is a vector of primary, and not secondary, energy intensities. Primary energy inputs here include coal, crude oil, and natural gas. Hydropower, nuclear, and wind energy are included as inputs into the 'Production and Supply of Electricity and Heat' sector, based on data from EBCEPY [18]. Note that this method differs from but is ultimately consistent with an approach where all energy inputs are allocated to the extractive sectors and all other sectors have an energy intensity of zero. To harmonize energy inputs across sectors and we convert the physical units listed in the energy input tables to energy units using heating values recommended by the Intergovernmental Panel on Climate Change [19].

To ensure that our results are consistent, we compare both our energy inputs and our embodied energy results against the total energy use estimated by the NBS. Some discrepancy between our intensity figures and NBS data is to be expected because we use different heating values and conceptual boundaries for primary energy than the NBS. In particular, because it is not clear what factors the NBS uses to calculate primary energy use in non-fossil fuel electricity generation we do not include conversion losses for non-fossil fuel sources in our primary energy calculations. A second reason for potential discrepancies is that some energy inputs, in particular "other petroleum products," are not included in sectoral energy inputs in the tables but are included in total energy. This latter factor is more minor and we do not attempt to correct for it. For the purpose of calculating energy intensities, these two factors lead us to lower estimates, but ones that are ultimately consistent with, NBS estimates of total energy consumption. A small percentage (around 5%) of primary energy is consumed directly by households, and we do not include this consumption in our share or intensity estimates. 'Total energy' below thus refers to the total energy embodied in goods and services.

By definition, the total energy that flows into the economy (E) in a given year must be equivalent to the energy induced by final demand in that year. In other words, the E values on both sides of Eq. (10) are identical.

$$E = \hat{X}^{-1} E_M Y \quad (10)$$

3.4. Imports

Imports are often, but not always, contained in both the intermediate use and final demand portions of I/O tables. For the NBS tables, we confirm that imports are included in the intermediate use and final demand portion of the table by examining the oil and gas extraction (O&GE) sector. The 2002 I/O table records total intermediate and final use of O&GE products (import inclusive) at

421.8 billion yuan, or US\$34.8 billion. In 2002, China imported 69.4 million tons of crude oil at a total value of US\$12.8 billion, or roughly US\$25 per barrel. Assuming, in line with consumption data, that the bulk of these US\$34.8 billion in expenditures are for crude oil, and that US\$25/barrel is an upper limit on domestic prices, total crude oil consumption in the Chinese economy would be on the order of 1.6 billion barrels, which matches statistical yearbook data [11].

Because our focus is on domestic primary energy consumption, for most of this analysis we use a domestic I/O table, which has the imports removed. Ideally, expunging imports from intermediate and final use statistics could be accomplished through the use of industry surveys that provide detailed information on imports by sector. In most cases, however, this information is not available and assumptions are required about the import content of intermediate and final goods. The most commonly used import content assumption is that imports are homogeneous components of both intermediate and final goods, excluding exports [15], and using an import ratio to systematically remove them.

The import ratio ($R_{IM,i}$) for each sector i is the ratio of imports (IM_i) to total intermediate use and non-export final demand for sector i , or

$$R_{IM,i} = \frac{IM_i}{\sum_j X_{ij} + (Y_i - EX_i)} \quad (11)$$

Actual removal of imports is done through

$$T^* = (I - \hat{R}_{IM})T + (I - \hat{R}_{IM})Y \quad (12)$$

where T^* is the new I/O table, T is the import-ridden intermediate use table, and Y is import-ridden final demand.

After making corrections to prices and imports, column and row sums in our 39-sector I/O tables are no longer equivalent. To restore I/O table symmetry, the tables must be rebalanced so that column and row sums are once again equal. We use a cross-entropy method [20] to rebalance the tables and arrive at a consistent set of accounts.

