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Energy Consumption and Carbon Emission-Based Productivity Change and Industrialization in Post-Reform China

Shiyi Chen,¹ and Amelia U. Santos-Paulino²

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Abstract

The paper investigates the determinants of productivity growth in China. It also analyses the sustainability of the country's industrial growth by estimating sectoral productivity, accounting for energy usage and emission since the start of the market-oriented reforms in the late 1970s. The growth accounting analysis indicates that productivity is the most significant driver of growth. Energy and capital are also important factors promoting China's industrial growth. The substantial productivity improvement of China's industry is attributable more to high-tech light industrial sectors. Heavy industry, characterized by high energy emission levels, lags behind in terms of productivity and overall technical change.

Keywords: productivity growth, industrial sustainability, energy consumption, carbon emission

JEL classification: D24, O47, Q25, Q32

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Acronyms

PNC	People's National Congress
SCE	standard coal equivalent
SOEs	state-owned enterprises
TFP	total factor productivity
TVEs	town and village enterprises
UNFCCC	United Nations Framework Convention on Climate Change

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1 Introduction

China's economic policy has been the focus of much attention and research. Since the start of land reforms in the late 1940s, the country's development strategy has focused on 'heavy-industry' in efforts to catch up with the developed world.¹ The strategy resulted in the persistence of a dual economy, leading to a decline of the agricultural GDP from over 50 per cent in 1952 to 11 per cent in 2006, and an increase in the industrial GDP share from nearly 18 per cent to more than 40 per cent for the same period. The higher than average rate of growth of the industrial sector (11.5 per cent) results from the transfer of resources from agriculture to industry, reflecting the so-called 'price scissors' policy. Before reforms, heavy industry absorbed more than 80 per cent of investments, and nearly the same percentage of the labourforce (Wu and Yao 2003; Fisher-Vanden and Jefferson 2008).

This paper seeks to address two main issues:

- i) What factors have driven industrial growth in China? Is productivity the most important indicator for assessing growth sustainability? How and to what extent is industrial growth affected by energy consumption, or pollution emission in China? And,
- ii) Can each sector's contribution to aggregate industrial productivity be identified? Specifically, what is the relative role of energy (emission) intensive sectors on productivity as compared with energy-saving sectors? Does technical change exist in China's industry and is it Hicks' neutral or biased?

Since the reform from central planning to markets in 1978, China's economic performance has been remarkable. GDP has expanded between 7 to 9.8 per cent per annum, and growth has become steadier than before, as shown in Figure 1. Following the launch of the growth consensus in the late 1970s, the high growth of Chinese industry was characterized by high investment, elevated energy consumption and high emissions during the course of the early industrialization period. Based on the importance of the real economy, this paper aims to investigate the sustainable development of China's industries, particularly under the constraints imposed by both energy use and waste emission.

We aim to analyse the sustainability of China's industrialization by utilizing the industrial sectoral rather than aggregate production function. The productivity and growth accounting approach is followed, which quantitatively allows to distinguish the difference between level effect and growth effect. This is of great importance for comprehensively assessing the long-run prospects of sustainable growth. As Jorgenson and Stiroh (1999, 2000) note, growth differs widely among industrial sectors. For the industry as a whole, negative growth in one sector can offset positive growth in another; therefore it is essential to disaggregate industrial growth estimates to the sub-industry level. Thus, the paper concentrates on disaggregated data for the 38 two-digit industrial sectors over the period 1980-2006.

¹ Heavy industry constitutes mainly the energy industry comprising coal mining, petrochemical industry, electric power industry, etc., while energy- and emission-intensive industry is represented by steel and iron, cement manufacturing, etc.

The production function approach considers only one type of output, thus we use the gross output value of industry as normal output. That is, emission is not treated as a negative output (by-product). Furthermore, we do not consider emission to be an explicit input but incorporate energy into the production function only as an input itself and a proxy of emission, along with capital and labour. Thus, emission is included separately as an ancillary variable to analyse its impact on industrial productivity.

Although many researchers treat emission as an input, it is still difficult and not intuitive to interpret it within a growth equation framework as opposed to energy. Energy and emission are different concepts with their own economic implications. Emission, however, cannot be observed directly, and is normally estimated according to global energy consumption because fossil energy combustion is the largest source of industrial carbon. This inevitably leads to a high correlation between energy and carbon emission data and, therefore, provides us with the rationality to regard energy as a proxy of emission in the production process and to use both terms interchangeably. As clearly illustrated in Figure 1(b), this is particularly the case for China because the CO₂ emission data used in the paper are calculated from the combustion of primary fossil energy (coal, oil and gas). Brown coal accounts for most of the primary energy consumption in China, resulting in a stronger linkage and a higher correlation between energy and emission as compared to other countries. Our methodology, applying the decomposition approach, also differs from those that focus on determining which factors affect changes in energy consumption and pollution emission (Zhang 2003; Fisher-Vanden et al. 2006; Cole, Elliott and Wu 2008; Lee, Chang and Chen 2008).

Section 2 discusses sustainable development, and reviews the emission measurement in traditional growth models. Section 3 describes energy consumption and CO₂ emission in relation to China's progress with industrial reform. Section 4 defines the data for the empirical analysis and describes the methodology used. Section 5 discusses the empirical findings, while section 6 analyses the determinants of productivity change, including emission intensity. Section 7 concludes.

2 Energy, emissions and sustainable development

Most studies rely on the neoclassical growth theory framework and the transformation of growth model to measure the sustainability of economic development (Solow 1957, 1993; Ofer 1987; Krugman 1994; Young 1995, 2003; Irmen 2005; Zheng, Bigsten and Hu 2007). These argue that the extensive growth model based on the perpetual expansion of inputs, the so-called *level effect*, is unsustainable and that only the intensive growth model with continuous and substantial improvement of total factor productivity (TFP), referred to as the *growth effect*, is sustainable in the long run. Although a variety of practical definitions has emerged in distinct areas, the concept of sustainable development has evolved to encompass major elements such as economic, technological, environmental and social factors, and many models and indicators are used to measure the sustainability of development.

However, the early neoclassical growth model usually considers output to be determined by conventional inputs only, that is, capital and labour. Since the global oil crisis in 1973, the enthusiasm of researchers in applying modelling techniques in energy studies has increased. Interest was further enhanced from the 1980s by worldwide

awareness of environmental issues such as global warming and climate change. As a result, a number of modelling techniques have been developed to address complex energy and environmental issues. In recent years, many theoretical and empirical research studies have concluded that it is appropriate to incorporate energy as an input in the production process (see Moroney 1992; Pokrovski 2003; Ayres, Ayres and Warr 2003; Murillo-Zamorano 2005; Thompson 2006; Kandra and Schönb 2007; and Wang 2007 for details).²

In this process, energy is considered not only as an ordinary intermediate product that contributes to the value of output by adding its cost to the price, but also as a value-creating factor which has to be introduced with the factors of production in line with the conventional capital and labour. For example, the well-known KLEM model, which decomposes inputs into capital, labour, energy and intermediate materials for analysing productivity growth was first proposed and applied to the post-war United States economy by Jorgenson, Gollop and Fraumeni (1987), and followed by many other researchers. In related literature, waste emission in the production process is usually dealt with in two ways. First, it is treated as an input like capital stock and labour factors (see, for instance, Aghion and Howitt 1998; Uzawa 2003; Brock and Taylor 2005; Considine and Larson 2006; Stern 2006; Kalaitzidakis, Mamuneas and Stengos 2006).

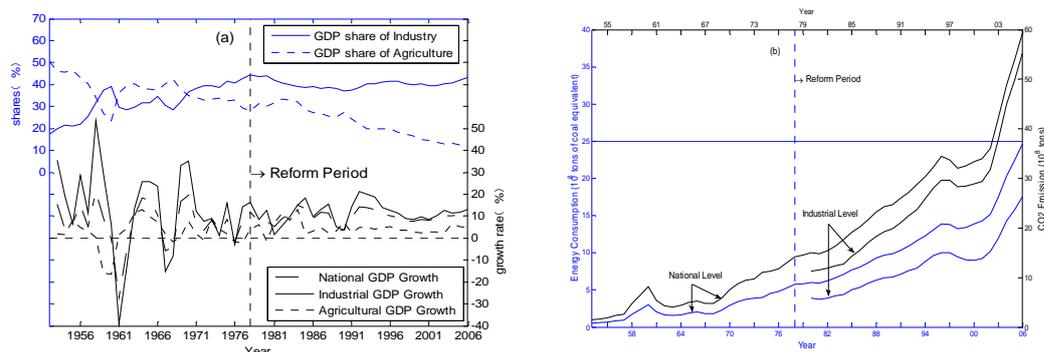
As an input, emission may affect growth through two channels. If natural environment (for example, its function as a waste sink) is considered to be an input in the production process, then emission represents the use of natural environmental capital, implying a positive effect on growth. If environmental quality enters the production function as an input, then pollution exerts a negative effect on growth by lowering the quality of the natural environment. Second, emission is considered an undesirable or bad output, and as such is modelled using the Shephard or directional output distance function (e.g., Chung, Färe and Grosskopf 1997; Färe, Grosskopf and Pasurka 2001; Boyd, Tolley and Pang 2002; Kumar 2006, among others).

