An Empirical Study on Energy Use, Carbon Emissions and Economic Growth in China

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To my parents

and

To Tongtong

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Abstract

Energy consumption, energy–related CO_2 emission and economic growth are three interrelated issues at the forefront of public attention. This dissertation aims to investigate the driving forces of China's energy use and carbon emissions, to analyze their roles in economic growth and to provide policy implications for energy conservation and carbon emissions abatement in China. This dissertation adopts methodologies from the demand–side, the hybrid input–output model, and the supply–side, the stochastic frontier analysis and translog production model, to achieve these objectives. In addition, energy flow charts of China and Japan are provided to describe the energy systems among main economies in the world.

Energy is always an important factor to the improvement of social and economic welfare in history. The demand for energy is a derived demand from the utilization of capital stocks. The use of coal and petroleum as the primary fuel began with the diffusion of steam engines in textile manufacturing since the late-1700s and the diffusion of internal combustion engines in transportation since the late-1800s. The energy transition from animate movers and biomass fuels to inanimate engines and fossil fuels has driven productivity growth significantly.

During the past few decades, the most significant changes in China's energy system include the following three points. First, China's energy supply still mainly relies on coal, but currently more than half of its petroleum supply is imported on the international market. Second, the direct use of coal in final demand has been significantly substituted by electricity, decreased from more than one-half to one-quarter. Third and most important, though China's energy intensity decreased two-thirds from 1978 and resembles an inverted

U-shape across per capita income, its total energy consumption has accelerated since the early 2000s and it became the largest energy consumer in the world in 2010. It is critical to understand the driving forces of China's energy use for the design of energy policy on both national and global scales.

Chapter three conducts a structural decomposition analysis (SDA) based on hybrid input–output tables, and discusses the driving forces of total energy use in China from 1992 to 2010. As shown in the results, China's energy uses are embodied in the three final demand categories — gross fixed capital formation, household consumption expenditures and exports. The impacts of these factors on total energy use shifted with the development of the economy. In the 1990s, China's energy use was still mainly driven by household consumption, which accounted for about two-fifths of the total energy use, but its contribution to the energy use change decreased from 31 percent (1992–1997) to 20 percent (1997–2002). In contrast, the contribution of exports to the changes in energy use increased from 30 percent (1992–1997) to 39 percent (1997–2002). In other words, China was shifting toward becoming an export–oriented economy in the 1990s.

However, investment has been a major factor driving China's economic growth in the past decade. The energy use embodied in gross fixed capital formation increased from approximately 30 percent of total energy use before 2002 to 39 percent in 2010, and its contribution to the change of energy use swelled to three-quarters during 2007–2010. This investment–led economic growth is unsustainable because the heavy dependence on investment not only created energy and environmental problems but also increased systematic risk, including surging local government debt. It is urgent for China to switch its economy from export– and investment–based growth to domestic consumption–oriented growth.

With exports and investment driving economic growth, the income of Chinese households has reached the level at which energy–intensive goods are affordable. Household consumption has contributed 30 percent of the total energy use and to one-quarter of its change in 2010. Given China's population and accelerating urbanization, the commercial and transportation sectors should expect to surpass the industrial sector as the main energy demand drivers in the future.

Chapter four adopts a hybrid environmental input–output model to investigate the energy–related CO_2 emission embodied in Chinese final demand. China became the largest emitter in the world in 2006 and currently contributes 27% of global annual carbon emissions in 2012. Its historical cumulative emissions climbed to 11% of global total emission in 2012, which is approximately 41% of the US. CO_2 emissions are byproducts of energy consumption in economic activities.

The results show that the final demand category of consumption is responsible for 51% of Chinese CO_2 emission in 1992 and decreased to 34% in 2010. The changes in consumption contributed around one-fourth (21% to 26%) to total CO_2 emission growth during each period from 1992 to 2010. The key drivers behind the growth of CO_2 emissions embodied in the household consumption are typically income level, consumption patterns, population and the household structure.

In contrast to the decreasing share of consumption, the investment activity related CO_2 emission increased from 31% in 1992 to 42% in 2010. The growing final demand for investment amounted to 2,430 Mt CO_2 between 1992 and 2010 (48% of total changes), of which 84% occurred between 2002 and 2010. In the period 2007–2010, especially, investment activity contributed 92% of total emission changes. Around 56% to 70% of emission embodied in investment between 1992 and 2010 are related to final demand for 'Construction', which is due to its emission–intensive supply chains, such as cement manufacturing, iron and steel production and electricity demand.

Exports related emissions have grown most rapidly compared to all the other final demand categories. Emissions from the production of goods and services destined for exports increased from 494 Mt (17% of total emissions) in 1992 to 1,870 Mt (24% of total emissions) in 2010. The composition of exported goods and services is changing, which indicates a shifting role of China in the global economy from a producer of cheap, labor–intensive goods toward high–end and more capital intensive products.

The indirect energy use and carbon emissions indicate the length of the roundabout production chain, or the roundaboutness of production, which was one of three concepts used to describe the specialization of economics. The increasing of division and specialization of labor are associated with the growth of productivity and the capital deepening process. My calculation shows that the share of indirect carbon emissions rose from 73% in 1992 to 87% in 2010, since the deepening division and specialization of labor with China's economic development.

Chapter three and four provide the demand side analysis of the energy and emissions in China by using a hybrid input–output model. *Chapter five* conducts a supply side analysis by constructing a three–factor translog production function with a stochastic frontier for Chinese economy. It is found that the output elasticity of energy input is approximately 0.4 in China since 1978, which means one percent growth in energy input would push about 0.4 percent of aggregate economic growth. The elasticity of substitution of capital–energy is about 0.23 before mid-1990s, and then dropped to only -0.26. The negative elasticity of substation reveals the perfect complementary between capital and energy input in China.

An inefficiency model is provided to explain the sources of economic inefficiency. I found that the provinces located in coastal regions and with a higher level of liberal economy have lower economic inefficiency, and the shares of fiscal expenditure in GDP and SOE in industrial production are positively correlated with technical inefficiency.

The calculated TFP index illustrates the sources of economic growth in China. Since the launch of the reform and opening policy in 1978, China's economic growth can be divided into three periods. First, TFP contributed about 22% to 44% of China's growth from 1978 to late-1980s. This productivity boom is a result of series reforms, such as the household–responsibility system and price reform. Second, China's economy supported by the devaluation of RMB, SOE and tax reform from early-1990s to late-1990s. Third, China's growth is mainly driven by investment activity from late-1990s, such as government spending on large–scale infrastructure projects, and both foreign and domestic investment in manufacture. Accompany the increasing investment, energy use surged in the last decade in China.

A provincial comparison on the total–factor energy efficiency reveals the difference between the actual energy use and the optimal energy input. I provide the energy–saving potential index among the provinces in China. It can be found that the higher developed provinces have higher energy efficiency. Scenario analysis is provided to describe the potential for energy conservation in China. Given the current technology and knowledge, China can reduce about 31 percent of its energy input if it operates as the same technical efficient as Guangdong province.

Finally, I have to emphasize that energy and environment issues are derivatives of economic and societal development. These systemic issues cannot be solved once and for all. Chinese policymakers should continue to deepen reform to build up a market–based economy and energy system. Let markets but not governments organize the use and distribution of energy resources and the environment.

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Nomenclature

Roman Symbols

AE Allocative Efficiency

BP British Petroleum

CES Constant Elasticity of Substitution

CO_2 Carbon Dioxide

CRS Constant Returns to Scale

DEA Data Envelopment Analysis

DJIA Dow Jones Industrial Average index

DRS Decreasing Returns to Scale

EAI Energy Avoided by Imports

ESP Energy Saving Potential

GDP Gross Domestic Product

I–O Input–Output

IDA Index Decomposition Analysis

IEA International Energy Agency

IRS Increasing Returns to Scale

L–K–E Labor–Capital–Energy

LMDI Logarithmic Mean Divisia Index

MEP Ministry of Environmental Protection

NBS National Bureau of Statistics

NOx Nitrogen Oxides

PIM Perpetual Inventory Method

PM Particulate Matter

POP Population

PPP Purchasing Power Parity

SDA Structural Decomposition Analysis

SE Scale Efficiency

SFA Stochastic Frontier Analysis

SO_2 Sulfur Dioxide

SOE State Owned Enterprise

SPR Strategic Petroleum Reserve

TE Technical Efficiency

TEU Total Energy Use

TFC Total Final Consumption

TFEE Total Factor Energy Efficiency

TFP Total Factor Productivity

TPES Total Primarary Energy Supply

VRS Variable Returns to Scale

WTO World Trade Organization

Chapter 1

Introduction

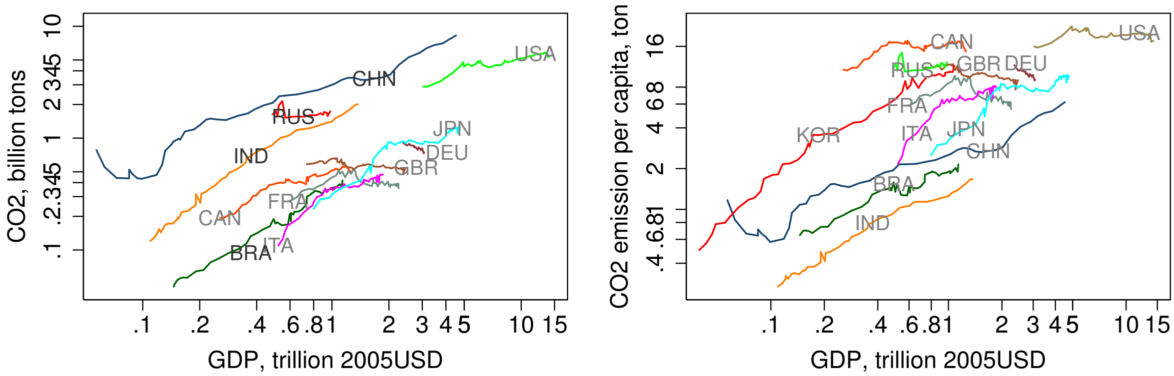
1.1 Research background

After three decades of unprecedented economic growth, China has become the second largest economy in the world since 2010. China's economic development has compressed into decades what took centuries in developed countries [LIU and RAVEN, 2010]. At the same time, its environmental challenges are growing significant, causing enormous social and economic consequences for China and the rest of the world.

Among the 325 cities monitored in 2012, 8.6% were considered heavily polluted, and only 11 cities (3.4%) reached the highest standard of the Ministry of Environmental Protection [MEP, 2013]. The major air pollutants are particulate matter (PM), SO_2, and nitrogen oxides (NO_x). In the 325 cities monitored in 2012, 57.2% were suffering from high levels of suspended particles, and 46.1% of the 466 cities were suffering from acid rain [MEP, 2013].

The main causes of China's air pollutions currently and in the future are related to the combustion of fuels in economic activities, such as industrialization and urbanization. The estimation by Zhang [2007] shows that the burning of coal releases 70% of total smoke (aerosols), 90% of SO_2, and 67% of NO_x. At the same time, the number of China's motor vehicles reached 240 million in 2012, half of which are cars. Therefore, the ever–growing number of motor vehicles has become one of most important contributors to increasing air pollution.

In the near future, the Chinese energy supply structure is not expected to change dramatically, and coal will remain one of the dominant energy sources. In addition, the



(a) Aggregate emission.

(b) Per capita emission.

Figure 1.1: CO_2 emission in G7 and BRIC, 1960–2010.

Data source: World Bank [2012].

pollution released from transportation and urban activities will increase rapidly in the coming years. Hence, the emissions of aerosols, SO_2, and NO_x are expected to increase continuously. It is significant to study the drivers of China's energy use and the improvement of energy efficiency in order to prevent further deterioration of air quality.

The annual mean temperature over China in 2013 was 10.2 ℃, 0.6 ℃ above normal, the fourth highest since 1961, and 0.8 ℃ higher than 2012. Globally, 2013 was again one of the 10 warmest years on record [Blunden and Arndt, 2014].

This observed climate change or global warming is largely caused by the accumulation of approximately 16 categories of greenhouse gases in the atmosphere, with carbon dioxide being the principal one of anthropogenic origin. China is now the largest CO_2 emitter annually in the world (see Figure 1.1). Although the annual aggregate CO_2 emissions of China have surpassed those of the United States, per capita emissions were only 35% of the U.S. levels in 2010. Unless drastic steps are taken, the emissions in China will continue growing substantially for at least the next several years due to the increasing use of resources through the expansion of economic activities.

1.2 Research objective and framework

The fundamental objectives of this study are to achieve a better understanding of the driving forces of energy use and carbon emissions, to analyze their roles in the economic growth of China and to provide the energy conservation and carbon emissions abatement policies. More specifically, this study addresses the following research questions:

- What are the features of China's energy supply and demand system? What are the differences between China's energy system and that of other countries'?
- What determined China's current energy use? How is the Chinese economic structure is affecting its energy consumption?
- What are the driving forces behind China's carbon emissions? How can we understand the economic aspect of carbon emissions?
- How is energy consumption related to alternative inputs and to the economic growth of China? How do we evaluate the total–factor energy efficiency or what the energy–saving potentials are in China?

The main content of the dissertation can be summarized into four parts according to the research objectives and questions, as the schematic overview of the structure presented in Figure 1.2. The remainder of this dissertation is organized as follows.

The present chapter outlines the background of this study from two aspects of environment and energy challenges in China. I highlight the objectives of this dissertation and the questions to achieve those objectives. The summarized framework and organization of the dissertation are also introduced.