4. Results: growth and structural change

4.1. Aggregate trends

Among the many I/O table permutations with which we examine the changing structure of energy flows in the Chinese economy over 1997, 2002, and 2004, three robust trends emerge.

First, the energy intensity of all final demands decreased significantly between 1997 and 2004, as each final demand source grew faster than its embodied energy consumption (Table 1). This decline was driven to a large extent by slow, 2% annual average

Table 1
Annualized growth in final demand, embodied energy, and embodied energy intensity (%).

		Households	Government	Investment	Exports	Total
1997–2004	Final demand	8	14	13	17	12
	Embodied energy	4	6	6	9	6
	Energy intensity	–3	–8	–6	–7	–6
2002–2004	Final demand	5	6	17	27	14
	Embodied energy	12	13	17	28	18
	Energy intensity	7	7	0.1	1	4
1997–2002	Final demand	9	18	12	13	12
	Embodied energy	1	3	2	2	2
	Energy intensity	–7	–13	–9	–10	–10

Note: "Total" here refers to an economy-wide average.

energy demand growth between 1997 and 2002, a trend which changed abruptly after 2002 [1]. The energy intensity of exports and government expenditure recorded the most rapid declines, while the energy intensity of household consumption decreased more slowly than other final demands. It is important to note in Table 1 that the annualized change in intensity is not equal to the difference between the annualized growth in embodied energy and final demand, though the two values are in fact close. Intuitively, if final demand grows faster than energy use then energy intensity falls, and vice versa.

Second, declines in intensity over 1997–2004 mask a minimum in 2002, and between 2002 and 2004 the energy intensity of all final demands increased, driven by higher embodied energy use (Table 1). This increase in embodied energy use is consistent with and ultimately identical to the 16% growth in total energy use between 2002 and 2004 reported in statistical yearbooks [1]; the discrepancy between this 16% and the 18% reported in Table 1 is the result of NBS energy data corrections, which we discuss in Section 2, above. Increases in energy intensity were driven predominantly by household and government consumption. Due to compositional shifts that we describe below, the energy intensity of investment and exports remained relatively constant over this time period, despite a 4% economy-wide increase in energy intensity.

Third, differing rates of expenditure and embodied energy growth led to a shift in the shares of embodied energy from 1997–2002 to 2002–2004 (Table 2). Shares of embodied energy did not change significantly between 1997 and 2002. After 2002, household and government expenditure's share of embodied energy declined roughly 9% on an annualized basis, whereas the share of exports grew by roughly 9% on an annualized basis. Despite 17% annual average growth from 2002 to 2004, investment's share of embodied energy remained roughly constant between 2002 and 2004.

In each of the three periods in question, 1997–2002, 2002–2004, and 1997–2004, the economy-wide mean ("Total" in Table 1) provides a useful nucleus for thinking about relative shifts in the embodied energy shares and intensity of household and government consumption, investment, and exports. Despite its rising energy intensity, consumption declined as a share of total energy demand in the Chinese economy from 2002 to 2004 because growth in consumption (5% annual) was so much lower than economy-wide final demand growth (14% annual). Investment's share of energy demand remained constant, as the energy embodied in investment grew (17% annual) slower than total energy demand growth (18%) and investment grew (17% annual) faster than total final demand (14% annual). Exports' share of domestic energy consumption rose significantly from 2002 to 2004, as exports and export-induced energy demand (27% and 28% annual, respectively) grew faster than respective economy-wide averages.

Energy intensity can be similarly analyzed. The energy intensity of consumption rose from 2002 to 2004 as the energy embodied in consumption grew faster than consumption growth. Investment and export energy intensity remained relatively constant because

embodied energy and expenditure grew at roughly the same rate (Table 3). Intensity across final demands fell from 1997 to 2004 as GDP grew faster than energy consumption. The decline in China's energy intensity from 1997 to 2002 has recently been the subject of intensive study, focusing primarily on whether real or structural factors are behind reductions in intensity [22–29]. An emerging consensus is that efficiency gains, including rising relative energy prices and technological change, drove energy intensity declines in China over this period. China's post-2002 experience highlights the importance of final demand-specific factors as drivers of changes in energy intensity.