3 Energy and emission in China's industrialization after reform

The high growth of energy consumption partly reflects the expansion of China's industry in the reform period, as shown in Figure 1. Industrial output accounts for approximately half of the national output, mostly at the cost of energy consumption and carbon emission, and results from the catch-up strategy. China's strategy emphasized heavy industrialization over structural reforms, and is typical of a dual economy. The elements emanating from the central economy, such as the planned allocation of resources, distorted energy pricing system, insufficient financial resources for geological surveys and exploration of energy sources, and compartmentalization of administrative organizations led to inadequate energy supplies, which for a long time hindered the country's industrial growth. Therefore, a reform of China's industry was needed, notably of its energy and emission polices. Next, we briefly review the changes in the development of energy and emission as characterized by China's various phases of industrial reform after 1978.

² The concept of sustainable development gained significant policy relevance following the 1992 Earth Summit, and the adoption of the United Nations' *Agenda 21* (WCED 1987; United Nations 1993).

Figure 1
Economic growth, energy consumption and CO₂ emission in China, 1953-2006



Source: Calculated and plotted by authors based on data from *China Statistical Yearbook*, *China Energy Statistical Yearbook*.

3.1 Phase of encouragement, 1978-92

The years 1978-92 represent the trial phase of China's industrial reform, wherein the main task was to resolve, based on a long-term perspective, its production shortage, including the critical energy supply. Therefore, early reform of the energy industry focused on promoting energy production, and this was supported by the government's formulation of an energy-saving policy in 1980.

Akin to the industrial reform, which was aimed at increasing the operating autonomy in the urban areas, a system of contract responsibility reformed such energy-intensive industries as coal mining, petrochemical and electric power enterprises. Notably, the most thorough reforms were targeted to the coal industry. The industry was subject to fierce competition, as the state had decentralized authority to local governments, relaxed entry barriers of coal enterprises and encouraged the extraction of coal by townships, communes and brigades (*shedui*), individuals and foreign investors. Driven by prospects of rapidly acquired wealth from mining and local government support to promote local interests, coal production surged into a state-wide boom, resulting in a dramatic increase of non-state-owned mines. Town and village enterprises (TVEs), in particular, contributed to this expansion, producing 150 million tons of the 250 million ton increase recorded during 1981-85, the sixth national Five-Year Plan. Similarly, numerous other small enterprises producing coal power, steel and iron, machinery, fertilizers and cement also prospered, dispersing production and reducing the degree of concentration of China's industry.

Overall, industrial reform during this phase effectively resolved not only the energy supply difficulties but also stimulated light industries such as textile and food production. This was a key factor in shifting the country's industrial development from one based on the pre-reform catch-up strategy to a focus on labour- and energy-intensive sectors that reflected China's comparative advantages.

3.2 The phase of restriction, 1992-2001

Deng Xiaoping's southern tour gave an enormous impetus to the historically decisive industrial reform during 1992-2001. The transition to market economy began with

complete liberalization of product prices in the early 1990s and privatization of state-owned enterprises (SOEs) in the latter part of the decade. These laid a solid foundation for the success of the reform programme and China's successful entry into global trade and financial forums, notably its accession to the World Trade Organization (WTO) in 2001. This phase also represents the formal implementation of environmental protection plans, as the government started to restrict the development of energy enterprises, contrary to policies followed in the 1980s.

The rash development of small energy-intensive enterprises during the first phase initially eased the energy shortage, but the uncontrolled production of coal led to a national surplus. Furthermore, destructive exploitation, lack of environmental protection measures, and the relatively low production cost of the small coal mines led indirectly not only to financial losses for the state-owned mines, but also resulted in a waste of coal resources, serious damage and environmental pollution. Control and prevention of industrial wastes throughout the 1980s and earlier had focused only on managing its sources and treating end-of-pipe pollution. It was not until the concept of sustainable development became globally acknowledged in the early 1990s and pursued in international polity circles that awareness of environmental protection became important for the Chinese. At this point, measures for environmental conservation and policies to save energy were effectively implemented by the government.

China was one of the countries involved in drafting *Our Common Future* in 1987 and in 1992 it signed the Rio Declaration and United Nations *Agenda 21*. In 1994, the country took the lead in releasing the first national China Agenda 21. Official document³ authorized by the People's National Congress (PNC) in 1996 confirmed sustainable development as one of the basic strategies of the nation and highlighted energy as an important element of that development plan. PNC also reconfirmed the energy policy of 'simultaneously saving and developing energy', as originally proposed in 1980, enacting the Save Energy Law in 1998.

The tenth national Five-Year Plan in 2001 outlined a goal to be achieved in every area of sustainable development. Prevention of industrial pollution and treatment became an important element of environmental protection. Focus, amongst other measures, shifted from end-harnessing to the control of pollution sources and production processes, from controlling waste sources to comprehensive regulation on drainage and regional areas, and from treating certain individual enterprises to improving the industrial structure, and developing circulative economy.

A substantial reform of the SOEs was promoted by the concept 'grasping the large and letting go of the small' (*zhuadafangxiao*), and by policy developments that restricted rather than encouraged energy industry, and that emphasized financial profits and environmental conservation instead of increasing energy supplies. As a result, between 1996 and 2000 the government closed down 84,000 small energy- and emission-intensive enterprises, and curbed the uncontrolled production of energy, increasing in the process the degree of industrial concentration.

At the beginning of the 1990s, the dual-track pricing system, in which the planned economy and the market had coexisted, was successfully liberalized in the product

³ In particular, *Outlines of the Ninth Five-Year Plan and Long-term Target towards to 2010*.

market, but the factor market remained underdeveloped. With respect to coal, the dual-track price system (managed by the state) was first phased out in 1994 and later fully liberalized, as opposed to the pricing mechanisms for oil and electric power. Full formation of a coal market, in conjunction with the closure of many small mines and the SOEs' furlough policy (*xiagang*), balanced supply and demand and reversed the overall loss of the coal industry. Reform of the petrochemical and electric power industry was minor in comparison to that of coal. The petrochemical industry was strategically reconstructed in 1998 with the creation of two main corporations: Petroleum and Petrochemical Corporation. Electric power was reorganized by separating government functions from enterprise management and power plants from national grid: both still operate under the national monopoly.

The development strategy emphasizing labour-intensive light industry was relevant during this phase. Even though the development of energy and emission-intensive heavy industry was restricted, energy production continued to increase steadily. Likewise, the policy of energy conservation and emission abatement resulted in noticeable improvement.

As illustrated in Figures 1 and 2, after long period of continuing growth, the consumption of primary energy and carbon emissions declined, remaining constant for the first time between 1997 and 2001. For instance, during the years 1996-2001, industrial energy consumption declined from one billion tons of coal to 0.92, industrial CO₂ emissions dropped from 2.96 billion tons to 2.90, and energy intensity decreased as well during this period. Conversely, the carbon emission intensity first increased from 2730 tons per million USD in 1980 to a peak in 1991 (5359), and then declined to 2585 in 2002. This change was even more obvious in the international context.

At the start of economic reform in the late 1970s, China's energy intensity was over six times that of the United States; by 2002, it had dropped to slightly more than three times the US level. Similarly, China's carbon emission per unit of GDP was more than seven times that of United States in 1991 but decreased to about four times in 2002. From 1980 to 2001, the elasticity of energy consumption was less than one (except in 1989), implying that high economic growth was achieved with a limited increase in energy consumption. During this phase, under a policy that encouraged the exploitation of new and renewable energy, coal consumption as a share of total primary energy fell from nearly 76 per cent in 1990 to 66 per cent in 2000, and during the same period, the consumption of oil, gas, hydro, nuclear, wind and solar energy increased over 40 per cent.

3.3 The return of heavy industrialization, 2001 to present

Industry during this phase still adheres to the strategy that emphasizes labour-intensive light industry and sustainable development, characterized by energy conservation and emission abatement. The 16th Party Congress in 2002 outlined a new direction for industrialization, on the basis of which a scientific outlook on development was proposed in the 3rd Plenum, and the development of a harmonious society in the 4th Plenum.

Climate change is a popular topic in the field of energy. China ratified the Kyoto Protocol in 2002, and in 2004 submitted an official document⁴ that included national greenhouse gas inventories to the tenth conference of the United Nations Framework Convention on Climate Change (UNFCCC). In 2007, the government released the first national green plan among developing countries, known as *China's National Plan for Coping with Climate Change*. In summary, the Chinese legislature by 2008 had drafted some 30 national laws relating to resources, energy and environmental conservation, and the State Council had issued more than 100 administrative regulations on sustainable development.

Guided by these policies, during 2001-04 the government blacklisted products of backward production capacity, discontinued 30,000 resource-wasteful enterprises, halted 1,900 projects in seriously polluting sectors such as cement, steel and iron, electrolysis aluminium, etc. In 2005, another 2,600 energy- and emission-intensive enterprises were closed.

However, the phenomenon of heavy industrialization re-surfaced after the 2002 reforms. As seen in Figures 1 and 2, the consumption of primary energy and carbon emission increased unprecedentedly after 2001, reaching in 2006 the peak of 2.46 billion tons of coal equivalent (1.75 for industry) and 5.9 billion tons (5.5 for industry), respectively. Energy intensity also reversed its long-term decreasing trend, and carbon emission intensity rose during 2002-05, albeit declined slightly in 2006. During the first two phases, the averaged elasticity of energy consumption was about 0.5, indicating that a one per cent GDP growth was accompanied by an increase in energy consumption of only 0.5 per cent; after the new millennium, the averaged elasticity exceeded one, which also signals the return of heavy industrialization.