Chapter two provides a brief overview of energy use in history. Two energy flow charts for China in 1992 and 2010 are provided to describe the Chinese energy supply and use

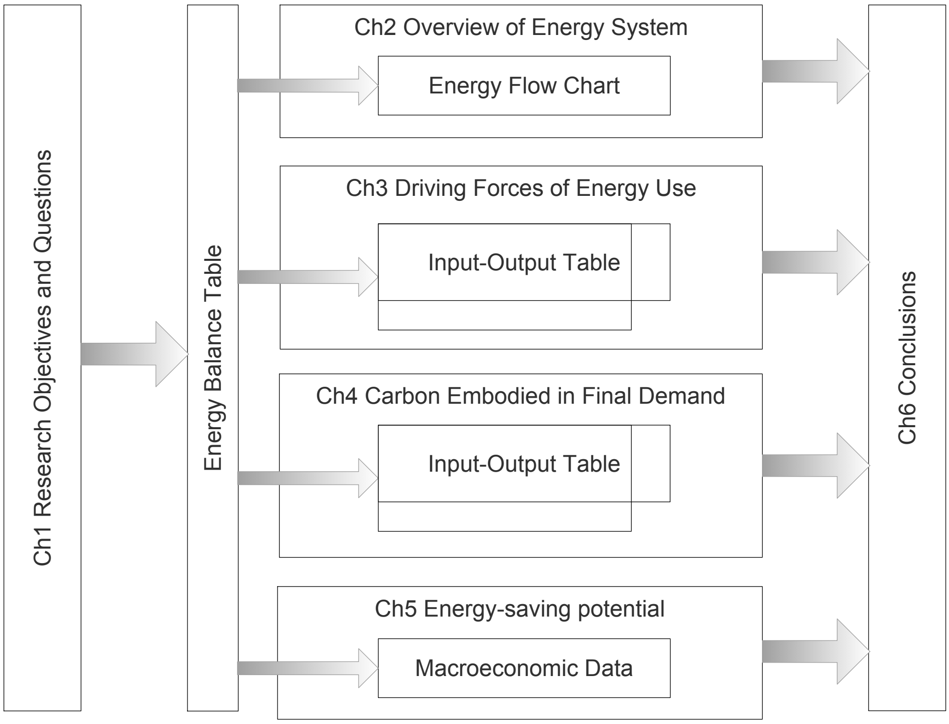


Figure 1.2: Analytical framework of the dissertation.

Source: Author.

system and its changes. The energy flow charts of Japan, U.K. and U.S. in 2010 are also presented in Appendix C. Finally, I make an international comparison of energy systems between the main economies of the world.

Chapter three discusses the driving forces of China's energy use from 1992 to 2010 — the years for which I have detailed energy and input–output statistics. Section 3.1 surveys the literature on the theory of dematerialization and the long term relationship between energy use and economic growth in China. Section 3.2 introduces the energy input–output model and the application of LMDI in this model. The compilation of hybrid input–output tables is described in section 3.3. Section 3.4 provides the results and discussions of decomposition of total energy use and its change. Section 3.5 gives the limitations of this study, such as the effects of data reliability and sector aggregation on the results. Finally, section 3.6 discusses conclusions and policy implications.

Chapter four illustrates the energy–related carbon embodied in Chinese final demand. The first section introduces the literatures on Chinese carbon emissions or carbon footprint. The subsequent section gives the environment input–output framework by using the hybrid units approach and explaining its difference with the direct coefficient approach. The emission abatement policies are discussed in the final section.

Chapter five constructs a three–factor translog stochastic production function for China's economy. Based on the L–K–E translog production function with a stochastic frontier, I estimate the total–factor productivity of China's aggregate economy. The energy–saving potential index is calculated for the evaluation of energy efficiency among provinces.

Finally, chapter six summarizes the findings in the previous chapters and introduces the issues that can be expanded on the future study.

Chapter 2

Overview of Energy Supply and Demand System

2.1 A brief history of world energy

Energy is always an important factor to the improvement of social and economic welfare in human history. The expanding of human activities are determined by energy's overall use, quality, intensity, and conversion efficiency. Smil [2004] divides human evolution into four distinct energy eras by four great energy transitions — biomass fuels, draft animals, waterwheels and windmills, fossil fuels and electricity. This chapter divides the energy history into the pre-fossil fuel era and fossil fuel era by the substitution of draft animals and biomass–fuels by engines and fossil–fuels in the mid-1700s.

2.1.1 Pre-fossil fuel era

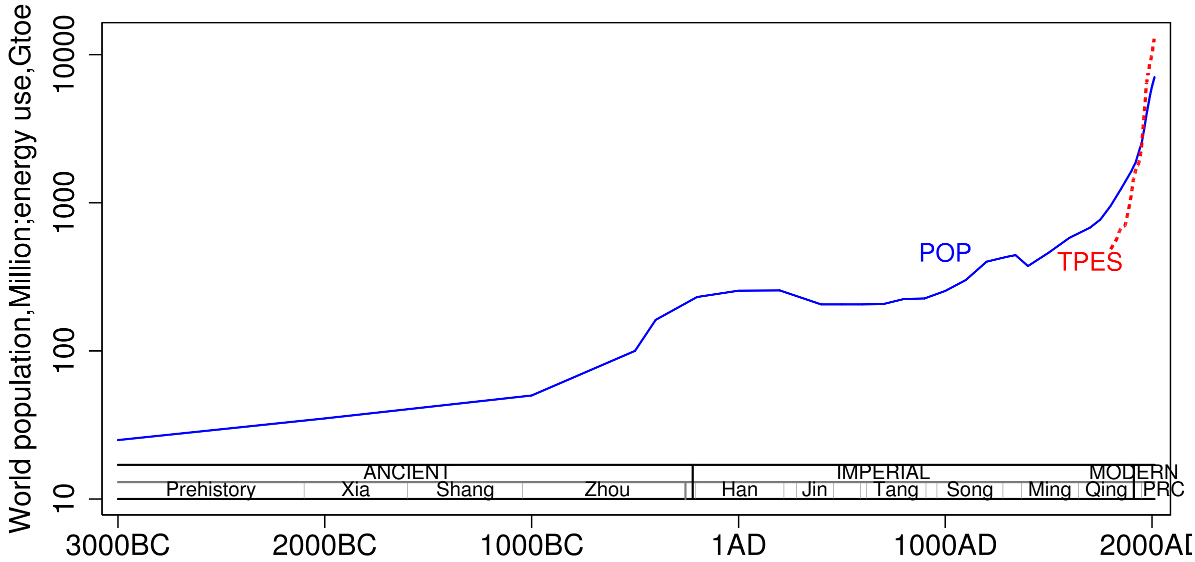
In the long span of prehistory, humans depended on their muscles to survive, and the healthy adults could only maintain rate of work at around 50 to 90 W. In prehistoric societies, the only extra–somatic energy transformation that humans mastered was the use of fire for cooking and heating. The direct evidence of mankind's utilization of fire was found outside a cave at Zhoukoudian in Beijing from 500,000 to 200,000 years ago.

The first great energy transition consisted of the domesticating of draft animals for production activities and the harnessing of fire for making durable materials like metals. The best draft animals in early times, like oxen and horses, could provide power surpassing 500 W, which is equal to the labor of six to eight adult men. Horses were first ridden in what is now the Ukraine before 4,000 BC. In China, the first reference to the existence of draft horses is in the I Ching, which was thought to be an accretion of Western Zhou (900 BC). The early settled societies also adopted fire to produce durable materials, such as bricks, containers and metals. For example, copper was first produced in Egypt before 4,500 BC and iron after 1,400 BC. During the ancient period, humans also learned to use charcoal that was converted from wood, but with higher energy density and superior quality such as being smokeless.

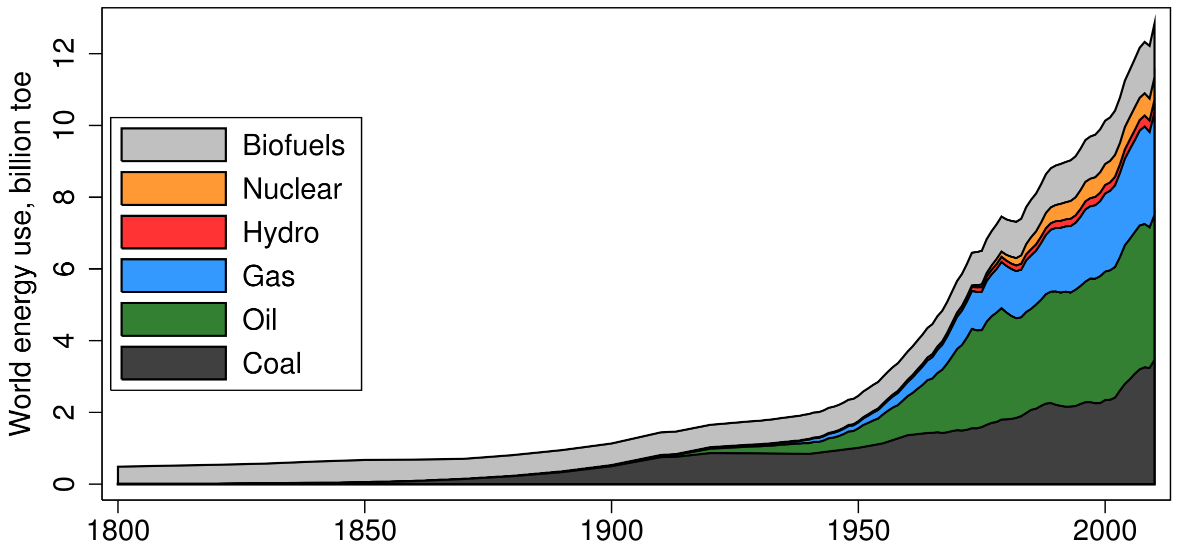
The second energy transition was the substitution of a large share of muscular exertions by waterwheels and windmills. Throughout the Middle Ages (500AD–1,500AD), the dominance of animal power extended but its efficiency had improved via inventions like collar harness, iron horseshoes, etc. The draft animals were increasingly augmented by waterwheels and windmills, which were widely adopted for water pumping and grain milling. Paddle–driven water–lifting wheels had appeared in ancient Egypt by 400 BC. The waterwheel was found in China from 30 AD onwards, when it was used to trip hammers, the bellows in smelting iron, etc. A waterwheel named "dragon bone water lift" was still widely used for irrigation purpose in the rural areas of China in the 1990s. The waterwheels used as a power source are able to provide energy of around 100s W to 10 KW. The earliest known windmill was in Greece around 100 AD. In China, the windmill was used since the Eastern Han (400AD). Europe's great seafaring voyages during the 15th and 16th centuries efficiently harnessed the wind energy. The maximum power of early windmills is around 100s W to 10 KW.

2.1.2 Fossil fuel era

The third great energy transition was the substitution of draft animals and biomass fuels by engines and fossil fuels since the mid-1700s in a few European countries. With Newcomen's invention of steam engine after 1700, the dependence on animate sources and biomass fuels over millennia came to an end, and coal began to be used as the fuel for the new engines. James Watt improved the existing engine and transformed it from a machine with limited utility to a prime mover with unprecedented power that was applicable to



(a) POP (3000BC–2010AD), TPES (1800AD–2010AD).



(b) TPES and energy structure (1800AD–2010AD).

Figure 2.1: World population (POP), total primary energy supply (TPES) and energy structure in history.

Data source: Biraben [1980]; BP [2013]; Smil [2010]; World Bank [2012].

many kinds of works. Since the steam engine was improved by Watt, the British began a thorough industrial revolution which spread to Western Europe and the United States within a few decades.

As shown in the Figure 2.1, the share of coal in world's total primary energy supply

(TPES) climbed to 50% in 1910s from single digits in the 1800s. Coal was the main energy source for many European countries by the 1900s, while the energy used in China's rural areas still differed little from hundreds of years before until the end of the imperial era in 1911. Even in the 1950s, biomass fuels such as wood and crop straw etc., still contributed more than one–half of China's TPES. The share of biomass fuels in total had been reduced to 15% by the year 2000. As Figure 2.1 shows, biofuels currently still account for nearly ten percent of world energy use as it remains one of main energy sources for many developing countries.

The **fourth** and latest energy transition was the course of electrification and the increasing dependence on hydrocarbon fuels (petroleum and natural gas) since the 1880s. The commercially viable electricity system was invented by Edison and his colleagues in a remarkably short period from the early 1880s. Every aspect of humans' daily activities and productive activities has been enormously changed by the inexpensive and reliable supply of electricity.

The petroleum era started in the same decade as that of electricity during the 1890s, when the internal combustion engine was invented to built modern automobiles. After the Wright brothers built the world's first successful airplane, commercial and military flight experienced two periods of development with reciprocating engines (1904–1950s) and jet engines (1950s–). The higher demand for crude oil was mainly due to transportation, and together with natural gas, both later also became important for heating, and both crude oil and natural gas are used for many chemical synthetics. The share of hydrocarbon fuels (crude oil and natural gas) climbed to approximately 60% of the world's TPES in 1970s from almost zero within seventy years. At the same time, the share of coal dropped to 25% from 50%.

After the oil crisis in the 1970s, the world energy structure has been relatively stable throughout the last forty years. In this period, hydrocarbon fuels have accounted for approximately 55% of world's TPES, coal for around 25%, biofuels for around 10% and primary electricity (hydro– and nuclear–) for the last 10% (see Figure 2.1). Each of those great energy transitions mentioned above have driven up productivity, and pushed world population growth almost exponentially in the last two hundred years (see Figure 2.1). More detailed discussion on energy history and the chronology of energy–related events in human history can be found in the studies by Hunt and Evans [2011]; Kostic [2007]; Smil [2004].