The most arresting statistic in Tables 1 and 2 is that investment and exports together accounted for 63% of China's domestic energy consumption in 2004, and more than 70% of the growth in China's domestic energy consumption between 2002 and 2004. These shares confirm the intuition that, just as China's economy is investment and export driven, so is the country's energy use. The tables also give an initial sense of the importance and complexity of economic reform as a lever through which to manage energy and resource use in China's economy. Encouraging shifts in aggregate final demand (e.g., from investment to consumption) can decrease the energy intensity of growth, but the composition of these shifts is equally important.

4.2. Compositional shifts within final demands

We focus our discussion here on compositional shifts within investment and consumption, which together form the key fulcrum of current macroeconomic imbalances within the Chinese economy [30]. Exports are the fastest growing source of both final demand and embodied energy in China, and a shift to higher value added products should reduce their energy intensity. However, China's export regime and its broader economic and resource implications warrant greater coverage than we can provide here, and we provide more detailed discussion of the composition and embodied energy implications of exports elsewhere [21].

Investment is the largest and most energy-intensive part of China's GDP. Gross capital formation² in China, both in terms of value and in embodied energy, has historically been dominated by the construction sector. In the NBS I/O tables we examine, the construction sector accounted for a range of 52–71% of investment spending and 58–74% of the total energy embodied in investment (2004–1997 and 2004–2002 I/O tables, respectively) over the period 1997–2004; construction sector investment accounted for 18–23% of China's total domestic energy use over this time period.³ As the Chinese economy has become increasingly manufacturing intensive, the construction sector's share of investment spending and investment embodied energy have fallen, at a gradual 2% and 1% annual average, respectively, from 1997 to 2002. Between 2002 and 2004, these two shares plummeted, with each falling by an annual average of roughly 10%. As Table 4 illustrates, this precipitous decline is largely the result of higher growth in investment in non-construction and non-equipment sectors, which collectively were approximately 30–40% less energy intensive than combined investment in the construction and equipment sectors over the 1997–2004 period. This shift in the destination of investment, though not verifiable from statistical yearbook data and perhaps not sustained after 2004, illustrates the potential for compositional

Table 2
Shares of total embodied energy, 1997–2004.

	Household	Government	Investment	Exports
1997	0.34	0.08	0.34	0.24
2002	0.33	0.08	0.34	0.24
2004	0.30	0.07	0.34	0.29

Notes: Shares may not add to one due to rounding. Export shares reported here are higher than the shares we report elsewhere [21], both because the denominator here does not include primary energy consumption by households and because the methods we use in the two papers are different. It is important to note that these shares are necessarily estimates, and that a more accurate accounting would require a more accurate allocation and removal of imports through the use of sectoral import surveys.

² Investment traditionally includes gross capital formation and inventory change; the latter is typically small relative to the former, and we use the terms 'investment' and 'gross capital formation' interchangeably here.

³ Total domestic energy use here includes primary energy consumption by households.

Table 3
Embodied energy intensities, 1997–2004 (MJ/1990 yuan).

	Household	Government	Investment	Exports
1997	6.79	5.86	9.26	9.47
2002	4.71	2.95	5.78	5.56
2004	5.38	3.37	5.79	5.67

shifts within aggregate investment to reduce the Chinese economy's longer-term energy needs.