Heavy industrialization was also apparent in the structure of exports. From the late 1990s, Chinese exports shifted from labour-intensive light products such as textiles to capital- and energy-intensive products like machinery, chemicals, cement, etc. The degree of sophistication of exports and their productivity has reached the level of countries with a GDP per capita three times that of China (Rodrik 2006). Anderson (2007) further notes that the export surplus in heavy industry since 2005 is one of the important reasons for China's current dramatically increased foreign trade surplus.

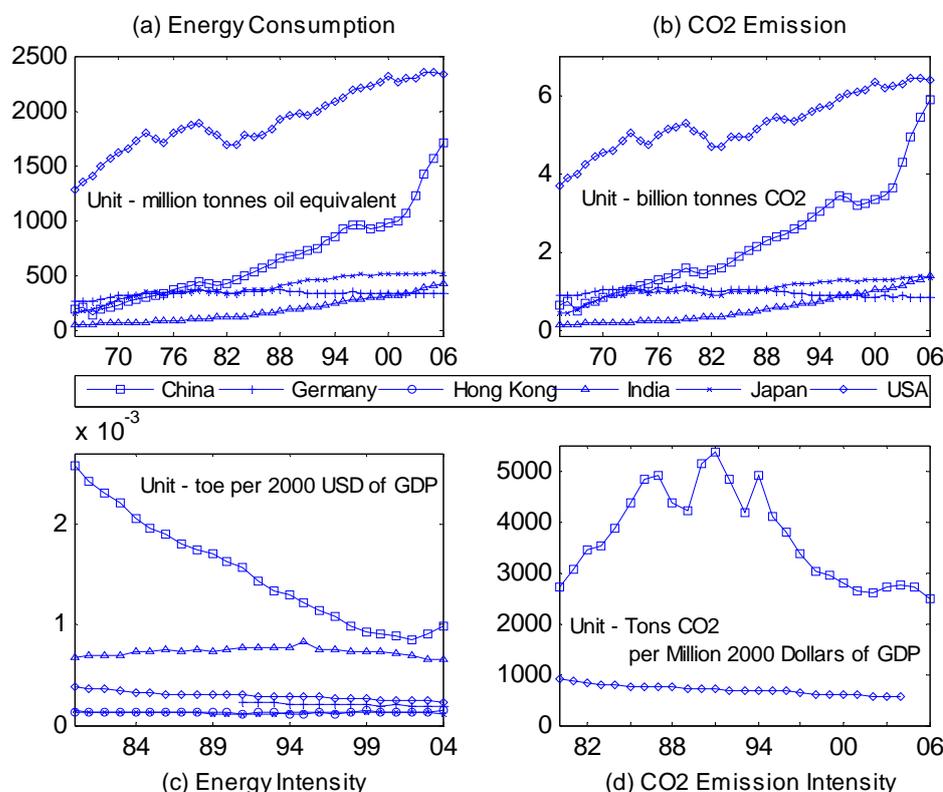
This phenomenon has led to considerable debate: is heavy industrialization inevitable and necessary for China today? Can high energy consumption and carbon emission drive sustainable industrial growth in the future? The development of heavy industrialization during this phase may be different than that during the catching-up strategy before reforms, as light industry develops fast, but seems to differ from the new industrialization plan proposed at the beginning of this century. This merits special attention, and can be attributable to either short-term or long-term factors. Short-term measures include the continuous and massive infrastructure investments, new entry of private capital in heavy industries due to the low price of natural resources, accelerated transfers of international manufacturing to the country, etc., while long-term impacts resulted from upgraded consumption structures, increased level of urbanization, and the

⁴ This document is known as *The People's Republic of China Initial National Communication on Climate Change*. In the same year, China enacted the 'Outlines of China Medium and Long-Term Energy Saving Plan 2004-2020'.

empirical regularity that heavy industry develops faster at the middle stage of industrialization.

Based on this, the eleventh national Five-Year Plan introduced in 2006 the goal of energy conservation and emission abatement, that is, to decrease energy consumption per GDP by 20 per cent and total pollution emission by 10 per cent over the years 2006-10. Concrete measures promoting the conversion to a low carbon economy are justified because, first, these aim to provide financial support for energy-saving and emission-abating projects. The energy industry itself is unable to finance its development because it is a capital-intensive sector but has a low value of output due to low energy prices. Based on the theory of public finance, this is the government's responsibility, as enterprises striving for profit maximization are unwilling to invest in energy conservation. Consequently, treasury bonds and financial investments of the central government on E&E projects reached 23.5 billion *yuan* in 2007 and 50 billion in 2008. Second, measures were introduced in 2006 to modify the foreign trade policy regime, by cancelling tax rebates, increasing tariffs, reducing quotas, and forbidding certain export products with high energy consumption, pollution emission or serious resource waste. Other measures included the restriction of energy-intensive projects developing through different channels such as land, credit and foreign investments, consolidating taxes and environmental pollution fees, granting of tax advantages to enterprises with the lowest pollution emission or those producing environment-conservation products, and liberalizing resource prices such as product oil.

Figure 2
Energy consumption, CO2 emission and their intensity among different economies



Source: Calculated and plotted by the authors based on data from *Statistical Review of World Energy* (2007), China Statistics Press.

However, it is a challenge for China to conserve energy and reduce emissions, as the country will continue with its policy of industrialization and urbanization. Energy- and emission-intensive industries such as chemical products, cement, and iron and steel will continue to play a fundamental role in China's economy, both at present and in the foreseeable future. Thus, the country faces a dilemma in its need to adjust its economic structure and growth model, while promoting industrialization and economic growth, especially in view of the latest international financial crisis. Energy consumption and emissions per capita are very low in China, but it is nevertheless currently the second largest energy consumer and carbon emitter in absolute terms in the world, just behind the United States. There is still a considerable gap with regard to energy and emission intensity between China and the advanced economies, or even the developing countries like India, as can be seen from Figure 2. These have raised great concerns from the international community.

The problem of reducing pollution emission is compounded by China's unbalanced composition of primary energy consumption. Rich in coal reserves, the country exhibits a dominant share of coal consumption, although this has declined in recent years. The CO₂ emitted per thermal unit of coal is 36 per cent or 61 per cent higher than that of oil and gas. Poor endowment of cleaner sources of energy, the low level of technology related to energy, and the lack of investments will inevitably mean a rigid energy consumption structure, and subsequent difficulties in reducing pollution emission for a long time.

4 Data and methodology

4.1 Data

While the aggregate industrial trends are interesting, as noted in the introduction, this paper is concerned with analysing the impact of energy (emission) on growth at the two-digit sub-industrial level. Sub-industries are classified according to China's National Standard of Industrial Classification (GB/T4754) revised in 2002. The data available for the period after the 1978 reforms make it possible for the analysis to be undertaken for 38 different industrial sectors, comprising three bigger categories: mining; manufacturing; electric power, gas and water production and supply.⁵

The production function modelling—and the successive analysis of different productivity patterns—implies that data be available on input as well as output quantities. The output data used in this study is sub-industrial gross output value with the unit of 100 million *yuan* at the 1990 price level, denoted by *Y*. This has the advantage of providing an explicit role for intermediate materials (e.g., energy) in determining economic growth at the sub-industrial level. For example, intermediate materials, such as coal, are indispensable for the production of electric power, particularly in China. By identifying these intermediate inputs explicitly, the contribution of electric power investments—whether in the form of coal production or

⁵ All data used in this study, if not otherwise mentioned, originate from the *China Statistical Yearbook* (1983-2007), *China Industry Economy Statistical Yearbook* (1988-2007), *China Energy Statistical Yearbook* (1991-2007), *China Compendium of Statistics* (1949-2004), *China Urban Life and Price Yearbook* (2007), etc. available from the National Bureau of Statistics of China.

electric power generation—to economic growth can be estimated separately. The labour input, L , is defined as the annual average employed workers (unit: 10,000 persons) and energy input, E , is the total energy consumption (unit: 10,000 tons of coal equivalent).⁶

Capital stock and carbon dioxide (CO₂) emissions cannot be obtained directly and thus need to be estimated. The capital stock, K , in 1990 prices, is calculated by using the ‘perpetual inventory approach’, first proposed by Goldsmith (1951) and later improved by Denison (1967) and Jorgenson (1963). According to the World Bank definition, CO₂ emissions are those that stem from the burning of fossil fuels and the manufacture of cement, with the former accounting for at least 70 per cent of total CO₂ emissions. Therefore, the CO₂ emissions used in this paper are related only to fossil energy combustion, and computed from the consumption of primary solid coal, liquid oil, and gas fuels according to the following expression.

$$C_t = \sum_{i=1}^3 C_{i,t} = \sum_{i=1}^3 E_{i,t} \times NCV_i \times CEF_i \times COF_i \times (44/12) \quad (1)$$

where C represents the flow of carbon dioxide with the unit of 10,000 tons, NCV is net calorific value provided by the *China Energy Statistical Yearbook* in 2007, CEF is the carbon emission factor provided by 2006 National Greenhouse Gas Inventories in Intergovernmental Panel on Climate Change (IPCC 2006). COF is the carbon oxidization factor set to be one in this study. Therefore, in the case of China, the calculated CO₂ emission coefficient for coal is 1.973 (kg CO₂/kg coal), for oil 3.065 (kg CO₂/kg oil) and for gas 2.184 (kg CO₂/m³ gas).