2.1.3 Super cycles in fuels prices

Not only does the energy demand relate to the invention and utilization of new capital stocks, but the long–term energy prices are also affected by the diffusion of major technologies. Figure 2.2 displays the diffusion of major technologies in the twentieth century, and the trends of prices of Dow Jones Industrial Average (DJIA), petroleum and coal from 1990 to 2013.

As shown in Figure 2.2, the stock market index surged during the diffusion of new technologies. DJIA growth from 59 in 1907 to 300 in 1928 was due to the diffusion of automobiles and electric power, from 181 in 1947 to 969 in 1965 was due to the television and from 964 in 1980 to 10787 in 2000 was due to home computers and cellular telephones. At the same time, however, the prices of oil and coal were flat, in particular after the World Wars, and surged in between these new technologies. Since the early 2000s, for example, the price of oil has increased from about 20 USD/bbl to the current 110 USD/bbl, and coal price growth has been from about 40 USD/short ton to the current 60 USD/short ton. Hence, there is an inverse relationship between the DJIA and fuels.

Not only petroleum and coal, but other commodities such as metals and grains have similar price trends to energy. I can classify the commodities, such as fuels (oil, coal and

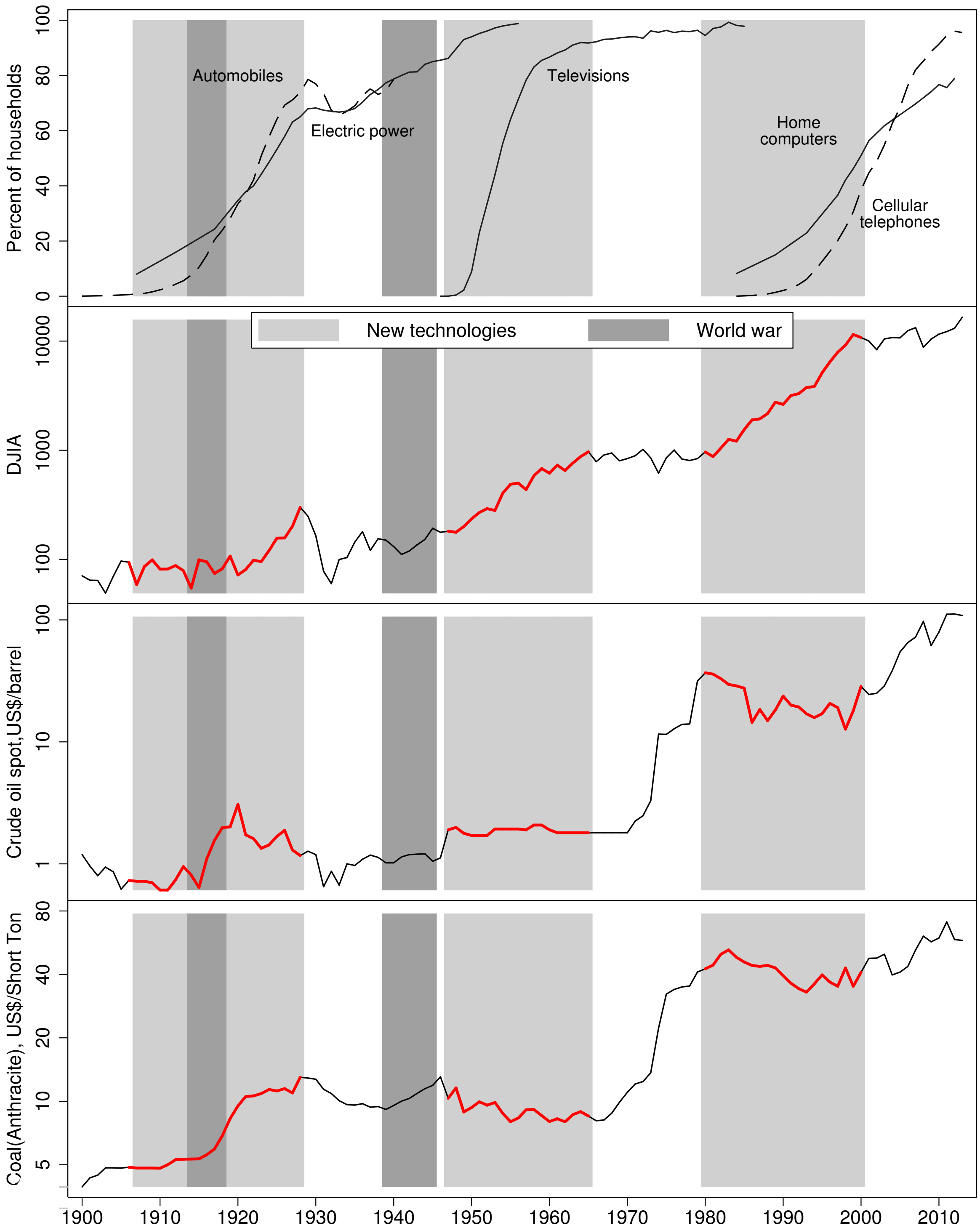


Figure 2.2: Diffusions of major technologies, DJIA index, oil and coal prices, 1900–2013.

Data source: Samuelson and Nordhaus [2009]; U. S. Council of Economic Advisers [2000]; BP [2014]; EIA [2011]; U.S. Bureau of the Census [1975].

natural gas), metals (gold, silver and copper etc.) and grains (corn, wheat and soybean etc.), and real estate as tangible or hard assets. On the contrary, I can classify currencies, bonds and stocks as financial or paper assets. These two categories of assets are inversely interrelated with each other. I can view the tangible assets and financial assets as the Yin and Yang, correspondingly, which were two opposing principles in Chinese philosophy. As this dissertation is not a study in finance, I will not discuss the prices of fuels further.

2.2 Energy supply and consumption in China

2.2.1 Energy statistics

2.2.1.1 Energy balance table

The energy supply and consumption within an economy rely on its statistical energy data, which is currently reported in the format of an energy balance table in most countries. It presents both the supply and use of each energy category in a single column [Mandil, 2004]. An energy balance table allows the researcher to track the energy from initial production to final use by sector and fuel type. China's energy balance tables are published by the National Bureau of Statistics (NBS) in the "China Energy Statistical Yearbook" annually since the 1980s [NBS, 1987, 1990, 1992, 1998, 2001, 2004, 2005, 2006a, 2007, 2008a,b, 2010b, 2011a,b, 2012a, 2014]. These sets of energy statistics have long been considered the best, most comprehensive source of national level energy data for China, and they are also the starting point for statistics published by many organizations, such as IEA and BP etc.

The energy statistics in an energy balance table can be expressed in either natural/physical units[1], such as Cubic meter (m^3), Barrel (bbl) and ton etc., or energy units, such as Terajoule (TJ), Mtoe and Million Btu etc (see Table A.1 and Table A.2). The

[1] Energy balance table is also known as commodity table in this case.

Table 2.1
Aggregate NBS energy balance table in China, 2010 (Mtoe).

Supply and Consumption	Coal	Coal Products	Crude Oil	Petroleum Products	Natural Gas	Electricity & Heat	Total
Production	1,591	25	203	0	88	82	1,990
Imports	82	0	238	55	15	0	390
Exports	-11	-2	-3	-38	-4	-2	-59
Stock Change	-89	-11	-9	-5	0	0	-114
TPES	1,573	12	429	12	99	81	2,206
Statistical Difference	39	6	0	9	0	0	54
Power Station	782	19	0	10	20	-351	480
Oil Refineries	1	0	419	-405	0	0	15
Other Transformation	322	-285	0	0	0	0	37
Own Use	57	6	6	58	13	51	191
Distribution Losses	0	0	2	0	2	23	27
TFC	372	265	2	340	64	357	1,402
Agriculture	9	0	0	14	0	8	32
Industry	269	252	1	68	18	247	856
Transport	3	0	0	207	9	6	225
Commerce	21	0	0	13	5	35	74
Residence	48	4	0	18	21	60	151
Non-Energy Use	22	9	1	20	10	0	63

Data source: NBS [2011b].

aggregation of different fuels is estimated via weight sum approach, $e = \sum_i \lambda_i e_i$, where the weight is the heat content of fuels — net calorific value. Default net calorific values of fossil fuels are given in Table B.1. The aggregate energy production and consumption are measured in tons of oil equivalent (toe)[1] in this dissertation, which is equivalent to 41.868 GJ or 39.68 MBtu (see Table A.1).

Table 2.1 presents an aggregate energy balance table of China in 2010 published by NBS. As this table shows, the fuels appearing in NBS statistics are divided into four groups: (a) Coal and Coal Products, (b) Crude Oil and Petroleum Products, (c) Natural Gas and (d) Electricity and Heat. Detailed fossil fuels categories, which are reported in the NBS energy balance table, are given in Table B.1.

The rows of the energy balance table show the supply and use of each energy category. The relationship between energy supply and use is based on the first law of thermodynam-

[1]Tons of coal equivalent (1tce=0.7toe) is widely used in China as coal is the main energy source for China.

ics, which states that energy can be transformed from one form to another, but cannot be created or destroyed. In other words, total primary energy supply (TPES) in one economy should equal its total energy use (TEU) for each energy category. TPES is the summation of all sources of energy, such as production (domestic), imports, exports, and stock change. TEU is a summation of energy losses in the conversion processes, such as power generation, oil refineries and other transformations, and total final consumption (TFC) in final sectors, such as agriculture, industry, transport, commerce, residence and non-energy use.

2.2.1.2 The differences of energy balance tables published by NBS and IEA

Firstly, the coverage and definition of primary energy used by NBS and IEA are different, although there is no argument on the definition from the technical point of view. First, coal production in NBS statistics refer to raw coal which is unwashed and unscreened, whereas IEA's coal statistics refer to coal after washing and screening for the removal of inorganic matter. Second, the time series for primary solid biomass, liquid biofuels, solar photovoltaic, solar thermal generation and geothermal heat production consumption are released by IEA based on their estimates. However, neither of those time series is reported in the national energy balance of China.

Secondly, there are also differences in the sectoral breakdown in TEU reported by NBS and IEA. NBS uses the national classification system for economic activities — GB/T 4754, which was released in 1994, and revised in 2002 and 2011. IEA uses International Standard Industrial Classification (ISIC). Both IEA and NBS publish three–digit levels of final energy use in industrial sectors.

Thirdly, their treatments on the energy industry own use (EIU) and non-energy use (NEU) are different. According to IEA, the energy industry own use should be reported in conversion block but not in TFC block [Mandil, 2004]. NBS reports energy own use within TFC. For non-energy use, which is energy used to producing fertilizer, IEA reports it separately from energy use. Although NBS reports the total values of NEU for each energy category, I have to estimate the non-energy use and energy use in finer sectors.

Fourthly, the figures given in 'transport' should be related only to uses for transportation itself but not for consumption by the transport company for non-transport purposes [Mandil, 2004]. Similarly, fuels used for transport activity in industry or other non-transport sectors should be reported in 'transport', but not in the industry and other sectors. However, the NBS energy statistics are collected by energy category and enterprise, without considering its purpose. Therefore the figure shown in the sector of "Transport, Storage, Postal & Telecommunications Services" accounts for both transport activity and non-transport activity–related energy consumption in transport enterprises. However, the energy consumed for transport purposes in other sectors, such as, agriculture, industry, residence, were excluded from the "Transport, Storage, Postal & Telecommunications Services".

The energy figures in Table 2.1 are modified according to the above discussion, except the first point, which requires detailed biofuels information. After transposing Table 2.1, the rows of the new table express energy flows from the supply side to the demand side, which can be presented as an energy flow chart.