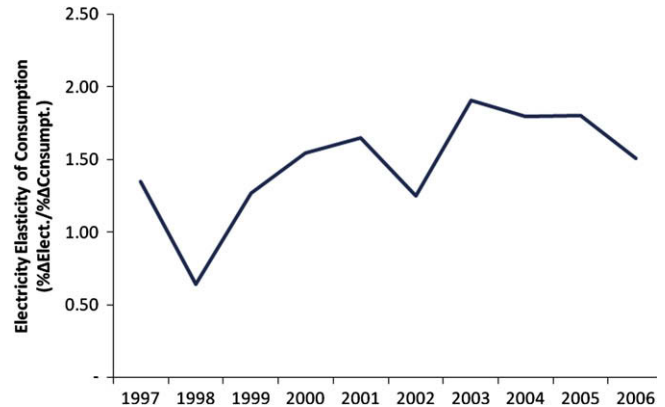
There is broad consensus, both within China and abroad, that the current share of investment in Chinese GDP is too high, and that the Chinese economy needs “rebalancing.” The reasons for sustained, high levels of investment in China are complex and disputed, but are linked in part to the country's currency regime and lack of greater control over monetary policy; the absence of a system to reallocate state-owned enterprise profits; and high levels of household precautionary savings [31–35]. Strategies for reducing investment share of GDP range from active efforts to encourage investment–consumption shifts [33], to more passive efforts based on the assumption that current levels of investment are anomalous and self-correcting in the form of marginally slower GDP growth [31]. In either case, a lower investment share of GDP could flatten China's energy consumption trajectory, but changes in the composition of final demand sectors that shift as a result are important for determining how much trend growth might be reduced. For instance, because the average embodied energy intensities of investment (5.79 MJ/yuan) and household consumption (5.38 MJ/yuan) were close in 2004, an equivalent shift from investment to household consumption would have a relatively small effect on economy-wide energy use or energy intensity. Alternatively a shift from construction sector investment (6.51 MJ/yuan) to household expenditure on services (2.84 MJ/yuan) would have a much larger effect.

Although investment and exports accounted for more than 70% of the growth in the Chinese economy's energy use between 2002 and 2004, domestic consumption accounted for most of the increase in economy-wide energy intensity during this period. For households, the focus of our discussion here, the I/O tables indicate that the largest contributor to this rise in intensity was an increase in the share of electricity consumption in household expenditures, from 2% to 4%, from 2002 to 2004. Although the embodied energy intensity of the electricity sector itself declined over the entire period 1997–2004, because the electricity sector is extremely energy intensive on a lifecycle basis (33.39 MJ/yuan vis-à-vis a 5.36 MJ/yuan economy-wide average) electricity's share of household embodied energy consumption grew by a disproportionate 8 percentage points. Electricity expenditures accounted for 60% of the growth in the energy embodied in household consumption from 2002 to 2004.

Table 4
Percentage of investment spending, embodied energy, and embodied energy intensity, construction, equipment, and other sectors, 1997–2004.

	Unit	1997	2002	2004
Construction	% Total investment spending	71	76	52
	% Total investment embodied energy	74	64	58
	Embodied energy intensity (MJ/yuan)	9.7	6.4	6.5
Equipment	% Total investment spending	24	24	28
	% Total investment embodied energy	22	24	27
	Embodied energy intensity (MJ/yuan)	8.7	5.3	5.5
Other	% Total investment spending	6	11	20
	% Total investment embodied energy	3	7	15
	Embodied energy intensity (MJ/yuan)	5.6	3.4	4.4

Note: “Equipment” is a composite of the mechanical, transportation, electronic, and electrical equipment sectors; “Other” includes all remaining sectors.

**Fig. 5.** Electricity elasticity of household consumption, China, 1997–2006. Sources: electricity consumption data are from EBCEPY [18]; household consumption data are from NBS [1].