Since the empirical work of Hoffmann (1958) and Chenery, Robinson and Syrquin (1986), the standard perception of industrialization is a general shift in relative importance from light to heavy industry, as experienced by China after the reforms. Light industry is normally of great importance during the early stages of industrialization and has relatively low energy and emission intensity. On the other hand, heavy industry features during the middle or late phase and has relatively high energy and emission intensity. To investigate further the impact of CO₂ emissions on productivity, we divide all sectors into the two groups: light and heavy industrial groups based on their emission intensity ranking (EI) in 2004, where the former group corresponds to the sectors with a lower EI value, and the latter to sectors with larger EI . We refer to these as the low-emission group and the high-emission group, or light industry and heavy industry in brief from now on.⁷

The descriptive statistics of the variables used in the study are given in Table 1 for both emission groups. Importantly, the table shows that the mean of capital stock, energy consumption and CO₂ emissions in the high-emission group are about three, seven and thirty times higher than the low-emission group, respectively. But the mean of industrial gross output in the high-emission group is lower than that in the low-emission group. In particular, the highest gross output is observed in the newly developing high-tech

6 China uses coal as its main energy source and the standard coal equivalent (SCE), defined as coal with a heat content of 7000 kc, is used to measure various forms of energy in official statistics.

7 The list of 38 sectors, their codes and ranking according to emission intensity in 2004 can be obtained from the authors on request.

industrial sector: ‘manufacture of communication equipment, computers and other electronic equipment’ (53773), which recorded the lowest energy and emission intensity in 2006.

Also, although the sectors in the high-emission group utilize higher amounts of inputs such as capital and energy, they do not absorb as much labour as other sectors. There is also a greater variability within the high-emission group for all inputs, capital, labour, energy and emissions. Based on these statistical information, China’s heavy industrial sectors, defined in this study according to their emission intensity, are characterized by high investment, high energy consumption, high carbon emission but marginal output, which implies that these sectors should feature lower productivity levels.

Table 1
Descriptive statistics of the variables used in this study, 1980-2006

Variable	Mean	Std deviation	Minimum	Maximum
Low-emission group				
Gross output value (100 million <i>yuan</i>)	1,468.10	3,953.70	17.09	53,773.0
Capital stock (100 million <i>yuan</i>)	365.19	430.63	12.52	2,718.4
Labour (10,000 workers)	112.37	98.09	13.14	450.6
Energy consumption (10,000 sce)	503.52	460.29	37.44	2,576.0
CO ₂ emission (10,000 tons)	476.20	483.46	15.79	1,972.3
High-emission group				
Gross output value (100 million <i>yuan</i>)	1,210.00	1,547.10	32.73	107,41.0
Capital stock (100 million <i>yuan</i>)	1,171.10	1,841.80	28.29	15,313.0
Labour (10,000 workers)	158.98	150.69	7.00	756.0
Energy consumption (10,000 sce)	3,833.70	5,310.50	105.00	42,812.0
CO ₂ emission (10,000 tons)	12,800.00	25,778.00	144.06	237,980.0

4.2 Methodology

China’s industrial sector is described by a well-defined production function as:

$$y_{it} = f(K_{it}, L_{it}, E_{it}, t) \quad (2)$$

where y is the industrial value of gross output, K, L, E are the quantity of capital, labour and energy inputs defined previously and a time trend $t = 1, 2, \dots, 27$, corresponding to the years from 1980 to 2006, is used to capture the technical change. The subscript i indicates the i th industrial sector ($i = 1, 2, \dots, 38$). The production function is used to estimate productivity and to undertake the growth accounting exercise.

Correspondingly, total factor productivity (TFP) is defined as the ratio of gross output to total factor inputs which is the weighted average of all factor inputs and normally specified as exponential form, say, $x = K^{s_K} L^{s_L} E^{s_E}$, where s_K, s_L, s_E represent the weights of capital, labour and energy inputs, assuming that the sum of all factors equals to 1. That is:

$$TFP = y/x = y / (K^{s_K} L^{s_L} E^{s_E}) \quad (3)$$

Following the definition of Solow (1957), the growth of TFP can be calculated through the expression:

$$\dot{TFP}_t = \dot{y}_t - s_{K_t} \dot{K}_t - s_{L_t} \dot{L}_t - s_{E_t} \dot{E}_t \quad (4)$$

where the superior dot (·) indicates the growth rate of the variable. Equation (4) is derived by taking natural logarithm and the first difference on both sides of Equation (3).

Under the assumption of competitive producer equilibrium and constant returns-to-scale, the output share of each input is equal to its output elasticity and can be used as the weights to calculate TFP growth directly. Similarly, the output elasticity of each input can be estimated by using the production function and then employed directly as the weights to compute productivity in the case of constant returns-to-scale. Otherwise, the normalization of output elasticity of inputs is necessary for calculating productivity. For example, setting output elasticity of capital, labour and energy equal to: $\alpha_K, \alpha_L, \alpha_E$, the scale elasticity is then the sum of all output elasticity of inputs expressed as:

$$e = \sum_{j=1}^3 \alpha_j \quad (5)$$

where $j = 1, 2, 3$ correspond to the input factor of capital, labour and energy. Under the assumption of varying returns-to-scale, the weights to calculate productivity are $s_K = \alpha_K / e, s_L = \alpha_L / e, s_E = \alpha_E / e$, respectively, and Equation (4) can be rewritten as:

$$\dot{TFP}_t = \dot{y}_t - \sum_{j=1}^3 \frac{\alpha_j}{e} \dot{x}_{ij} \quad (6)$$

The nominal growth rate of TFP in Equation (6) is referred to as Solow residuals in standard literature. To decompose the growth rate of TFP further, differentiating expression (2) and dividing it by output y on both sides, we obtain:

$$\dot{y}_t = \dot{T}C_t - \alpha_{K_t} \dot{K}_t - \alpha_{L_t} \dot{L}_t - \alpha_{E_t} \dot{E}_t \quad (7)$$

where, $\dot{T}C_t = \frac{\partial \ln f(\alpha_t, t)}{\partial t}$ captures the growth rate of technical change in the i th sector while $\alpha_j = \frac{\partial \ln y_i}{\partial \ln x_{ij}}$ is the output elasticity of input j in this sector.

Substituting Equation (7) into (6):

$$\dot{TFP}_t = \dot{T}C_t + (e - 1) \sum_{j=1}^3 \frac{\alpha_j}{e} \dot{x}_{ij} \quad (8)$$

To avoid the limitations of restrictive Cobb-Douglas (CD) production function such as constant return-to-scale, Hicks-neutral technical change and unit elasticity of substitution, for the purpose of our study this paper employs more flexible translog production function form. The translog function does not impose any *a priori* restrictions as in the case of the CD function, and could contain the CD function as a special case. The parametric industrial sector translog function, corresponding to Equation (2), is specified as follows:

$$\begin{aligned} \ln y_{it} = & \beta_1 + \beta_i + \beta_t t + \frac{1}{2} \beta_{tt} t^2 + \sum_{j=1}^3 \beta_j \ln x_{ij} \\ & + \frac{1}{2} \sum_{j=1}^3 \sum_{k=1}^3 \beta_{jk} \ln x_{ij} \ln x_{ik} + \sum_{j=1}^3 \beta_{ij} t \ln x_{ij} + \varepsilon_{it} \end{aligned} \quad (9)$$

In addition to the variables defined in Equation (2), x represents the inputs and subscripts j and k denote capital, labour and energy inputs (i.e., $j=1,2,3$). β s are the regression coefficients to be estimated, where β_i represents the individual effect of each sector if the fixed-effect model can be used for the industrial input-output panel data. Note that the introduction of the interaction term including trend variables of each input (in logs) aims to capture the biased technical change of each input.

In estimating a production function, it is necessary to consider the validness of the chosen estimation method. If an individual effect does not exist, the translog production model can be estimated by using pooled OLS only; otherwise, it needs to be determined whether a fixed effect or random effect is more parsimonious. The former can be tested with the general F -test statistics and the latter with the Hausman Wald test. There may be additional problems of autocorrelation and heteroscedasticity, which may be safely ignored since the time trend variable and individual effect will absorb the autocorrelated and heteroscedastic components of the disturbance term. And since the output and inputs variables are transformed into a logarithmic scale, the disturbance term ε_{it} , therefore, follows the assumptions of classical linear regression model.

Then, statistics such as technical progress, output elasticity of inputs, elasticity of substitution and biased technical change can be calculated based on the estimated regression coefficients.

The estimated growth rate of technical change is formulated as:

$$\hat{TC}_{it} = \hat{\beta}_t + \hat{\beta}_{tt} t + \sum_{j=1}^3 \hat{\beta}_{tj} \ln x_{itj} \quad (10)$$

where the superscript $\hat{}$ indicates the estimator of that variable.