2.2.2 China energy flow chart

An energy flow chart is one application of a Sankey diagram, which is named after engineer Matthew H. Sankey from Ireland [Phineas, 2014; Schmidt, 2008]. This chart is typically used to visualize energy flows from energy supplier to final users. The widths of the bands in China's energy flow chart are shown proportionally to the flow quantity and the colors for different energy categories. I provide China's energy flow charts in 1992 and 2010 in Figure 2.3 and Figure 2.4. They are developed based on the pattern of the UK energy flow

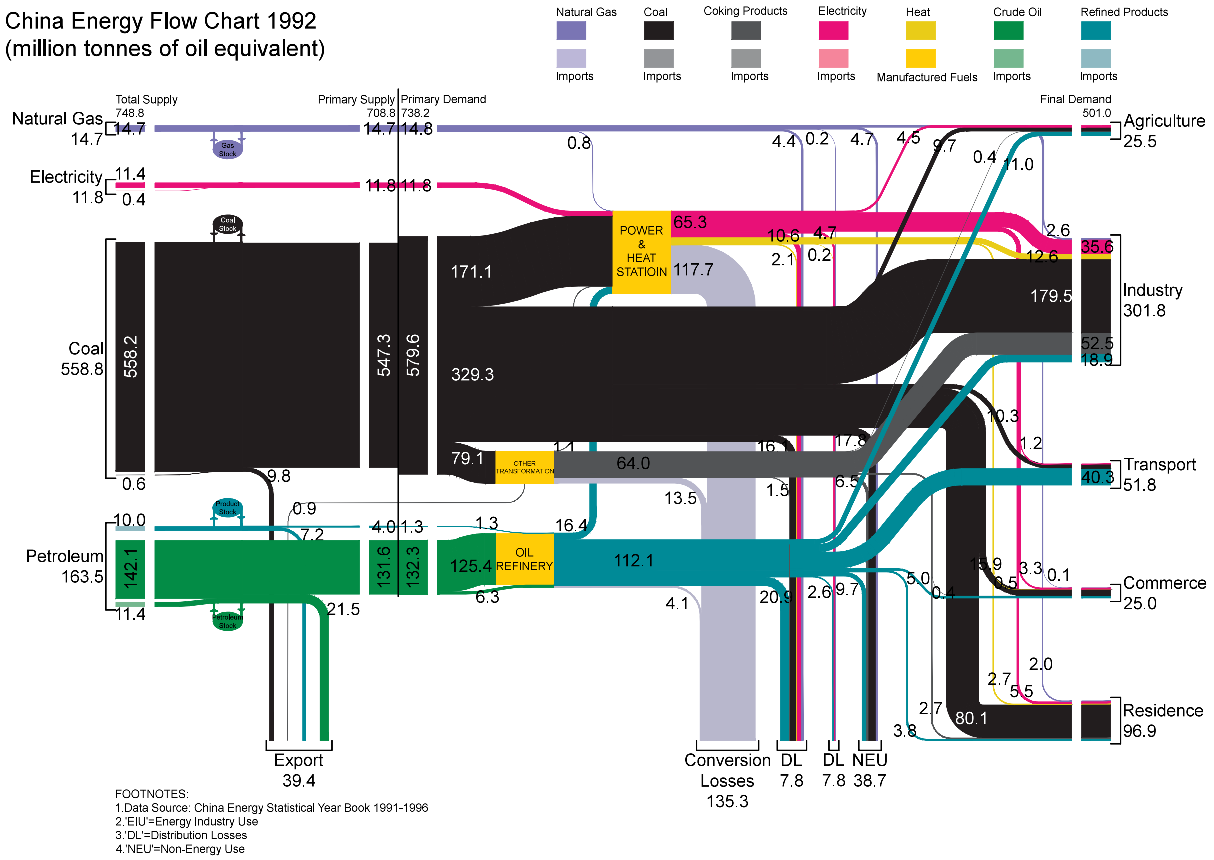


Figure 2.3: China's energy flow chart 1992.

Data source: NBS [1998].

chart to show Chinese energy statistics [DECC, 2013; Xie et al., 2009]. The energy flow charts allow us to trace the energy flows throughout the Chinese economy and provide a complete pictures of the energy system and its changes in China.

The left–hand side of the energy flow charts present the sources of energy supply in China (see Figure 2.3 and Figure 2.4). Between 1992 and 2010, driven by rapid economic growth, Chinese total primary energy supply increased nearly threefold (from 709 million toe in 1992 to 2,206 million toe in 2010), at six percent p.a. Obviously coal is the main energy source for China. In 2010, the Chinese economy relied on coal for two–thirds (68%) of its TPES, petroleum for one–fifth (19%), natural gas for four percent and primary electricity for another nine percent. This coal–based energy supply system has

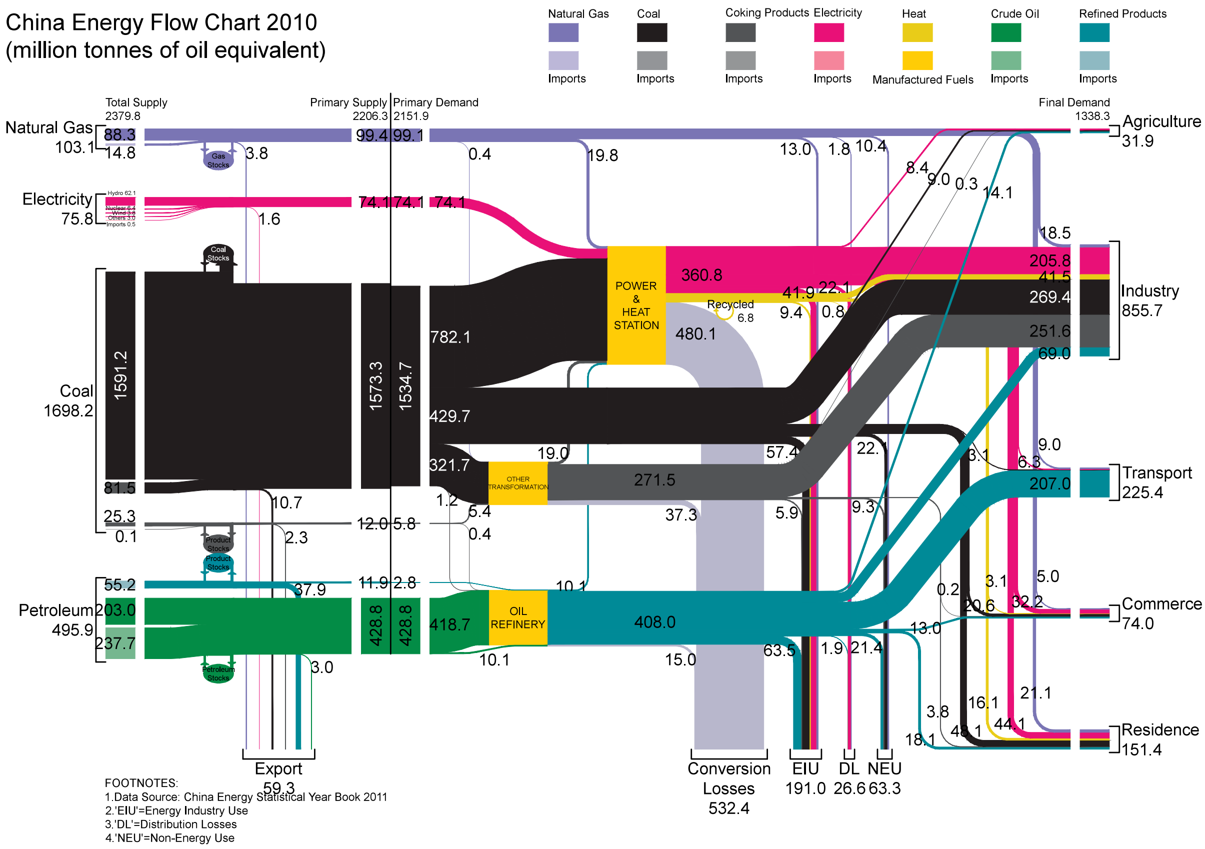


Figure 2.4: China's energy flow chart 2010.

Data source: NBS [2011b].

been stable for more than three decades since the 1970s. During the two decades before the 1970s, increasing domestic petroleum production reduced China's coal dependence. However, with limited petroleum reserves, domestic production was unable to support its continually increasing demand. China now relies on international markets for more than half (53% in 2010) of its petroleum consumption, while it remained an oil net exporter between 1970 and 1992. Similar to petroleum, with the substitution of coke gas by natural gas and inadequate domestic production, the gas supply is becoming more import dependent in recent years (Figure 2.5).

The right–hand side of the energy flow charts describe the energy flows to transformation sectors (yellow rectangles), power and heat stations, oil refineries and other transformations, and to final energy consumers, agriculture, industry, transport, com-

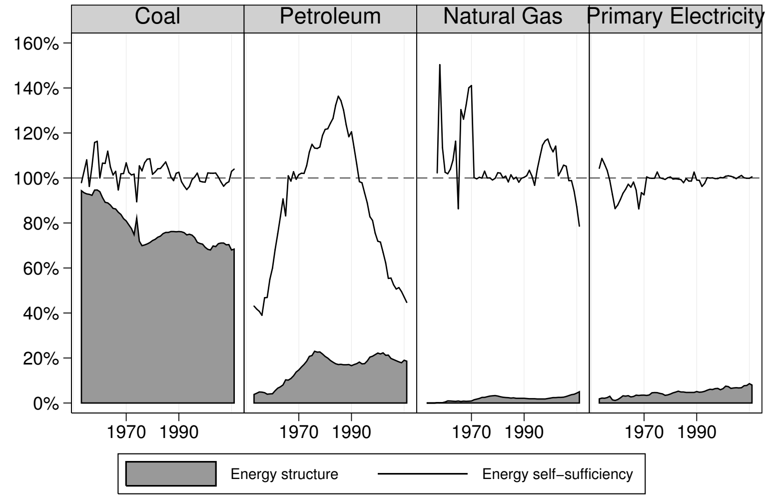


Figure 2.5: Energy supply structure and self–sufficiency by fuel type, 1953–2010. Data source: NBS [2010a, 2012b].

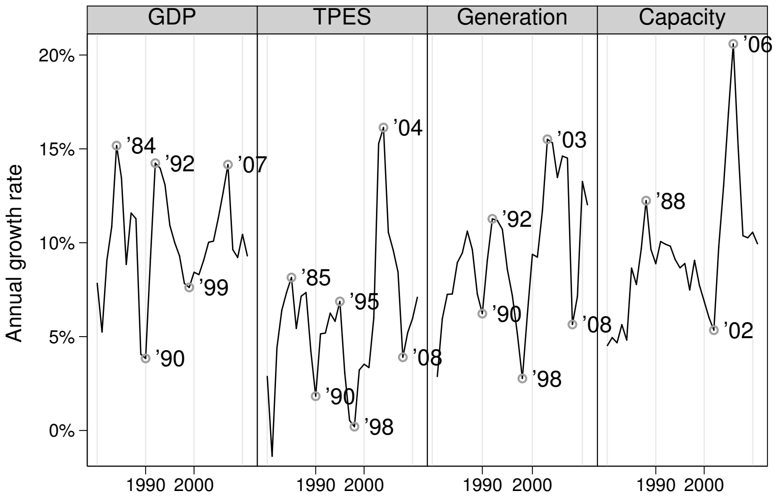


Figure 2.6: Annual growth rates of GDP, TPES, power generation and capacity. Data source: CEP [2012]; NBS [2011b, 2012b].

merce, residences and non-energy use (see Figure 2.3 and Figure 2.4). Between 1992 and 2010, the proportion of the direct use of coal decreased from more than one–half (57% in 1992) to one–quarter (28% in 2010), while the indirect use of coal for electricity generation increased from one–third (30%) to one–half (51%). The electricity generated from fossil fuels (mainly coal, 97% in 2010) accounted for 80 percent of the total electricity supply, hydropower for 20 to 15 percent, nuclear, wind and others for the remainder. Driven by economic development and electrification in both the industrial and residential sectors, the total power generation grew at an average rate of 10% p.a., from 754 terawatt–hours (TWh) in 1992 to 4,207 TWh in 2010. The installed power capacity rose at an average rate of 10% p.a., from 167 GW in 1992 to 966 GW in 2010. In the short term, power generation is highly correlated with the business cycle, and it slowed when financial crises occurred in 1997 and 2008 (Figure 2.6).

Finally, the secondary energy production from transformation sectors and the direct use of primary energy flow into non-energy industrial and residential sectors (see Figure 2.3 and Figure 2.4). Between 1992 and 2010, the most significant change in the final energy demand was the substitution of coal by electricity in all sectors. The proportion of coal in residences, for example, fell from 83 percent in 1992 to 32 percent in 2010, while that of electricity rose from 6 percent to 29 percent. Industrial sectors are always the largest energy consumers, accounting for over 60 percent of the total final use. The energy used for transportation grew slightly faster than any other sector, but still accounted for only 17 percent of the total final use in 2010. The energy growth for transportation will be one of the main energy and environmental challenges for China in the future.

2.3 Comparison of international energy systems

The energy flow chart is also widely used in many other countries to describe their energy supply and demand system. For example, the Department of Energy and Climate Changes (DECC) has published the UK energy flow chart every three years since 1974 and annually since 2007 [DECC, 2013] (see Figure C.2). The Lawrence Livermore National Laboratory (LLNL) has published the US energy flow chart annually since 1973 [LLNL, 2011] (see Figure C.3). The Agency for Natural Resources and Energy (ANRE) has published

Japan's energy flow chart in Japan's energy white paper since 2010 [ANRE, 2010]. This study also provides a Japan energy flow in 2010 (see Figure C.1). International Energy Agency (IEA) has upload interactive Sankey diagrams for the world based on its energy database [IEA, 2013c]. All of these energy flow charts mentioned above allow us to make an international comparison of energy systems in the corresponding countries. The following subsections will compare energy systems from both the total primary energy supply (TPES) side and the total energy use (TEU) side in nations of the G7[1] and BRIC[2].

2.3.1 Total primary energy supply, TPES

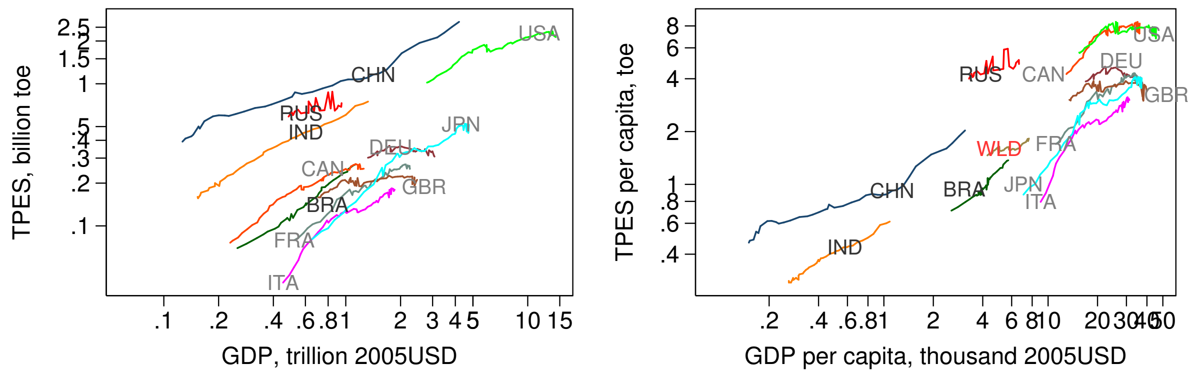
The G7 and BRIC countries are the top largest eleven economies in the world. In the year of 2010, the total economy output (in current USD), energy use and population in G7/BRIC account for 50%/18%, 31%/34% and 11%/42% of the world total, correspondingly [World Bank, 2012]. The trends and structure of energy use in these countries are representative cases of the world energy system.