NBS statistical yearbook data suggest that the higher expenditure share of electricity use was driven more by a fall in total household consumption growth rates than by a spike in residential electricity demand. Physical residential electricity consumption (i.e., in energy units) in 2003 and 2004 hewed within 1.3 percentage points of annual average growth in residential electricity consumption over 1997–2004 (10%) [18], while growth in household consumption (in monetary units) declined to its lowest rate over the 1997–2004 period (7.3 annual average) in 2003 and 2004 (6.0% and 5.8%, respectively) [1]. As a result, the electricity elasticity of household consumption, or the percentage change in electricity consumption divided by the percentage change in household consumption, rose to a local peak between 2003 and 2005 (Fig. 5). Residential electricity consumption actually appears to have accelerated at the end of the 1990s and a total, real household expenditure level of just over 2.5 trillion yuan (Fig. 6), but the future of this trend is unclear. In the U.S., for instance, electricity consumption began to saturate as a function of private expenditure in the late 1970s. Where and when China's electricity consumption will begin to saturate is uncertain.

China's consumption dilemma is well known, but is particularly salient with regards to energy use and its attendant domestic and global impacts. On a per capita basis, residential energy consumption in China is a fraction of OECD levels. For instance, per capita annual residential electricity use in the U.S. (4533 kWh/person-year) was more than 21 times higher than in China (216 kWh/person-year) in 2005 [1,2,18].⁴ However, at 282 TWh China's total residential electricity use is higher than total electricity consumption in several major OECD and middle income countries, including Australia (220 TWh), Mexico (183 TWh), South Africa (211 TWh), and Spain (243 TWh) [2]. Additionally, China's electricity consumption has significant room to grow, driven by declining household size, rising incomes, reduced dependence on traditional biomass in rural areas, and urbanization. Simply raising average rural per capita electricity consumption (149 kWh/person-year) to average urban levels (304 kWh/person-year) would require an additional 116 TWh [18]. Although a continued shift toward services can offset some of the implications of rising household expenditure in China [36], a basic level of energy consumption is, in fact, an important development priority [37]. Consumption, more than any other final demand source, reflects the importance of a large-scale, near-term deployment of alternative energy sources in China.

⁴ U.S. population data are from the U.S. Census Bureau website.

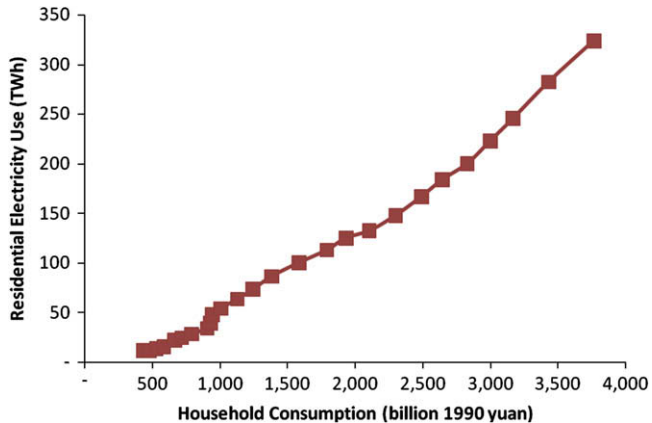


Fig. 6. Residential electricity use as a function of household consumption, China, 1981–2006. Notes and sources: the markers on this curve reflect annual data point; the distance between each point reflects the magnitude of inter-annual increases. This distance rapidly increases toward the latter part of the curve, which illustrates the speed of income growth in China in recent years. Electricity consumption data are from EBCEPY [18] and Lawrence Berkeley National Lab's China Energy Databook; household consumption data are from NBS [1].

5. Concluding thoughts

More so than any other large economy, China demonstrates the important linkages among economic growth, changes in economic structure, and energy consumption and intensity. Since 2002, the Chinese economy's energy needs have grown substantially (Fig. 1), with a marked rise in investment- and export-driven GDP growth following the country's entry into the World Trade Organization in December 2001. Growth in energy use was paralleled by an abrupt upswing in the energy intensity of China's GDP beginning in 2002, which, although peaking in 2004 and falling slowly since, reversed a two-decade trend of steady declines in energy intensity (Fig. 1). Recognizing the need to rebalance economic growth and reduce the economy's energy intensity, China's central government has made structural adjustment a key policy platform since December 2004, and reducing the energy intensity of GDP has become a national priority during the 11th Five-Year Plan (2006–2010).