The output elasticity of each input can be estimated by:

$$\hat{\alpha}_j = \hat{\beta}_j + \sum_{k=1}^J \hat{\beta}_{jk} \ln x_{itk} + \hat{\beta}_{tj} t. \quad (11)$$

As shown in Equations (10) and (11), the estimated $\hat{\beta}$ s and then $\hat{\alpha}_K, \hat{\alpha}_L,$ and $\hat{\alpha}_E$ are used to calculate the needed quantities; thus, Equation (8) does not hold exactly in the case of an empirical study. Setting the real residual term to be res , the empirical form of Equation (8) could be expressed as:

$$TFP_t = \underbrace{\widehat{TC}_t}_{\text{technical change}} + \underbrace{(\sigma - 1) \sum_{j=1}^8 \frac{\alpha_j}{\sigma} x_{tj}}_{\text{scale effect}} + res \quad (12)$$

Equation (12) implies that the nominal TFP growth, the so-called Solow residuals, can be decomposed into three components: technical change, scale effect and the real residual term. In this study, the real residual term, res , needs to be excluded from the Solow residuals, which is normally ignored in previous productivity studies. Growth rate of the aggregate industrial TFP will be computed as the weighted average of sector productivity in which the gross output share of each sector constitutes the weights. By doing so, the sources of productivity growth can be identified at the level of the individual industrial sectors, providing a more detailed understanding of the forces driving aggregate trends.

The elasticity of substitution is the proportional change in the ratio of the use of two inputs brought about by a change in the ratio of marginal rate of substitution (RTS) for two inputs. Therefore, the expression to calculate the substitution elasticity between input j and k can be derived as below:

$$\sigma_{jk} = \frac{d \left(\frac{x_k}{x_j} \right) / \frac{x_k}{x_j}}{dRTS_{jk} / RTS_{jk}} = \frac{1}{\left(1 + \frac{\hat{\alpha}_j - \hat{\alpha}_k}{x_k - x_{kj}} \right)} \quad (13)$$

If $\sigma_{jk} > 0$, input j and k are substitutes for each other; if $\sigma_{jk} < 0$ then both inputs are complements.

Another variable of immediate interest is the bias in technological change. The biased technological change, in the spirit of Hicks, is defined originally according to two inputs, capital and labour, while in the case of multiple inputs, it is measured as the proportional change in the marginal rate of substitution (RTS) between any pair of inputs over time. This is equivalent to the relative proportional change of output elasticity for pairwise inputs. That is, the bias in technical change between a pair of factor inputs, j and k , is given as:

$$B_{jk} = \frac{\partial}{\partial t} (RTS_{jk}) / RTS_{jk} = \frac{\partial \alpha_j / \partial t}{\alpha_j} - \frac{\partial \alpha_k / \partial t}{\alpha_k} = B_j - B_k \quad (14)$$

A positive (negative) sign on B_{jk} indicates that technical change is factor j (k) intensive, and B_{jk} equals 0, implies that technical change is Hicks-neutral.

In this paper, however, Hicks' definition of bias in technological change is defined in a more simplified form as:

$$B_j = \frac{\partial \alpha_j / \partial t}{\alpha_j} = \frac{\beta_{tj}}{\alpha_j} \quad (15)$$

Technological change is said to be j th input saving, neutral or in the Hicksian sense as $B_j < 0$, $B_j = 0$ or $B_j > 0$. The advantage of the modified version is that it provides a single measure of bias for each factor, while Hicks's original definition produces $J-1$ measures of bias for each factor in the J -factor case.

To justify the translog specification of Equation (9), several hypothesis tests are necessary. Since much of the literature uses a CD production function for disembodied technological change, we first test the hypothesis that this specification of CD form is preferable to translog function. That is:

$$H_0 : \beta_{jk} = \beta_{tj} = 0 (j, k = 1, 2, 3)$$

Constant returns-to-scale are a testable hypothesis for the translog production function, which requires the following set of restrictions on the values of the estimated parameters:

$$H_0 : \beta_{jk} = \beta_{tj} = 0, \sum_{j=1}^3 \beta_j = 1 (j, k = 1, 2, 3)$$

Rejection of the null hypothesis implies that returns-to-scale are either increasing or decreasing.

We then perform a test on the nature of technical change in the context of Equation (9). The hypothesis of no technical change is as follows:

$$H_0 : \beta_t = \beta_{tt} = \beta_{tj} = 0 (j = 1, 2, 3)$$

The hypothesis of Hicks neutral technical change (or, no technical change bias) is tested by examining the joint significance of the coefficients on the interaction terms between the factor inputs and the trend variable.

$$H_0 : \beta_{tj} = 0 (j = 1, 2, 3)$$

These restrictions are maintained as hypotheses to test the functional specification of the production structures. They could be tested by the general F test since the fixed-effect model is in nature pooled least squares on the time demeaning of the original equation.

5 What is the role of productivity change in industrialization?

The estimated parameters of the translog production function and the probability values for China's sub-industries are reported in Table 2. The estimates are statistically sound,

as confirmed by the diagnostics statistics. The fraction of variance due to sector effect ($\rho = 0.9088$) indicates that the difference in individual effects can explain most of the variation in industrial growth. The F -statistic of 93.23 favours the panel data model rather than pooled OLS. The Wald statistic or Hausman specification test also justifies the fixed effect (within) regression model used in our analysis.

Table 2
Estimates of fixed-effects (within) regression of translog production function

Var.	Coef.	Std err.	p value	Var.	Coef.	Std err.	P value
cons	4.9602	0.7137	0.000	1nL1nE	-0.0776	0.0481	0.107
t	0.0422	0.0186	0.023	(1/2)1nK2	-0.0392	0.0834	0.639
(1/2)t2	0.0066	0.0007	0.000	(1/2)1nL2	0.6132	0.0727	0.000
lnK	-0.3751	0.2139	0.080	(1/2)1nE2	-0.3029	0.0650	0.000
lnL	-1.8508	0.2191	0.000	tlnK	-0.0246	0.0051	0.000
lnE	1.1752	0.2109	0.000	tlnL	0.0429	0.0043	0.000
lnKlnL	-0.1954	0.0539	0.000	tlnE	-0.0175	0.0042	0.000
lnK1nE	0.3125	0.0718	0.000				
sigma_u		1.0024		No. of obs	1,026		
sigma_e		0.3175		No. of groups	38		
rho		0.9088		Obs per group	27		

Notes: R-sq: within = **0.8795**; F test that all slopes equal to zero: F (14,974) = **508.01**, p value = 0.0000.
F test that all individual effects equal to 0: F (37,974) = **93.23**, p value = 0.0000.
Hausman Test: Wald chi2(14) =119.4, p value = 0.0000.

5.1 Growth accounting and production structure

The statistical tests concerning the production structure of China's industrial sectors are reported in Table 3. First, the hypothesis that sectoral production can be described by a Cobb-Douglas production function is tested and strongly rejected. Table 4 reports the sources of industrial growth and the contribution of inputs, based on the estimated translog function for each of the 38 sectors. Input contribution is defined as the growth rate of that input multiplied by its estimated output elasticity, all values being simple averages for the entire sample period. That is, output growth is equal to the sum of the contributions of inputs, productivity growth and residuals.

The results highlight the importance of the high-tech industries, and show that these industries grew rapidly both in terms of output and productivity.⁸ The slowly growing sectors were high energy-usage and pollution-emitting activities and exhibited below-average output growth and low or even negative TFP growth.⁹

⁸ High-tech industries include the 'manufacture of communications equipment, computers and other electronic equipment'; 'transport equipment'; 'manufacture of measuring instruments and machinery'; and the 'manufacture of electrical machinery and equipment'.

⁹ The 'extraction of petroleum and natural gas'; 'processing of petroleum and coking'; 'production and supply of water and gas'; 'mining and processing of nonmetal ores' and 'non-ferrous metal ores' represent the slow-growth sectors.

Table 3
Hypotheses tests for the production structure of China's industry

Hypothesis test	General F value	Degrees of freedom	Exact probability
Cobb-Douglas production function	36.2	(9,974)	0.0000
Constant returns-to-scale	58.4	(10,974)	0.0000
No technical change	93.2	(5,974)	0.0000
Hicks-neutral technical change	35.7	(3,974)	0.0000

Table 4
Sources of China's industrial growth, averaged over the post-reform period