Figure 2.7 displays the trends of TPES along with economic growth in the G7 since 1960 and in the BRIC since 1971 (Russia since 1990). Obviously, TPES have a positive relationship with economic output, as the growing of an economy requires increasing energy inputs. The energy requirements in developed economies are fluctuating and even decreasing recently, such as in the United Kingdom, Germany, Japan and United States, while the energy demand in developing countries has accelerated, for example, TPES in China have doubled in the last decade.

I also found that the TPES curves of BRIC countries are located on the top of the

[1] The Group of seven (G7) is a group consisting of seven advanced economies: Canada (CAN), France (FRA), Germany (DEU), Italy (ITA), Japan (JPN), the United Kingdom (GBR) and the United States (USA).

[2] The BRIC is a group that includes the countries of Brazil (BRA), Russia (RUS), India (IND) and China (CHN), which are all deemed to be at a similar stage of newly advanced economic development.



(a) Aggregate TPES

(b) Per capita TPES

Figure 2.7: TPES and GDP in G7 and BRIC, 1960–2010.

Data source: World Bank [2012].

graph, which means that the same amount of economic output in BRIC, especially China, require more energy inputs compared to G7 economies. The high energy intensities in BRIC are determined by their technology and economic structure. Regarding technology, as less energy–efficient capital is deployed, the energy requirements for a given level of output increase. Regarding economic structure, as a unit of industrial output needs more energy inputs than a unit of service output, the industrializing economy needs more energy inputs.

As the right–hand side of Figure 2.7 shows, China is located at the left bottom although its corresponding x-axis and y-axis have evidently changed. In other words, Chinese per capita energy consumption is increasing sharply with its remarkable economy development. However, per capita energy use and economic output are still lower than that of developed countries. Another point is that per capita energy use in most G7 countries has been declining in the last few years.

Figure 2.8 illustrates the sources of TPES in G7 and BRIC in 2010. It shows that the share of coal in the TPES is 67% for China in 2010, the highest among eleven countries, 43% for India, around 20% for USA, Japan, and Germany, and less than 10% in other

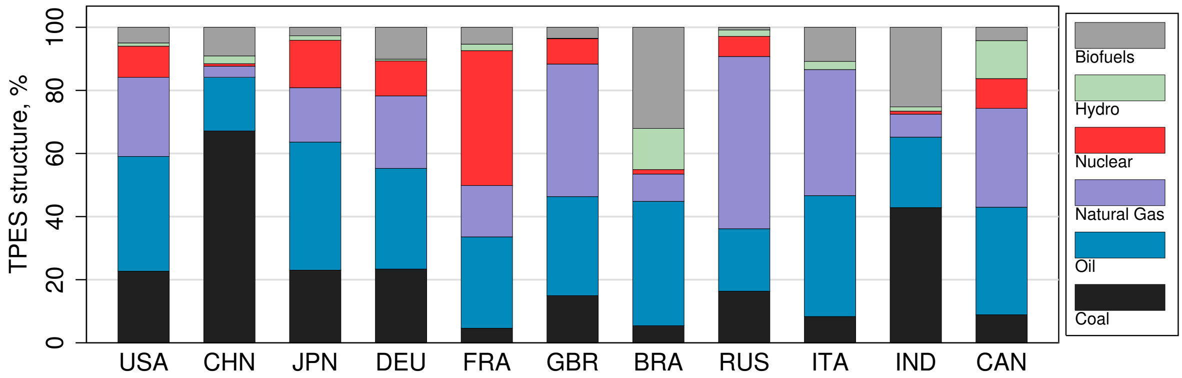


Figure 2.8: The structure of TPES in G7 and BRIC, 2010.

Data source: IEA [2013a,b].

economies. The heavy coal dependence in China is mainly determined by its resource endowment, as it has abundant coal deposit but is poor in oil and gas resources. The share of petroleum was 17% for China in 2010, the lowest in all countries, and around half of it currently comes from the international market. The share of natural gas and primary electricity still very low, only 7% in total. Biofuels have fell from 50% in the middle of the 19th century to the current 9%. However, biofuels are still one of the important energy sources for Brazil and India.

China's current fuels mix directly results in heavy pollution and also limits the improvement of energy efficiency. As we know, all fossil fuels contain carbon, while coal has the highest carbon content and also impurities, such as sulfur. To provide the same amount of heat, the burning of coal releases more CO_2, SO_2 etc., which damages the environment and people's health. It is important and urgent for China to diversifying its energy source to clean and efficient fuels, like natural gas and nuclear power.

The coal–based energy supply system has allowed China to remain energy independent through most of its history (see Figure 2.5). However, energy independence does not mean energy security[1] [Rosen and Houser, 2007]. The effects, such as diversifying energy

[1]Houser defines the energy security as the ability to secure adequate and consistent supplies of energy

sources (fuel types and fuel origins), increasing the capacity of strategic reserves, etc, can also enhance an economy's energy security. Since the oil crisis in 1973, many developed countries started to build their strategic petroleum reserve (SPR). Each member of the IEA is committed to maintaining a reserve that is equivalent to 90 days of the prior year's net oil imports. The purpose of SPR is to providing economic and national security during an energy crisis. China now relies on imported oil for more than half of its petroleum demands (53% in 2010, see Figure 2.4 and Figure 2.5). However, China began its SPR in 2007, which is designed to be completed in three phases. The planned SPR will provide around 90 days of net oil imports by 2020 [XINHUA, 2011].

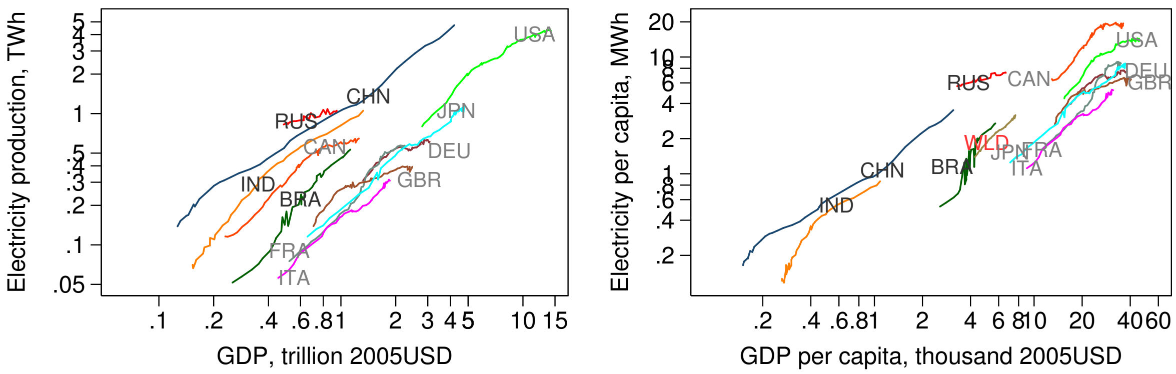
2.3.2 Total energy use, TEU

2.3.2.1 Electricity generation

Since the late 19th century, electricity has been the most important energy in all fields of production and living. As with TPES, the use or generation of electricity is also highly positively correlated with the economic outputs (see Figure 2.9). China has been the largest energy consumer since 2010 and the largest electricity consumer since 2011 driven by its unparalleled economic growth. In the left–hand side of Figure 2.9, China spans on above left, which shows the electric requirement per unit of economic outputs larger than most countries. This might be due to China's industrialization process and huge population. However, the per capita electricity use in China is still very low, only 22% of the USA and 36% of Japan.

Electricity sources by fuels in G7 and BRIC are given in Figure 2.10. Coal keeps its dominant role as an electricity sources in China (77% in 2010), similar to its TPES structure. Hydro power is the second largest electricity source for China (17% in 2010). The oil used to generate electricity has been substituted by other fuels in China and also

to fuel an economy at a price that doesn't bring it to its knees.



(a) Aggregate electricity

(b) Per capita electricity

Figure 2.9: Electricity production in G7 and BRIC, 1960–2010.

Data source: World Bank [2012].

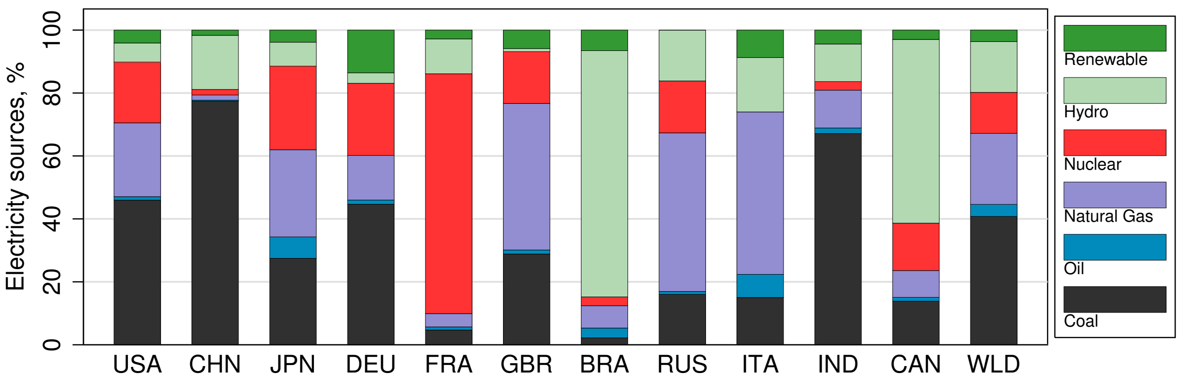
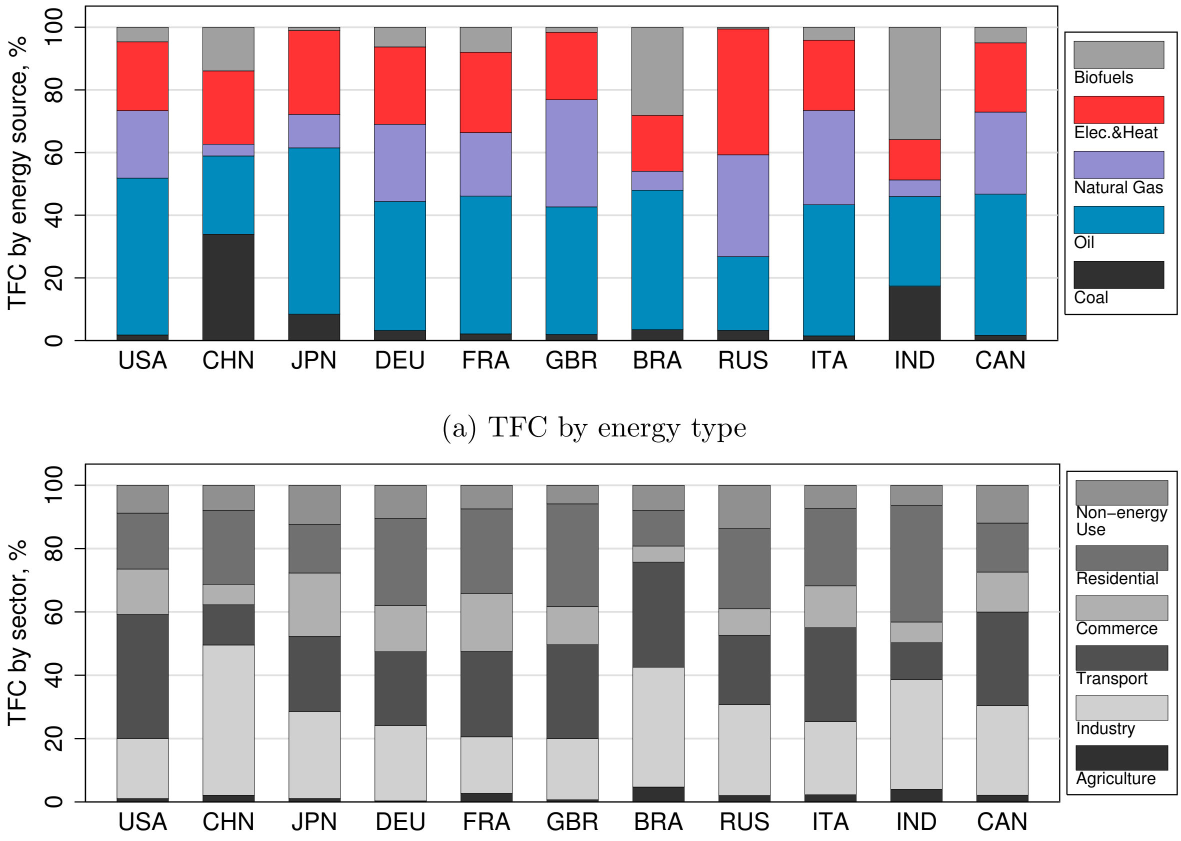


Figure 2.10: The sources of electricity in G7 and BRIC, 2010.

Data source: World Bank [2012].

in other countries. The shares of natural gas and nuclear are too low in Chinese power generation, which is less than 7% in total in 2010. To diversify the electricity structure and protect the environment, China should increase the proportion of natural gas and nuclear.