How much macroeconomic and energy policies can influence China's long-run energy consumption path is a critical question. As Fig. 7 shows, returning China to its 1980–2002 energy use trajectory would reduce the Chinese economy's energy needs by nearly one-quarter by 2030 at linearly extrapolated growth rates. To put these two trends in context, the 37 EJ difference between the two consumption pathways in Fig. 7 is equivalent to 8% of total world primary energy consumption (488 EJ) in 2005; at a 2005 total CO₂ emission factor of 75MMTCO₂/EJ for China, 37 EJ corresponds to 2.8 GtCO₂, or 10% of global energy-related CO₂ emissions in 2005 (28.2 GtCO₂) [2]. China's long-run energy consumption pathway will be shaped by the scale and structure of final demand, and understanding emerging energy–expenditure relationships will be an important part of designing policies that rationalize the country's energy needs.

This paper examines emerging energy–expenditure relationships in China, based on an analysis of NBS data from 1997, 2002, and 2004. Most of the recent growth in China's energy demand has been driven by investment and exports. The two accounted for more than 70% of the growth in energy consumption from 2002 to 2004, and exports in particular have been the fastest growing contributor to growth in energy consumption. Nevertheless, the energy embodied in investment still accounted for the largest share of total embodied energy and investment was the most energy intensive component among final demands in 2004; investment reached a staggering 43% of Chinese GDP in 2006. Reducing the share of investment in GDP has the potential to flatten trend growth in energy consumption in China, but the extent of this trajectory change will be determined by the composition of shifts in final demand. For instance, an equivalent exchange of GDP shares between investment and household consumption, based on 2004 average embodied energy intensities (5.79 MJ/yuan and 5.38 MJ/yuan, respectively), would not lead to a significant change in economy-wide energy intensity because their averages are similar. Alternatively, the effects of a shift from construction sector investment (6.5 MJ/yuan) to household spending on services (2.8 MJ/yuan) would be more pronounced. In other words, simply shifting final demands will not necessarily change the energy and resource intensity of the Chinese economy. Regardless of final demand category, these shifts must ultimately be from more