Industry	Output growth	Contribution of inputs			Solow residuals	
		Capital	Labour	Energy	Real TFP growth	Residuals
Coal mining	0.080	0.017	-0.003	0.011	0.106	-0.051
Petroleum extraction	0.013	0.084	-0.007	0.030	0.059	-0.152
Ferrous mining	0.141	0.064	0.008	0.045	0.014	0.010
Non-ferrous mining	0.102	0.023	0.002	0.026	0.076	-0.022
Non-metal mining	0.086	0.018	0.001	0.039	0.071	-0.042
Wood exploiting	0.033	0.003	-0.011	-0.010	0.100	-0.049
Food producing	0.100	0.032	-0.003	0.017	0.104	-0.050
Food manufacturing	0.104	0.034	-0.002	0.021	0.104	-0.054
Beverage	0.127	0.040	-0.002	0.036	0.104	-0.052
Tobacco	0.116	0.066	-0.021	0.049	0.047	-0.026
Textiles	0.086	0.022	-0.009	0.012	0.124	-0.063
Apparel	0.128	-0.002	0.014	0.043	0.188	-0.115
Leather	0.131	0.001	0.011	0.033	0.141	-0.055
Wood processing	0.160	0.034	0.008	0.018	0.088	0.012
Furniture	0.138	-0.008	0.013	0.031	0.111	-0.009
Paper	0.122	0.043	-0.002	0.018	0.088	-0.025
Printing	0.118	-0.001	-0.005	0.065	0.138	-0.080
Cultural articles	0.158	-0.006	0.013	0.052	0.117	-0.018
Petroleum processing	0.065	0.076	-0.005	0.025	0.064	-0.095
Chemical products	0.110	0.039	-0.002	0.008	0.088	-0.023
Medicine	0.162	0.044	0.004	0.019	0.105	-0.010
Fibres	0.185	0.063	-0.015	0.044	0.035	0.058
Rubber	0.113	0.031	0.003	0.026	0.096	-0.037
Plastic	0.154	0.025	0.002	0.043	0.127	-0.044
Non-metal manufacturing	0.109	0.033	-0.008	0.010	0.091	-0.017
Ferros metal pressing	0.112	0.039	-0.003	0.010	0.079	-0.012
Non-ferrous pressing	0.123	0.042	0.000	0.035	0.076	-0.031
Metal products	0.124	0.021	-0.009	0.021	0.118	-0.028
General machinery	0.109	0.008	-0.010	0.009	0.094	0.008
Special machinery	0.113	0.007	-0.009	0.012	0.102	0.000
Transport equipment	0.177	0.011	0.000	0.022	0.132	0.012
Electrical equipment	0.167	0.008	0.001	0.033	0.147	-0.022
Computers	0.307	0.008	0.013	0.066	0.174	0.045
Measuring instruments	0.169	-0.001	-0.001	0.026	0.119	0.026
Electric power	0.133	0.051	0.002	0.038	0.107	-0.065
Gas producing	0.077	0.158	-0.070	0.055	-0.036	-0.031
Water producing	0.071	0.050	-0.029	0.057	0.053	-0.061
Others	0.145	0.052	-0.007	0.016	0.114	-0.031

Certain sectors ('mining of ferrous metal ores'; 'manufacture of chemical fibres') recorded fast growth rates, but growth was driven mainly by capital and energy, not productivity. Other sectors (the 'manufacture of textile wearing apparel' and of 'leather, fur and feather products') experienced high productivity and labour contribution but very low, or even negative, capital contribution, together with some unexplained factors in the residuals, which resulted in their relatively low output growth. Labour input played a relatively significant role only in the case of the 'manufacture of textile wearing apparel', 'leather, fur and feather products', 'furniture', 'articles for culture, education and sports activities', which is understandable given the labour-intensive nature of these sectors. In particular, the fastest growing sector ('manufacture of communications equipment, computers and other electronic equipment') reflected the second highest productivity, relatively strong labour absorptivity but very low capital demand, factors which seem to be very instructive for China's future industrialization. Of course, this sector was a significant consumer of secondary electricity (energy), which is not reflected in the primary energy consumption and emission ranking because the emission data used were compiled from primary energy only.

Table 4 provides information on the contribution of input and TFP to output. It is noticeable that China's industrial productivity has improved substantially. This in turn had a positive impact on growth, and was, with a few exceptions,¹⁰ among the primary driving forces of growth for each sector. In high energy-use sectors,¹¹ capital factor was the major driving force; and in the 'production and supply of water' section, energy emerged as the main determinant.

Energy and capital, respectively, represented the second growth engine in the other 17 sectors. At the same time, only one sector recorded a negative contribution for the energy input, four sectors for capital and most of the sectors for labour. Thus, we can conclude that in addition to productivity, energy and capital have been the main engines of growth for China's industry. The results presented in Table 4 highlight extensive variation among the industries, reinforcing our premise that the aggregate production function masks important growth disparities within the sectors. Therefore, to understand the forces driving China's aggregate growth, it is essential to assess the individual contribution of each industrial sector.

The growth accounting exercise for the three industrial reform phases as well as for the entire period, simply averaged over the 38 industrial sectors, is briefly reported in Table 5, which includes the growth rate and contribution of inputs and productivity change. As the figures show, China's massive industrial reform led to increased industrial growth and productivity. The aggregate growth rate of nominal productivity change for the entire reform period was 6.5 per cent, but real TFP growth reached 9.7 per cent. During the first phase (1981-91), TFP growth was 2 per cent per annum and accounted for one-fifth of the 10.4 per cent output growth. The rest of the output growth is attributed to increases in factor inputs (47 per cent) and capital and energy (34 per cent). In contrast to inputs, the slower rate of productivity growth indicates that during

¹⁰ 'Production and supply of gas'; 'mining of ferrous metal ores'; the 'manufacture of chemical fibers', and 'tobacco' are the notable exceptions.

¹¹ Represented by the 'extraction and processing of petroleum'; 'mining of ferrous metal ores'; 'production and supply of gas'; the 'manufacture of chemical fibres'; and 'tobacco'.

Table 5
Contribution to China's industrial growth, averaged over sectors

Phase	Output growth	Capital	Labour	Energy	Nominal TFP growth	Nominal TFP growth	
						Real TFP growth	Residuals
1981-91	0.104	0.049	-0.001	0.035	0.020	0.074	-0.054
	100	47	-1	34	20	72	-52
1992-2000	0.118	0.020	-0.014	0.014	0.098	0.096	0.0002
	100	17	-12	12	83	81	2
2001-06	0.164	0.020	0.006	0.041	0.097	0.138	-0.041
	100	12	4	25	59	84	-25
1981-2006	0.123	0.032	-0.004	0.029	0.065	0.097	-0.032
	100	26	-3	24	53	79	-26

Note: Contribution is reported in the second line for each phase (%).

this early stage, China's industry was still experiencing extensive expansion, which is consistent with the experience from East Asia in 1960s and 1970s. This suggests that inputs accumulation is more important than productivity gains during economic take-off (Lucas 1993; Krugman 1994; Young 1995; and Berthélemy 2001). China transferred from the extensive industrial growth model applied during the first stage to intensive model in the subsequent two phases, as evidenced by the fact that the growth of productivity exceeded that of capital accumulation and energy consumption by approximately 10 per cent.

But the contribution of nominal TFP to output growth achieved its highest level during the second stage, and then decreased. Real TFP growth was higher than inputs, yet the Chinese industrial growth model appeared to be sustainable during the three stages as well as the entire period. The increasing contribution of real TFP to growth also indicates that the sustainability was robust.

Our estimates of productivity growth are somewhat larger than in other studies, especially when the residuals from nominal productivity change are excluded. For example, Bosworth and Collins (2008) find that the annual growth of industrial TFP in China was 3.1 per cent between the years 1978-93, 6.2 per cent between 1993-2004, and 4.4 per cent over the whole sample period. Perkins and Rawski (2008) estimate the TFP growth of the Chinese economy to have been 0.5 per cent between 1952-78, and 3.8 per cent between 1978-2005. Chow (1993), on the other hand, finds no evidence of productivity change between 1952-80 while Chow and Lin (2002) suggest that TFP contributed nearly 30 per cent to China's economic growth between the years 1978-98, which is less than capital but higher than labour. These studies employ aggregate data and are concerned only with the traditional input: capital and labour. Based on the growth accounting exercise in this paper, we can conclude that the substantial improvement of productivity has driven China's industry to an intensive and sustainable path.

The contribution of capital to growth declined over time. And, energy's contribution plummeted during the second phase, but resumed growth during the years 2001-06, which corresponds to the substantial shutdown of many energy-intensive enterprises and the return of heavy industrialization. On average, capital and energy played similar roles in the industrial growth of the country, second only to productivity. The contribution of

labour to growth, always low, was the lowest during the second phase that was characterized by the furlough policy (*xiagang*) used for privatizing the SOEs at that time.

Another feature of the production structure is the elasticity of substitution, for which average values are reported in Table 6. The high-emission group recorded a high substitution between capital and labour, as gauged by the elasticity of substitution, equalling 0.52, contrary to the low-emission group. Specifically, there is still space for heavy industry to absorb cheap labour and save expensive capital. In the low-emission group, capital and energy should be scarce resources and investment ought to be spent mainly on energy purchases. Thus, capital and energy inputs have a high degree of substitution, as opposed to 0.29 for the high-emission group. The heavy-industry sectors have abundant or even surplus capital and energy, but generally waste these, as they have not been totally phased away from state-directed investment and resources that could lead to a less binding budget and energy constraints. Energy, contrary to capital, can be substituted by labour more easily in light rather than in heavy industry. The finding of labour being the best substitute for both capital and energy in the high-emission group indicates that in view of the experience of industrialized economies with hump-shaped employment patterns, China is still in the early phases of industrialization, able to absorb more workers and even develop a labour-intensive component in its heavy industry.

Table 6
Average substitution elasticity between inputs for two emission groups

Q _{jk}	Low-emission group		High-emission group	
	K	L	K	L
L	0.486		0.520	
E	0.657	1.382	0.291	0.577

5.2 Productivity and technical change

Based on the importance of productivity's contribution to growth, it is worth analysing its determinants further. Figure 3 displays the sub-industrial contributions to aggregate TFP growth: each sector's contribution is calculated as the product of sectoral real productivity growth and its weights (gross output shares) averaged for 1980-2006. The sum across the 38 sectors is 11.6 per cent per annum for the period studied; this is larger than the simple averaged real TFP growth (9.7 per cent) reported in Table 5, and provides another estimate of aggregate TFP growth of China's industry.