According to IEA [2013b], the energy losses in the energy conversion process, mainly power generation, have risen from 13% in 1971 to 37% in 2009 in China. Although electricity generation efficiency in China was raised from 34% in 1990 to 38% in 2009, it is still lower than that in Japan and the world average — 42% and 41%. It's urgent to



(a) TFC by energy type

(b) TFC by sector

Figure 2.11: Total final consumption by energy type and by sector in G7 and BRIC, 2010. Data source: IEA [2013a,b].

build more efficient and clean coal-fired power stations in China, such as the Integrated Gasification Combined Cycle (IGCC) power station, when the alternative fuels are not abundantly available.

2.3.2.2 Total final consumption, TFC

Total final consumption (TFC) by end-users includes secondary energy produced from transformation sectors and the direct use of primary fuels. Figure 2.11a shows the energy structure of TFC in G7 and BRIC in 2010. The most significant progress of TFC energy structure in China is the substitution of coal and biofuels by electricity. According to IEA [2013b], the share of electricity in TFC in China has risen from 3% in 1971 to 23% in 2010, while biofuels and coal dropped from 45% and 41% (86% in total) to 14% and 34%

(48% in total) correspondingly. As energy is consumed complementarily with the capital stock, this fuel substitution represents the huge increase of capital in both industrial and residential sectors in China during the last half century. Natural gas in TFC is still negligible, only 4% in 2010, while the average in G7 countries reached one-quarter. It's important to stress the policy that promotes the substitution of biofuels and coal by natural gas in China. In other words, China has huge potential to expand its natural gas market.

The Total Final Consumption (TFC) can be broken down to six sectors: Agriculture, Industry, Transport, Commerce, Residential and Non-energy use. Figure 2.11b illustrates the TFC by sector in G7 and BRIC in 2010. Industry is the main final energy consumer in China, the share of which rose from 32% in 1971 to 47% in 2010, while that in most G7 countries was approximately one-fifth in 2010. This is a result of industrialization processes in China and services–oriented economic patterns in developed countries. Residential is the second largest final energy consumer in China, but its share dropped from 57% in 1971 to 23% in 2010. The residential energy use is mainly determined by the quantity of capital or durable goods held by households, such as televisions, washing machines, refrigerators, and air conditioners, which are reliant on family income.

2.4 Conclusions

This chapter presents a brief historical overview of energy use. Two energy flow charts for China in 1992 and 2010 were provided to describe Chinese energy supply and use system and its changes. The energy flow charts of Japan, U.K. and U.S. in 2010 were also provided. Finally, I made a comparison of energy systems between the main economies in the world.

As per discussion on the brief history of energy use, there are four great energy transitions in history: the domesticating of draft animals for productive activities and the harnessing of fire for making durable materials; the substitution of a large share of muscular exertion by waterwheels and windmills; the substitution of draft animals and biomass fuels by engines and fossil fuels; the course of electrification and the increasing dependence on hydrocarbons. According to the energy transitions, I can simply divide the humankind's history into a pre-fossil fuel era and fossil fuel era by the mid-1700s, when Watt improved the steam engine and also when Smith published "The Wealth of Nations", which represents the beginning of classical economics. Human productivity has increased significantly since the world entered the fossil fuel era. The population, for example, experienced exponential growth from less than 1 billion to the current 7 billion in the last two hundred years. Without the huge improvement of productivity, the earth would be unable to support such a population. Technological innovation, which is the new capital stock in economics, pushed productivity growth in the long term. The demand for energy is a derived demand from the utilization of capital stocks. Coal and petroleum used as fuels, for example, started with the diffusion of steam engines in textile manufacture from the mid-1700s and the diffusion of internal combustion engines in transportation from the late 1800s.

China's energy flow charts in 1992 and 2010 present the energy supply and use system in China and its changes. From the energy supply side, the Chinese economy relied on coal for about two-thirds of its total primary energy supply (TPES), petroleum for one-fifth, natural gas for four percent and primary electricity for the remaining nine percent. This coal–based energy supply system has been stable for more than three decades since the 1970s. In addition, China now relies on the international market for more than half of its petroleum consumption. From the energy use side, electricity generated from fossil fuel (mainly coal) accounted for 80 percent of the total electricity supply in China. The proportion of the direct use of coal dropped from one-half in 1992 to one-quarter in 2010, while indirect use of coal for electricity generation rose from one-third to one-half. There is no significant change in the final energy use by sector in China during the last few decades. The industrial sector has been the largest energy consumers among final users. The transportation energy use grew slightly faster than any other sector, but still accounted for only 17 percent of total final consumption in 2010. The heavy dependence on coal and the energy growth for transports will be the most important energy and environmental challenges for China in the future. China's energy discussed here and in section 2.2 are based on the energy statistics published by NBS, which doesn't provide the information on biomass. According to IEA, biofuels still count for about ten percent of TPES in China.

Comparing the main economies in the world, I can found that the aggregate energy use in China surged sharply in the last half-century, but the per capita energy use is still very low. The natural resource endowment determined the coal-dominated energy structure in China. The substitution of coal by natural gas would be one of the most important potential improvements for the Chinese energy structure. It is important and urgent for China to diversify its energy source to clean and efficient fuels. For the consideration of energy security, China should also promote policies to diversify energy sources on both fuel types and fuel origins and increase the capacity of strategic reserves. Most of China's electricity is generated from coal. If alternative fuels are not abundantly available, it is crucial to build more efficient and clean coal-fired power stations, such as the IGCC power plant. Adjusting economic structure is also important for China, because manufacture requires more energy to produce the same amount of output.

Chapter 3

The Driving Forces of China's Energy Use

3.1 Introduction

3.1.1 Trends of energy intensity in the long term

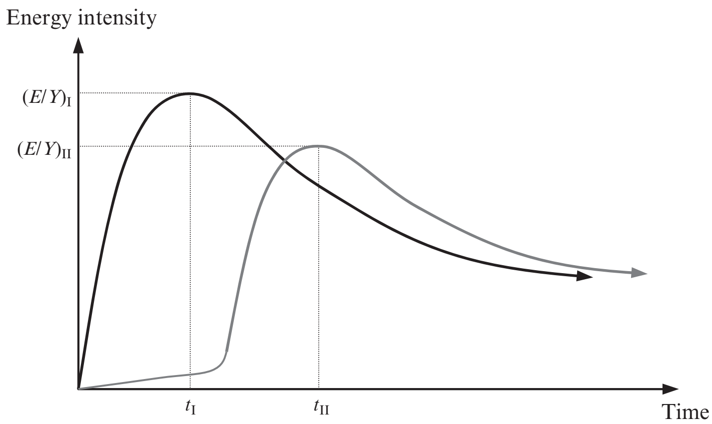
An economy requires a different input level of energy resources in different development phases. As Bernardini and Galli [1993] have identified, national energy intensity follows a bell shape or inverted U-shape pattern in the long term, which is defined as the theory of dematerialization (Figure 3.1a). In other words, an economy's total energy use typically grows faster than its gross domestic product (GDP) and eventually grows slower than the GDP during the course of economic development. Galli [1998] examined the energy intensity trends for ten emerging Asian countries during 1973–1990 and found that energy intensity decreases beyond some threshold level of GDP per capita. Medlock and Soligo [2001] analyzed the effect of sector–specific energy use growth rates on final energy consumption and identified energy intensity peaks at approximately $2600 (1985 PPP$).

The trends of energy[1] intensity[2] in China follow this inverted U-shape pattern (Figure 3.1b)[3]. Between 1949 and 1978, because of the pursuit of the Soviet style of industrialization in China, the share of industrial economic output increased from 18 to 44 percent, and the energy–GDP ratio almost tripled [Rosen and Houser, 2007]. After the launch of the Reform and Opening–up policy in 1978, energy intensity in China began falling, while Chinese per capita GDP remained at a few hundred US$. During the period

[1] The term "energy" used in this chapter refers to commercial energy only. Traditional fuels, mainly biomass, are excluded from this analysis due to data unavailability.

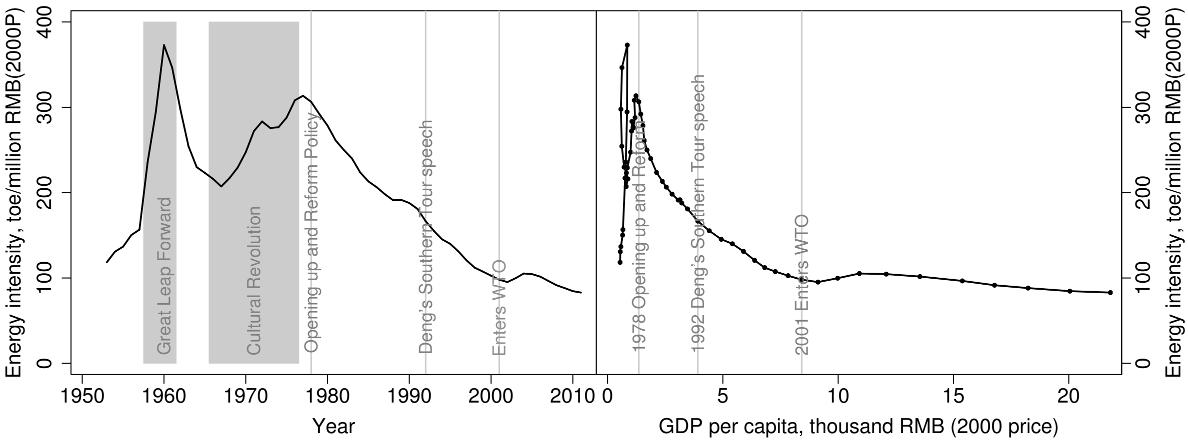
[2] The term "energy intensity" is defined as the ratio of energy consumption in its physical quantity over GDP in constant prices.

[3] The non-thermal electricity included here is not measured in calorific value but divided by the thermal–electric conversion efficiency in the same year. If the non-thermal electricity is not measured in calorific value in this paper, I will note this explicitly here.



(a) The theory of dematerialization

Source: Hunt and Evans [2011]



(b) Energy intensity trends in China, 1953–2011.

Data Source: NBS [2010a, 2011b, 2012b] (calculated by author).

Figure 3.1: Bell shaped energy intensity trends in the long term.

between 1978 and 2001, the energy–GDP ratio fell by two–thirds (68%), decreasing at an annual average rate of five percent [NBS, 2010a, 2011b, 2012b]. Zhang [2003] noted that this achievement is rarely accomplished in countries at this level of development.

However, this declining energy intensity trend has reversed since 2002. Over the period of 2002–2010, the energy–GDP ratio decreased at an annual average rate of only two percent. Given its unparalleled economic growth at an average of ten percent p.a. over three decades, China became the largest energy consumer in the world in 2010 [BP, 2013] even though its energy intensity dropped about three–quarters during the same period. At the same time, there is also a growing concern for the environment on both local and global scales associated with the increasing emissions from fossil fuel combustion. It is critical to understand the driving forces of China's energy use for the design of both Chinese and global energy and environmental policy.

3.1.2 Literature survey on energy use in China

Total energy use is the product of economic output and energy intensity. The energy intensity is determined by three fundamental factors: changes in the structure of final demand, increases in the efficiency of energy use, and the substitution of alternative inputs [Bernardini and Galli, 1993]. To gauge the effects of driving forces on energy use change, index decomposition analysis (IDA) and structural decomposition analysis (SDA) are two techniques widely used by researchers. The reviews of IDA can be found in Ang [2004] and Ang and Zhang [2000], and SDA can be found in Miller and Blair [2009] and Su and Ang [2012b]. Empirical studies conducted by Huang [1993]; Liao et al. [2007]; Ma and Stern [2008]; Sinton and Levine [1994]; Zhang [2003]; Zhao et al. [2010] using IDA decomposed China's industrial energy use change into production effect, structural effect, and technical effect[1]. These studies found that technical effect is the dominant contributor for energy intensity decline during the 1980s and 1990s, and the excessive expansion of energy–intensive sectors caused China's energy intensity fluctuation after 2001.

While the IDA studies mentioned above only discuss the change in industrial energy use, SDA studies developed from an input–output table can describe the economy–wide energy use. Although IDA is applied to track economy–wide energy efficiency trends [Ang, 2006; Ang et al., 2010], the differences between the scope of these two techniques in energy studies still exists. For example, typical SDA studies are able to provide more detailed factors, such as a Leontief effect (or technical effect) and a final demand effect

[1] The terms "efficiency effect" and "real intensity effect" are also used.

by both sector and demand source, and to estimate the indirect effect, such as the energy embodied in steel rebar which is used in construction. More similarities and differences between SDA and IDA can be found in studies by Hoekstra and van den Bergh [2003]; Su and Ang [2012b].

By using SDA and based on the input–output tables in 1981 and 1987, Lin and Polenske [1995] examined primary energy use changes in China from 1981 to 1987. They found that production technology changes reduced China's energy requirements, while final demand shifts increased energy use, and the driving force of the decline in energy intensity was energy efficiency improvements. Based on the input–output tables from 1987 and 1992, Garbaccio et al. [1999] decomposed the reduction in energy use into technical change and structural change. Their main conclusion is that technical change within sectors accounted for most of the fall in the energy–output ratio during the period of 1987–1992, and structural change actually increased the use of energy. Based on China's input–output tables in 30 sectors in 1992, 1997, 2002 and 2004, Chai et al. [2009] suggest that the fluctuation of energy intensity is mainly due to technological advances and the corresponding change in the industrial structure.

This chapter applies SDA to analyze the driving forces of China's energy use and its change between 1992 and 2010 — the years for which I have both detailed energy balance tables and input–output tables. It can be considered an update of the study by Lin and Polenske [1995]. This study differs from the previous analyses in three important aspects. Firstly, hybrid I–O tables used in this study are compiled based on published statistics. Secondly, two energy flow charts are provided to describe China's energy system. Third, I provide hybrid energy I–O models on both the energy supply and demand side. These models allow me to capture both direct and indirect energy demand associated with final demand, and eliminate the energy price variations across all sectors and final demand categories. This paper decomposes total energy use and its changes in China by using the energy demand side model.