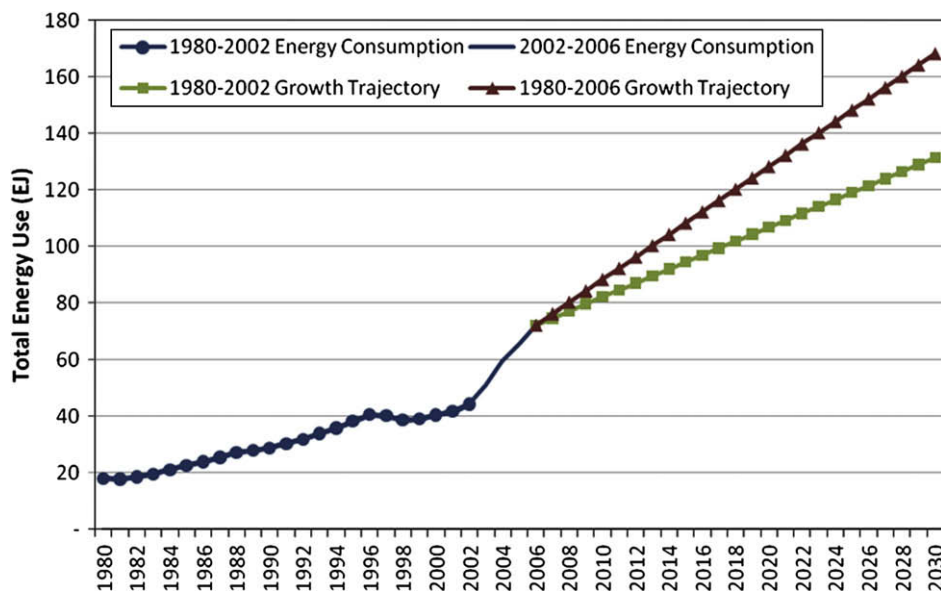


Fig. 7. Energy consumption pathways for the Chinese Economy, 1980–2030. Notes and sources: “1980–2002 Growth Trajectory” is a linear extrapolation of China's 1980–2002 energy consumption; “1980–2006 Growth Trajectory” is a linear extrapolation of China's 1980–2006 energy consumption. All data are from NBS [1].

energy intensive to less intensive sectors, which may require more active policy and regulatory intervention.

The reversal in the energy intensity of China's GDP was, from 2002 to 2004, driven in large part by consumption. For household consumption, our focus in the text, this shift was brought about by an increase in the share of electricity in household expenditure. Because electricity is extremely energy intensive on a lifecycle basis, electricity's share of the energy embodied in household consumption increased disproportionately to its expenditure share increase over 2002–2004. NBS statistical yearbook data suggest that the rise in the share of electricity expenditures in household consumption was due to a fall in consumption growth rates, rather than an abrupt jump in electricity consumption. As household consumption recovered post-2004, electricity consumption growth rates accelerated as well. Although it is not certain how long this trend will last, the implication is that, on average, household consumption in China is becoming more energy intensive.

These two trends have different implications and different time scales. The Chinese government is committed to structural adjustment, with policy prescriptions ranging from more active interventions in the economy, to more passive strategies based on the notion that the current rates of investment are part of a cyclical trend that will self correct. In either case, the transition toward less investment, and indeed export, driven growth will likely begin in the nearer term. Consumption poses a challenge for Chinese policymakers over the longer term, as China enters a period of more energy intensive consumption and the timing of energy demand saturation seen in many OECD countries remains uncertain for China. Per capita energy consumption in China is still dramatically lower than in OECD countries, but total residential energy consumption is already high. The domestic and global environmental implications of sustained growth in consumption, more so than other sources of final demand, call for a dramatic scaling up of alternative energy technologies in China.