Figure 3 reveals the different contributions of the sectors to TFP growth, indicating considerable divergence in both sector productivity growth and its weights. For example, the industry specializing in the 'manufacture of measuring instruments and machinery' experienced rapid productivity growth (11.9 per cent) but contributed only 0.14 percentage points to TFP. In contrast, the manufacturing sector for 'chemical products' showed slower productivity growth (only 8.8 per cent) but due to its larger size, its contribution to TFP was higher (0.58 percentage points). The sector 'production and supply of gas' recorded negative productivity growth rate (-0.036), making its contribution to aggregate TFP growth also negative, and thus reducing aggregate TFP growth by 0.152.

Figure 3 also indicates that energy- and emission-intensive sectors exhibited lower contributions to aggregate TFP growth, whereas larger contributions were normally from sectors with low energy consumption and carbon emission, common to high-tech light industry. In short, the chart reveals that while many sectors contributed significantly to TFP growth, others signalled negative or very low productivity growth, causing aggregate growth to plunge. To understand the complexity of productivity growth, it is essential to examine each industrial sector separately.

Table 4 and Figure 3 reveal the heterogeneity of productivity growth and the contribution of inputs among industrial sectors without a time trend. We now turn to discuss the varying patterns of real TFP growth, its two decomposing components (technical change and scale effect) and biased technical change over the entire period 1980-2006. Here, the sector classification is simplified into low- and high-emission groups.

Figure 4 displays the trend of accumulated TFP level, real TFP growth and its decomposition as the weight averaged, and disaggregation of the two groups over the

Figure 3
Sector contributions to aggregate industrial TFP growth, 1980-2006

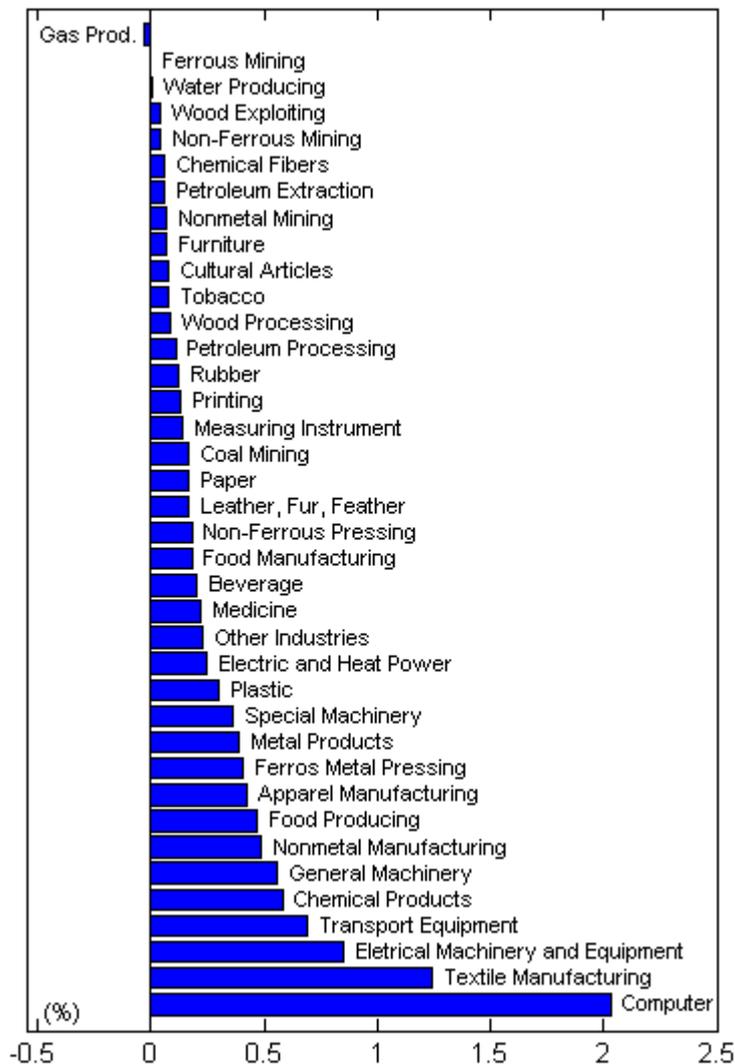
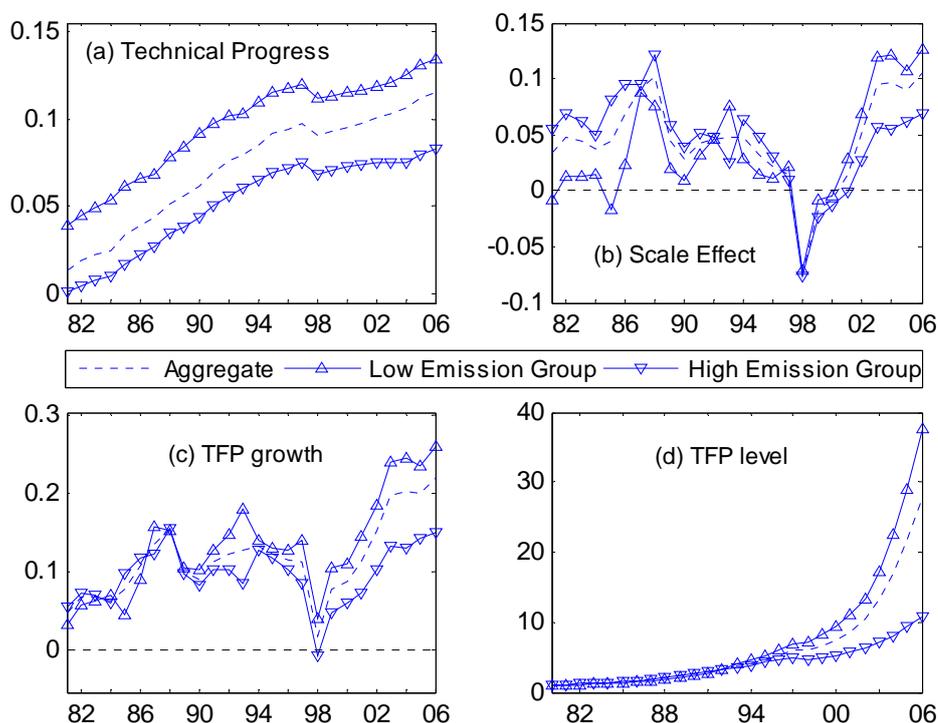


Figure 4
Averaged TFP growth and level, technical change and scale effects for the two emission groups, 1980-2006



whole period. Both sub-figures 4(c) and 4(d) exhibit a similar pattern, indicating that productivity was indeed lower in the high-emission group. This corroborates the descriptive statistics. As Nelson and Pack (1999) observe for the East Asian economies, aggregate productivity in China (dotted lines) also seems to have been driven by the expansion of modern sectors in light industry. Corresponding to the different phases of the country's industrial reform, the growth of industrial TFP first increased but, far from being stable during the early reform era, declined after 1994 due to the widespread financial deterioration of its enterprises. Rising sharply after the decisive reform of the SOEs in the late 1990s, TFP was dragged down by heavy industrialization after 2003. This pattern of productivity change is consistent with the evidence found by Li (1997) for Chinese enterprises in the 1980s, Sun and Tong (2003), Zhang, Shi and Chen (2003), Yusuf, Kaoru and Perkins (2005), Dong, Putterman and Unel (2006), Jefferson and Su (2006), Wan and Yuce (2007) for the 1990s and Bai, Lu and Tao (2009). But the value of productivity change in our study is somewhat larger than observed in previous findings due to the exclusion of the real residuals from the so-called Solow residuals.

Sub-figures 4(a) and 4(b) depict the patterns of technical change and scale effect, the two components of real TFP growth. We examine the effect of constant returns-to-scale (RTS): results are given in Table 3. Constant returns-to-scale do not hold in the case of China's industrial sector, as is shown in sub-figure 4(b). As the sum of the three input contributions is normally positive in each sector, according to Equation (10), China's industry experienced increasing returns-to-scale during the entire period. The negative temporary effect observed from 1998 to 2000 in sub-figure 4(b) is mainly due to negative energy and labour growth resulting from the shutdown of numerous small

energy-intensive enterprises and the accompanying reduction in labour demand rather than decreasing RTS. Moreover, the impact of increasing RTS is higher in the high-emission group than in the low group before 1998, but the pattern is reversed thereafter.

The test in Table 3 confirms that China's industries experienced technical change. Figure 4(a) shows that both groups exhibited increasing technology over time and, again, the low-emission group benefited from a higher rate of progress than the high group. Mukherjee and Zhang (2007) refer to this as the 'paradigm of adaptive innovation', whereby the technology and knowhow imported by China, mostly through the absorption of substantial FDI inflows and the establishment of foreign funded enterprises, became the key to its industrial success. Fisher-Vanden and Jefferson (2008) also argue that China's efforts in fostering technological development during the past 25 years have shifted from a state-dominated system to one in which the locus of innovation has been transferred to firms, research institutes and universities, making the rapid development of technology markets possible.