The remainder of this chapter is organized as follows. Section 3.2 introduces the energy input–output model and the application of LMDI to this model. The compilation of hybrid input–output tables is described in section 3.3. Section 3.4 provides the results and discussions of decomposition of total energy use and its change. Section 3.5 gives the limitations of this study, such as the effects of data reliability and sector aggregation on the results. Finally, section 3.6 discusses conclusions and policy implications.

3.2 The energy input–output model and decomposition method

3.2.1 Energy input–output model

The normal input–output (I–O) model analyzes the flows of products between industries in an economy. The I–O model is developed from an inter-industry transaction table, called an input–output table. China's I–O table shows imports within the transaction table, which is assumed as competitive imports (commodities that are also produced domestically) (Table 3.1). The rows of such tables describe the distribution of an industry's output throughout the economy, which can be summarized in matrix notation as

$$\mathbf{Zi} + \mathbf{Fi} - \mathbf{m} = \mathbf{x} \tag{3.1}$$

where $\mathbf{Z}$ is the $n \times n$ matrix of intermediate inputs; $\mathbf{F}$ is the $n \times o$ matrix of total final demand; $\mathbf{m}$ and $\mathbf{x}$ are $n \times 1$ (column) vectors of imports and total outputs, respectively; $\mathbf{i}$ is the $n \times 1$ vector of ones, which is known as a summation vector. Total final demand includes domestic final demand and exports (foreign demand),

$$\mathbf{F} = \mathbf{F}_d + \mathbf{F}_{Ex} \tag{3.2}$$

where $\mathbf{F}_d$ is the $n \times o$ matrix of domestic final demand in which the elements of exports are zero; $\mathbf{F}_{Ex}$ [1] is the $n \times o$ matrix of exports in which the elements of domestic final demand are zero.

An economy's total energy use consists of all the energy embodied in domestically produced goods and services, while energy embodied in imported goods and services is the energy demand in foreign countries. Thus, to measure the impacts of domestic production on total energy use, I divide the transaction flows of a competitive import type I–O table into domestic products and imported products (Table 3.2). The rows of each part can be expressed as

$$\mathbf{Z}^d\mathbf{i} + \mathbf{F}^d\mathbf{i} = \mathbf{x} \tag{3.3}$$

$$\mathbf{Z}^m\mathbf{i} + \mathbf{F}^m\mathbf{i} = \mathbf{m} \tag{3.4}$$

where $\mathbf{Z}^d = (\mathbf{I} - \mathbf{M})\mathbf{Z}$ and $\mathbf{Z}^m = \mathbf{M} \cdot \mathbf{Z}$ are the $n \times n$ matrices of intermediate inputs of domestic and imported products, respectively; $\mathbf{F}^d = (\mathbf{I} - \mathbf{M})\mathbf{F}_d + \mathbf{F}_{Ex}$ is $n \times o$ matrix of total final demand for domestic products; $\mathbf{F}^m = \mathbf{M} \cdot \mathbf{F}_d$ is the $n \times o$ matrix of total final demand for imported products; $\mathbf{M} = \hat{\mathbf{m}}(\widehat{\mathbf{Zi} + \mathbf{F}_d\mathbf{i}})^{-1}$ is the $n \times n$ diagonal matrix of the import ratio based on the assumption that imported products would not be exported directly and distributed at the same percent of total inputs to all intermediate sectors and domestic final demand categories. Miller and Blair [2009] and Su and Ang [2013] provide more detailed discussions on this non-competitive imports assumption.

Using the definitions of the technical coefficient matrix for domestic products, $\mathbf{A}^d = \mathbf{Z}^d\hat{\mathbf{x}}^{-1}$, and for imported products, $\mathbf{A}^m = \mathbf{Z}^m\hat{\mathbf{x}}^{-1}$, Equations (3.3) and (3.4) can be

[1] In China's I–O table, there is an "error" column in the final demand block. It was not shown in the equation because it represents the statistical difference between inputs and outputs only. I treat it the same as exports.

Table 3.1
Competitive import type input–output table.

Economic activities	Intermediate use	Final demand	Import	Total output
Intermediate input	$\mathbf{Z}$	$\mathbf{F} = \mathbf{F}_d + \mathbf{F}_{Ex}$	$-\mathbf{m}$	$\mathbf{x}$
Value added	$\mathbf{V}$			
Total input	$\mathbf{x}'$			

Source: Author.

Table 3.2
Non-competitive import type input–output table.

Economic activities	Intermediate use	Final demand	Total output/Import
Intermediate input	$\mathbf{Z}^d$	$\mathbf{F}^d = (\mathbf{I} - \mathbf{M})\mathbf{F}_d + \mathbf{F}_{Ex}$	$\mathbf{x}$
Import	$\mathbf{Z}^m$	$\mathbf{F}^m = \mathbf{M} \cdot \mathbf{F}_d$	$\mathbf{m}$
Value added	$\mathbf{V}$		
Total input	$\mathbf{x}'$		

Source: Author.

rewritten as

$$\mathbf{A}^d\mathbf{x} + \mathbf{F}^d\mathbf{i} = \mathbf{x} \tag{3.5}$$

$$\mathbf{A}^m\mathbf{x} + \mathbf{F}^m\mathbf{i} = \mathbf{m} \tag{3.6}$$

The summation matrix $\mathbf{A} = \mathbf{A}^d + \mathbf{A}^m$ is the direct input coefficient in the import exogenous I–O model. The solution to Equation (3.5) is given by

$$\mathbf{x} = (\mathbf{I} - \mathbf{A}^d)^{-1}\mathbf{F}^d\mathbf{i} = \mathbf{L}^d\mathbf{F}^d\mathbf{i}, \tag{3.7}$$

where $\mathbf{L}^d = (\mathbf{I} - \mathbf{A}^d)^{-1}$ is the $n \times n$ matrix of the Leontief inverse or total input requirements for domestic products. Equations (3.3)–(3.7) are known as the non-competitive import type I–O model or import endogenous I–O model.

To extend the general I–O framework to energy studies, most empirical studies applied to China simply multiply the total output by the energy coefficient. The discussion of the strengths and weakness of this approach can be found in the studies by Dietzenbacher and Stage [2006] and Miller and Blair [2009]. In this study, I use hybrid I–O tables where the monetary energy flows are replaced by physical energy flows.

In the hybrid I–O table, the rows of energy–related sectors present the distribution of energy products throughout economy, which can be summarized like Equations (3.5) and (3.6) as

$$\hat{\boldsymbol{\varepsilon}}\mathbf{A}^{d}\mathbf{x} + \hat{\boldsymbol{\varepsilon}}\mathbf{F}^{d}\mathbf{i} = \hat{\boldsymbol{\varepsilon}}\mathbf{x} \tag{3.8}$$

$$\hat{\boldsymbol{\varepsilon}}\mathbf{A}^{m}\mathbf{x} + \hat{\boldsymbol{\varepsilon}}\mathbf{F}^{m}\mathbf{i} = \hat{\boldsymbol{\varepsilon}}\mathbf{m} \tag{3.9}$$

where $\boldsymbol{\varepsilon}$ is the $n \times 1$ vector consisting of ones and zeros, elements of which are ones corresponding to energy sectors and zeros for all of the other sectors. The diagonal matrix, $\hat{\boldsymbol{\varepsilon}}$, is used to select rows of energy sectors from the hybrid I–O table. For example, $\hat{\boldsymbol{\varepsilon}}\mathbf{A}^{d}\mathbf{x}$ in Equation (3.8) represents the intermediate inputs of domestic energy. In hybrid I–O Equations (3.8) and (3.9), the units for each element in the matrices of $\mathbf{F}^{d}$, $\mathbf{F}^{m}$, $\mathbf{x}$ and $\mathbf{m}$ are expressed as $[\,^{toe}_{RMB}\,]$, and for $\mathbf{A}^{d}$ and $\mathbf{A}^{m}$ are $\left[\begin{smallmatrix} toe/toe & toe/RMB \\ RMB/toe & RMB/RMB \end{smallmatrix}\right]$. The solution to Equation (3.8) is given by

$$\hat{\boldsymbol{\varepsilon}}\mathbf{x} = \hat{\boldsymbol{\varepsilon}}(\mathbf{I} - \mathbf{A}^{d})^{-1}\mathbf{F}^{d}\mathbf{i} = \hat{\boldsymbol{\varepsilon}}\mathbf{L}^{d}\mathbf{F}^{d}\mathbf{i}, \tag{3.10}$$

Similar to Equation (3.7), this identity explains total energy production via the product of total requirement matrix for domestic energy, $\hat{\boldsymbol{\varepsilon}}\mathbf{L}^{d}$, and the total final demand for domestic products, $\mathbf{F}^{d}\mathbf{i}$.

The total energy use of an economy can be measured from either the energy supply side or energy demand side, according to the energy balance table. From the energy supply side, the total primary energy supply is the summation of primary energy production and other energy supply sources, such as imports, etc. The information of primary energy production, however, is not available from the hybrid I–O table directly. The reason is that the primary supply of electricity (hydro power, nuclear power, and wind power) is counted together with thermal power. The primary supplies of heat and coke (recovery energy[1]) have similar problems. Lin and Polenske [1995] solve this problem by introducing a hypothetical sector into the I–O model. In this paper, I bring an $n \times 1$ vector, $\boldsymbol{\alpha}$, to separate primary electricity from thermal electricity. The elements in the vector $\boldsymbol{\alpha}$ for secondary energy sectors are ratios of primary sources over total energy outputs, and for all of the other sectors are ones.

Therefore, the total primary energy supply (TPES) is given by

$$\mathbf{e}_{TPES} = \hat{\boldsymbol{\alpha}}\mathbf{e}_{\mathbf{x}} + \mathbf{e}_{\mathbf{m}} - \mathbf{e}_{Ex} - \mathbf{e}_{\Delta S} \tag{3.11}$$

where $\mathbf{e}_{TPES}$ is the $m \times 1$ vector of TPES; $\hat{\boldsymbol{\alpha}}\mathbf{e}_{\mathbf{x}}$, $\mathbf{e}_{\mathbf{m}}$, $\mathbf{e}_{Ex}$ and $\mathbf{e}_{\Delta S}$ are the vectors of total primary energy production, imported energy, exported energy and energy stock changes respectively. By substituting Equations (3.9) and (3.10) into Equation (3.11) and rearranging them, we have

$$\mathbf{e}_{TPES} = \hat{\boldsymbol{\varepsilon}}\hat{\boldsymbol{\alpha}}\mathbf{L}^{d}\mathbf{F}^{d}\mathbf{i} + (\hat{\boldsymbol{\varepsilon}}\mathbf{A}^{m}\mathbf{L}^{d}\mathbf{F}^{d}\mathbf{i} + \hat{\boldsymbol{\varepsilon}}\mathbf{F}^{m}\mathbf{i}) + \hat{\boldsymbol{\varepsilon}}\mathbf{F}\mathbf{u} \tag{3.12}$$

where $\hat{\boldsymbol{\varepsilon}}\hat{\boldsymbol{\alpha}}\mathbf{L}^{d}\mathbf{F}^{d}\mathbf{i}$ is the total primary energy production; $\hat{\boldsymbol{\varepsilon}}\mathbf{A}^{m}\mathbf{L}^{d}\mathbf{F}^{d}\mathbf{i}$ is the intermediate input of imported energy; $\hat{\boldsymbol{\varepsilon}}\mathbf{F}^{m}\mathbf{i}$ is final demand for imported energy; $\hat{\boldsymbol{\varepsilon}}\mathbf{F}\mathbf{u}$ is the energy delivered to exports and stock changes; $\mathbf{u}$ is the $o \times 1$ vector consisting of minus one for exports and stock changes and zero for all other final demand categories.

[1]The recovery energy is excluded from the total primary energy supply in the latest version of China's energy statistics. I still count it as a primary energy supply in this paper.

From the energy demand side, total energy use equals the summation of energy consumed in intermediate sectors and in households. In the intermediate input matrix, energy inputs to transformation sectors are not completely consumed but are converted into secondary energy, which appears again in the rows of secondary energy sectors. I introduce an $n \times 1$ vector, $\boldsymbol{\eta}$, to avoid this double accounting, elements of which are the energy transformation efficiencies in corresponding energy sectors and zeros for all of the other sectors.