References

- [1] National Bureau of Statistics (NBS). China statistical yearbook. Beijing: China Statistics Press; 2007.
- [2] Energy Information Administration (EIA). Annual energy outlook. Washington, DC: DOE/EIA; 2008.
- [3] Herzog T. China's carbon intensity target. Washington, DC: World Resources Institute. See also: http://www.wri.org/newsroom/topic_content.cfm?cid=4234; 2007.
- [4] National Development and Reform Commission (NDRC). China's national climate change programme. NDRC Policy Document. NDRC. <http://www.ccchina.gov.cn/WebSite/CCChina/UpFile/File188.pdf>; 2007.
- [5] International Energy Agency (IEA). World energy outlook 2007. Paris: IEA/OECD; 2007.
- [6] Lin J, Zhou N, Levine M, Fridley D. Achieving China's target for energy intensity reduction in 2010: an exploration of recent trends and possible future scenarios. Berkeley: Lawrence Berkeley National Laboratory; 2006.
- [7] Rosen DH, Houser T. China Energy: a guide for the perplexed. Washington, DC: Peterson Institute for International Economics; 2007.
- [8] Naughton B. The Chinese economy: transitions and growth. Cambridge, Massachusetts: The MIT Press; 2007.
- [9] Horii N, Gu S. Transformation of China's energy industries in market transition and its prospects. Chiba, Japan: Japan External Trade Organization; 2001.
- [10] Hajime A, Toshimasa O, Jun-ichi K, Nobuhiro H. Verification of energy consumption in China during 1996–2003 by using satellite observational data. *Atmospheric Environment* 2006;40:7663–7.
- [11] National Bureau of Statistics (NBS). China statistical yearbook. Beijing: China Statistics Press; various years.
- [12] Rawski TG. What's happening to China's GDP statistics? *China Economic Review* 2001;12.
- [13] Sinton J. Accuracy and reliability of China's energy statistics. *China Economic Review* 2001;12:373–83.
- [14] Fang W. China's grave energy and environmental situation. *China Power Enterprise Management* 2006;4:28–30.
- [15] United Nations Statistics Divisions (UNSD). Handbook of input–output table compilation and analysis. New York: UN; 1999.
- [16] Casler S, Wilbur S. Energy input–output analysis: a simple guide. *Resources and Energy* 1984;6:187–201.
- [17] Hendrickson CT, Horvath A, Joshi S, Lave LB. Economic input–output models for environmental life-cycle assessment. *Environmental Science and Technology* 1998;32(4):184A–91A.
- [18] Editorial Board of the China Electric Power Yearbook (EBCEPY). China electric power yearbook. Beijing: China Electric Power Press; various years.
- [19] Intergovernmental Panel on Climate Change (IPCC). 2006 guidelines for greenhouse gas inventories. Geneva: IPCC; 2006.
- [20] Robinson S, Cattaneo A, El-Said M. Estimating a social accounting matrix using cross entropy methods. In: Trade and macroeconomics discussion paper No. 33. International Food Policy Research Institute; 1998.
- [21] Kahl F, Roland-Holst R. Energy and exports in China. *China Economic Review* 2008;19(4):649–58.
- [22] Zhang Z. Why did the energy intensity fall in China's industry sector in the 1990s? The relative importance of structural change and intensity change. *Energy Economics* 2003;25:625–38.
- [23] Fisher-Vanden K, Jefferson GH, Liu H, Tao Q. What is driving China's decline in energy intensity? *Resource and Energy Economics* 2004;26(1):77–97.
- [24] Wang C, Chen J, Zou J. Decomposition of energy-related CO₂ emissions in China: 1957–2000. *Energy* 2004;30(1):73–83.
- [25] Fan Y, Liao H, Wei Y. Can market oriented economic reforms contribute to energy efficiency improvement? Evidence from China. *Energy Policy* 2007;35(4):2287–95.
- [26] Hang L, Tu M. The impacts of energy prices on energy intensity: Evidence from China. *Energy Policy* 2007;35(5):2978–88.
- [27] Liao H, Fan Y, Wei Y. What induced China's energy intensity to fluctuate: 1997–2006? *Energy Policy* 2007;35(9):4640–9.
- [28] Ma C, Stern DI. China's changing energy intensity trend: a decomposition analysis. *Energy Economics* 2008;30(3):1037–53.
- [29] Han Z, Fan Y, Jiao J, Yan J, Wei Y. Energy structure, marginal efficiency and substitution rate: an empirical study of China. *Energy* 2007;32(6):935–42.
- [30] Hu XL. China's approach to reform. *Finance and Development* 2007;44(3).
- [31] Anderson J. Solving China's rebalancing problem. *Finance and Development* 2007;44(3).
- [32] Aziz J, Dunaway S. China's rebalancing act. *Finance and Development* 2007;44(3).
- [33] Lardy NR. China: rebalancing economic growth. The China balance sheet in 2007 and beyond. Washington, DC: CSIS and IIE; 2007.
- [34] Kuijs L. How will China's savings–investment balance evolve?. World Bank policy research working paper 3958. Washington, DC: World Bank; 2006.
- [35] Wu JL. Understanding and interpreting Chinese economic reform. Mason, Ohio: Thomson/South-Western; 2005.
- [36] Peters GP, Weber CL, Guan D, Hubacek K. China's growing CO₂ emissions – a race between increasing consumption and efficiency gains. *Environmental Science and Technology* 2007;41(17):5939–44.
- [37] Pan JH. Meeting human development goals with low emissions: an alternative to emissions caps for post-Kyoto from a developing country perspective. *International Environmental Agreements* 2005;5:89–104.