Figure 5
Bias in technical change, 1980-2006

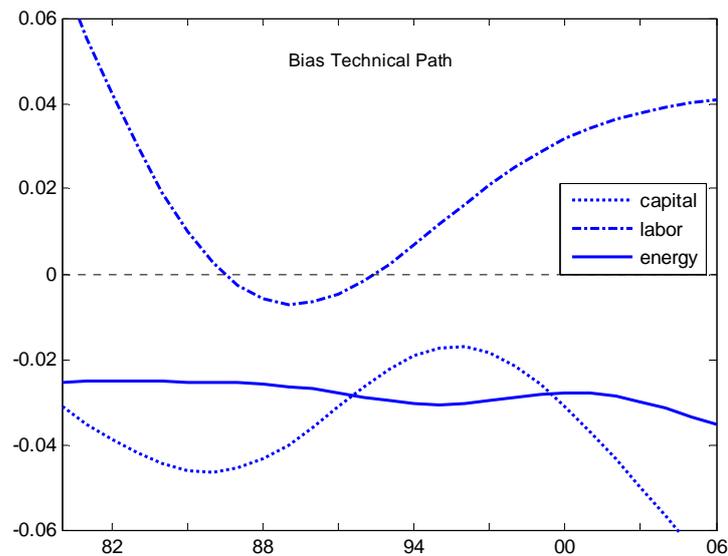


Figure 5 presents the estimations of technical bias in China since 1980, and sheds light on the distinctive patterns apparent during the different reform phases. To this end, the double five-year moving averages approach is applied to smooth each series. As shown in Figure 5, technical change was always labour-using, which corresponds to the development strategy pursued after 1978 that sought to promote labour-intensive, light industry. Technical progress based on capital consumption and energy utilization was undertaken during the years 1980-91. This is consistent with the policy of encouraging energy production that was in effect during this phase, but the biased technical path was reversed from 1992 to 1999 when the production of energy was restricted by policy.

In line with the return of heavy industrialization, the biased technical progress was switched to energy-use at the onset of the new century. In any case, there is no Hicks' neutral technical change, which is also justified by the fourth hypothesis test in Table 3. This relates to the findings by Fisher-Vanden and Jefferson (2008) who, in examining the role of factor bias, note that R&D spending played a key role in shifting China's

industry towards a more labour-using and capital- and energy-saving path, thereby motivating the country to become substantially more oriented towards the underlying comparative advantage of its economy.

6 The determinants of productivity change

Based on the empirical analysis in the paper, productivity change is undoubtedly the most important factor among a myriad of economic sources to be addressed if China is to achieve the transformation from extensive to intensive growth, a necessity for sustained growth in the long run. Lin (2004) asserts that productivity, or technological innovation, is the most important engine of sustainable growth. By adapting technological knowhow at lower costs from the advanced countries, as Japan and the newly industrialized economies of East Asia did after the Second World War, China is likely to be able to maintain a GDP growth rate of approximately 8 per cent for the next 20-30 years. Therefore, it is vital to establish which factors determine productivity growth in the country's industries, especially in the presence of energy consumption and carbon emissions.

Due to the incorporation of energy consumption as an input in the TFP growth estimates, CO² emission intensity is included as a determinant of productivity change to assess its impact on productivity. We expect that the potential shift from emission-intensive sectors, and the adoption of energy-saving technology as well as emission reduction will foster productivity growth. Following Kumar (2006), two theories are of interest in explaining productivity growth. The first is the convergence theory which states that productivity in low-income economies tends to converge towards those of high income ones. The convergence hypothesis is based on the concept of diminishing returns-to-capital. Second is the endogenous growth theory, which advocates that the difference in productivity between high- and low-income sectors remains constant or even diverges over time. The foundation of endogenous growth theories lies in the notion of increasing returns-to-scale. Normally, in high-income economies the capital-labour ratio is also found to be high in comparison to low-income economies. Thus, the variables industrial gross output per capita and capital-to-labour ratio are included as determinants of productivity change to investigate both theories. Positive relationship between the two variables and productivity change supports the endogenous growth theory, while a negative sign would favour the convergence theory because the marginal product of capital would be low in high-income sectors that exhibit a high capital-labour ratio. Other independent variables are the natural logarithm of foreign capital invested in Chinese industries and in-house R&D, and the output share of SOEs, a focal structural variable to capture the impact of industrial reform on productivity change in the late 1990s.

Table 7 reports the results of the analysis of productivity change, using panel data techniques over two periods, 1981-2006 and 1995-2006, respectively. The diagnostic statistics confirm that the random effect model is appropriate for model 1, and the fixed effect model for model 2, that is, the overall significance of both models is confirmed. The dependent variable is real TFP growth (in percentage). There are other qualitative explanatory variables in addition to the quantitative ones introduced previously. The time dummy variables *dummy_t1* (1 for the period of 1981-91 and 0 otherwise) and

Table 7
Determinants of real TFP change

	Model 1 (1981-2006)			Model 2 (1995-2006)		
	Coeff.	s.e.	p value	Coeff.	s.e.	p value
Constant	8.5395	0.9797	0.000	-2.3178	6.5305	0.723
Dummy_t1	-2.1305	0.4176	0.000			
Dummy_t3	3.6213	0.6418	0.000	3.9920	0.7700	0.000
Dummy_ei	2.2090	1.2281	0.072	(dropped)		
Emission intensity	-0.0014	0.0077	0.860	-0.0029	0.0175	0.868
Output per capita	0.0439	0.0136	0.001	0.0352	0.0187	0.061
Capital-to-labour ratio	-0.0642	0.0398	0.107	-0.4653	0.0716	0.000
Log (foreign capital)				0.9144	0.4334	0.035
Log (R&D)				1.4834	0.5864	0.012
Output share of SOEs				-0.1191	0.0330	0.000
Overall significance test	Wald chi2(6) = 223.17		0.0000	F(7,411) = 29.68		0.0000
Hausman test	Wald chi2(5) = 6.48		0.2620	Wald chi2(7) = 36.15		0.0000
Panel data model	Random-effects GLS regression			Fixed-effects (within) regression		
No. of obs	988			456		

dummy_t3 (1 for the period of 2001-06 and 0 otherwise) aim to find the time pattern of productivity growth. The dummy 'ei' is specified as 'one' for low-emission group and 'zero' for the high-emission group, to confirm the heterogeneity of productivity change in both groups, as given by Figure 4(c). The variables openness, R&D and the structural index of SOEs (in percentage) are used only in model 2 because of data availability. As shown in Table 7, most variables are statistically significant at least at the 10 per cent level.

The negative coefficient of the time dummy during the first phase and the positive one during the third phase confirm that the growth rate of real productivity in Chinese industry increased significantly over time, as seen in Figure 4. The statistically significant and positive coefficient of dummy_ei in model 1 also justifies the previous findings that light industry (with low-emission intensity) exhibits a higher TFP growth rate than heavy industry. The findings also suggest that the emission intensity of output, measured by CO₂ emissions per unit of industrial value-added, contributes negatively to real productivity change in both models, although the results are not statistically sound. This is also consistent with the findings by Islama, Munasingheb and Clarke (2003) who argue that sustainability requires a decrease in emissions, which is more easily met if the economy makes a rapid transition from natural resource-intensive industries, as this reduces the pollution intensity of output. Similarly to Kumar (2006), we also find in both models significantly positive relationship between TFP growth and output per capital, supporting the endogenous hypothesis, and negative correlation between productivity and capital-to-labour ratio, which is in line with the theory of economic convergence.

The variables of both foreign capital, including those from Taiwan, Hong Kong or Macau, and in-house R&D contribute positively to real productivity growth. This relates to the observation of Fisher-Vanden and Jefferson (2008) who note that the purchase of imported technologies, which are comparatively capital-using, was focused on the

development of new high-tech products, and R&D spending was robustly labour-using and capital- and energy-saving, thereby capitalizing on China's comparative advantage and improving productivity level. The estimated coefficient of the ownership structural variable, the output share of SOEs, is statistically significant and negative. This finding concurs with many results given in the literature. Thus, the ownership structure reform that converted SOEs to non-state enterprises from the latter part of the 1990s did increase productivity in China, as shown in Figure 4.

7 Conclusion

This paper analyses the determinants of China's economic growth and productivity during 1980-2006 at a detailed level of disaggregation in terms of industrial and sectoral decomposition. The study investigates the sustainability of China's growth under the constraints of high energy consumption and CO₂ emissions. The growth accounting exercise indicates that China's unprecedented industrial reform led to substantial improvements in productivity, which has become the most important growth engine for most sectors and aggregate industry. This has also promoted the country to evolve from an extensive industrial growth model to an intensive one.

However, productivity growth in China is attributable more to the high-tech light industry, which is characterized by low energy consumption and carbon emissions. Some heavy industries are still driven by the expansion of input quantities, recording very low productivity levels. The decomposition of the TFP growth reveals the pattern of technical progress experienced in China over the entire reform period: each reform phase introduced a different path of technical biasness, and increasing returns-to-scale generated by the externalities associated with the acquisition of technical knowledge. In addition to productivity being the principal growth engine, energy and capital inputs are also important factors in explaining China's industrial growth. The econometric analyses also find that productivity growth is affected by carbon emission and energy intensity in the production process.

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