Using the definition of energy transformation efficiency vector, $\boldsymbol{\eta}$, the total energy use can be expressed as

$$\mathbf{e}_{TEU} = (\mathbf{J} - \mathbf{S}\hat{\boldsymbol{\eta}}) \circ \mathbf{E}_I \mathbf{i} + \mathbf{e}_H \tag{3.13}$$

where $\mathbf{e}_{TEU}$ and $\mathbf{e}_H$ are the $m \times 1$ vectors of total energy use and household energy use respectively; $\mathbf{E}_I = \hat{\boldsymbol{\varepsilon}}\mathbf{A}\mathbf{x} = \hat{\boldsymbol{\varepsilon}}\mathbf{A}\mathbf{L}^d\mathbf{F}^d$ is the $m \times n$ matrix of intermediate inputs of energy, and $(\mathbf{J} - \mathbf{S}\hat{\boldsymbol{\eta}}) \circ \mathbf{E}_I$ refers to intermediate energy use that eliminates double accounting; $\circ$ refers to the Hadamard product [1]; $\mathbf{J}$ is a $n \times n$ matrix of ones; $\mathbf{S}$ is a $n \times n$ matrix, elements of which are share of conversion energy inputs for transformation sectors and zeros for all the other sectors. By combining Equations (3.10) and (3.13), I have

$$\mathbf{e}_{TEU} = \hat{\boldsymbol{\varepsilon}}(\mathbf{J} - \mathbf{S}\hat{\boldsymbol{\eta}}) \circ \mathbf{A}\mathbf{L}^d\mathbf{F}^d\mathbf{i} + \hat{\boldsymbol{\varepsilon}}\mathbf{F}\mathbf{v} = \hat{\boldsymbol{\varepsilon}}\tilde{\mathbf{A}}\mathbf{L}^d\mathbf{F}^d\mathbf{i} + \hat{\boldsymbol{\varepsilon}}\mathbf{F}\mathbf{v} = \hat{\boldsymbol{\varepsilon}}\mathbf{G}\mathbf{F}^d\mathbf{i} + \hat{\boldsymbol{\varepsilon}}\mathbf{F}\mathbf{v} \tag{3.14}$$

where $\tilde{\mathbf{A}} = \hat{\boldsymbol{\varepsilon}}(\mathbf{J} - \mathbf{S}\hat{\boldsymbol{\eta}}) \circ \mathbf{A}$ is the $m \times n$ matrix of direct energy use coefficients; $\hat{\boldsymbol{\varepsilon}}\mathbf{G} = \hat{\boldsymbol{\varepsilon}}\tilde{\mathbf{A}}\mathbf{L}^d$ is the $m \times n$ matrix of total energy use coefficients; $\hat{\boldsymbol{\varepsilon}}\mathbf{G}\mathbf{F}^d\mathbf{i}$ represents intermediate energy use; $\hat{\boldsymbol{\varepsilon}}\mathbf{F}\mathbf{v}$ is the energy delivered to households; $\mathbf{v}$ is the $o \times 1$ vector consisting of ones for

[1] For two matrices $\mathbf{A}$ and $\mathbf{B}$ of the same dimensions, the Hadamard product $\mathbf{A} \circ \mathbf{B}$ is a matrix of the same dimensions, the i, j element of $\mathbf{A}$ is multiplied with the i, j element of $\mathbf{B}$, that is $(\mathbf{A} \circ \mathbf{B})_{ij} = A_{ij}B_{ij}$.

households and zeros for all of the other final demand categories.

In Equation (3.14), intermediate energy use is a summation of the intermediate use of domestic energy and of imported energy, $\hat{\boldsymbol{\varepsilon}}\mathbf{G}\mathbf{F}^d = \hat{\boldsymbol{\varepsilon}}\tilde{\mathbf{A}}^d\mathbf{L}^d\mathbf{F}^d + \hat{\boldsymbol{\varepsilon}}\tilde{\mathbf{A}}^m\mathbf{L}^d\mathbf{F}^d$. It is also a summation of direct energy use and indirect energy use, $\hat{\boldsymbol{\varepsilon}}\mathbf{G}\mathbf{F}^d\mathbf{i} = \hat{\boldsymbol{\varepsilon}}\tilde{\mathbf{A}}\mathbf{F}^d + \hat{\boldsymbol{\varepsilon}}\tilde{\mathbf{A}}(\mathbf{L}^d - \mathbf{I})\mathbf{F}^d$. Household energy use can also be expressed as a summation of domestic energy and of imported energy, $\hat{\boldsymbol{\varepsilon}}\mathbf{F}\mathbf{v} = \hat{\boldsymbol{\varepsilon}}\mathbf{F}^d\mathbf{v} + \hat{\boldsymbol{\varepsilon}}\mathbf{F}^m\mathbf{v}$.

The sector of "Construction", for example, requires intermediate inputs of both domestically produced and imported products, such as energy, steel rebar and others, which are termed direct inputs. The production of steel rebar also requires inputs of both domestically produced and imported products, like energy and pig iron, which are defined as the first-round indirect inputs to the construction sector. In addition, producing pig iron also requires inputs, such as energy and iron ore, which are defined as second–round indirect inputs (see Figure 3.2). In mathematical notation, the Leontief inverse matrix $\mathbf{L}^d$ can be expressed as $\mathbf{L}^d = (\mathbf{I} - \mathbf{A}^d)^{-1} = \mathbf{I} + \mathbf{A}^d + (\mathbf{A}^d)^2 + (\mathbf{A}^d)^3 + \cdots$ [Miller and Blair, 2009]. Therefore, the total output in Equation (3.7) can be expressed as

$$\mathbf{x} = \underbrace{[\mathbf{I}]\mathbf{F}^d\mathbf{i}}_{\text{initial}} + \underbrace{[\mathbf{A}^d]\mathbf{F}^d\mathbf{i}}_{\text{direct}} + \underbrace{[(\mathbf{A}^d)^2 + (\mathbf{A}^d)^3 + \cdots]\mathbf{F}^d\mathbf{i}}_{\text{indirect}} \tag{3.15}$$

where the total output is the sum of 'initial', 'direct' and 'indirect' effects. Similarly, the total energy use in Equation (3.14) can be presented as

$$\mathbf{e}_{TEU} = \underbrace{\hat{\boldsymbol{\varepsilon}}[\mathbf{I}]\mathbf{F}\mathbf{v}}_{\text{initial}} + \underbrace{\hat{\boldsymbol{\varepsilon}}[\tilde{\mathbf{A}}]\mathbf{F}^d\mathbf{i}}_{\text{direct}} + \underbrace{\hat{\boldsymbol{\varepsilon}}[\tilde{\mathbf{A}}(\mathbf{A}^d + (\mathbf{A}^d)^2 + (\mathbf{A}^d)^3 + \cdots]\mathbf{F}^d\mathbf{i}}_{\text{indirect}} \tag{3.16}$$

where the 'initial' effect refers to household energy use; the 'direct' effect refers to the first round energy use to produce final demand; the 'indirect' effect $\hat{\boldsymbol{\varepsilon}}\tilde{\mathbf{A}}(\mathbf{L}^d - \mathbf{I})\mathbf{F}^d$ refers to the sum of round-by-round energy use to produce the first round final demand.

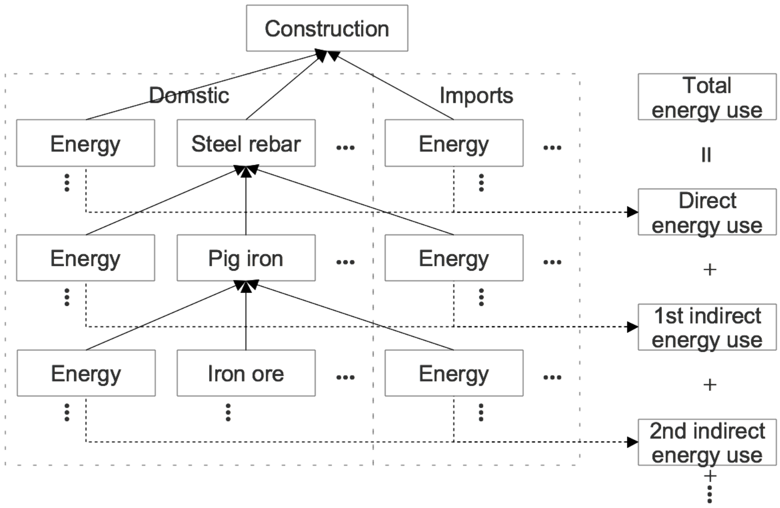


Figure 3.2: The definition of total, direct and indirect energy use.

Source: Author.

The difference between the total primary energy supply and the total energy use is the "statistical difference" in the energy balance table. Both of these concepts describe the total energy consumption in an economy. Lin and Polenske [1995] decomposed China's energy use from the energy supply side, so this paper chooses the energy demand side model given by Equation (3.14) for the following analysis. Note that the matrices' dimensions, n, m and o, refer to the number of sectors, energy sectors and final demand categories, respectively.

3.2.2 Decomposition method

Final demand can be further decomposed into three components: (1) the overall level of final demand; (2) the distribution of total expenditures across final demand categories, such as household consumption and exports; and (3) the product mix of each individual final demand category [Lin and Polenske, 1995; Miller and Blair, 2009]. In this paper, I added population as another component so that final demand can be expressed as

$$\mathbf{F}^d = \mathbf{B}^d \hat{\mathbf{d}}^d y^d p \qquad \text{and} \qquad \mathbf{F} = \mathbf{B}\hat{\mathbf{d}} y p \tag{3.17}$$

where $\mathbf{B}$ refers to the product mix effect; $\mathbf{d}$ refers to the distribution effect; y refers to the per capita level effect; p refers to the population effect; and the superscript ^{d} denotes the effect associated with domestic products.

Finally, the total energy use in Equation (3.14) can be express as

$$\mathbf{e}_{TEU} = \hat{\boldsymbol{\varepsilon}}\mathbf{G}\mathbf{B}^d \hat{\mathbf{d}}^d y^d p \mathbf{i} + \hat{\boldsymbol{\varepsilon}}\mathbf{B}\hat{\mathbf{d}} y p \mathbf{v} \tag{3.18}$$

Based on this equation, the total energy use change can be decomposed into the parts associated with changes in technology ($\mathbf{G}$) and related to changes in final demand, which can be further broken down into population change (p), the per capita level effect (y and y^d), the distribution effect ($\hat{\mathbf{d}}$ and $\hat{\mathbf{d}}^d$) and the product mix effect ($\mathbf{B}$ and $\mathbf{B}^d$),

$$\Delta \mathbf{e}_{TEU} = \Delta \mathbf{e}_{\mathbf{G}} + \Delta \mathbf{e}_{\mathbf{B}} + \Delta \mathbf{e}_{\mathbf{d}} + \Delta \mathbf{e}_{y} + \Delta \mathbf{e}_{p} \tag{3.19}$$

There are many ideal decomposition methods reported in previous studies. According to the guidelines for decomposition method selection proposed by Ang [2004] and Su and Ang [2012b], the logarithmic mean Divisia index method (LMDI)[1] is adopted to decompose the driving forces of energy use. LMDI was first introduced by Ang and Choi [1997] and first applied to energy study by Wachsmann et al. [2009]. It provides an ideal decomposition and is time–reversal invariant and easy to use. The effects described in

[1] I adopt the advice from Su Bin and Zhang You Guo to explain the LMDI decomposition method.

Equation (3.19) can be estimated by

$$\Delta \mathbf{e_v} = \sum_{m,n,o} \bar{\mathbf{e}}_{\mathbf{v}}^{D} \Delta ln \mathbf{v} \tag{3.20}$$

where $\mathbf{v}$ refers to factors $\mathbf{G}$, $\mathbf{B}$, $\mathbf{d}$, y and p; $\bar{\mathbf{e}}_{\mathbf{v}}^{D} = L(\mathbf{e_v}^T, \mathbf{e_v}^0)$[1] is the logarithmic mean function. The detailed formulations are summarized in Appendix D. The zero and negative value problems in LMDI are resolved with the "analytical limits" (AL) strategy recommended by Ang and Liu [2007a,b] and Wood and Lenzen [2006].

3.3 The data

The main data requirement for this analysis is hybrid I–O tables, where monetary energy flows in the original I–O table are replaced by physical energy flows. The hybrid I–O table integrates the I–O table with the energy balance table, both of which are available from public statistics.

The original I–O tables used in this study are competitive import type tables (Table 3.1), which have been compiled by the Chinese National Bureau of Statistics (NBS) every five years since 1987. I use five Chinese I–O tables for the years 1992, 1997, 2002, 2007 and 2010 [NBS, 1996, 1999, 2006b, 2009, 2012e]; the first four of them are benchmark I–O tables, and the last one is updated from 2007 by NBS. The analysis of energy use changes over time requires a constant price for these I–O tables. I use the price indices published by the NBS [2012c,d] and the methods suggested by Liu and Peng [2010] and Su and Ang [2012b] to deflate the I–O tables to constant 2000 prices. The national production activities are divided into twenty–eight sectors as Table 3.3 shows, six of which are energy–related industries[2]. Final demands, which are sourced from seven categories,

[1] $L(a, b) = (a, b)/(lna - lnb)$ for $a \neq b, L(a, b) = a$ for $a = b$.

[2] The I–O tables for 2002, 2007 and 2010 count "extraction of crude petroleum and natural gas" in one sector because petroleum and natural gas are byproducts. I split inputs (column data) in this sector into two sectors based on the production share of crude petroleum and natural gas. The outputs (row

and imports[1] are shown in Table 3.4.

Table 3.3
Sector classification in the hybrid input–output table.

ID28	ID09	Sector classification	ID28	ID09	Sector classification
S01	S01	Mining and washing of coal	S15	S03	Chemicals and chemical products
S02	S01	Extraction of crude petroleum	S16	S04	Non-metallic mineral products
S03	S01	Extraction of natural gas	S17	S05	Basic metals
S04	S01	Refined petroleum products and nuclear fuels	S18	S05	Metal products
S05	S01	Coking, production and distribution of Gas	S19	S06	Machinery and equipment
S06	S01	Electricity, steam production and supply	S20	S06	Transport equipment
S07	S02	Agriculture, forestry, and fishing	S21	S06	Electric machinery and equipment
S08	S05	Mining of metal ores	S22	S06	Electric and telecommunication Equipment
S09	S04	Other mining and quarrying	S23	S06	Measuring Instrument and Machinery for Cultural Activity & Office Work
S10	S02	Food and tobacco products	S24	S06	Artwork, other manufacture, waste, materials recovery
S11	S02	Textiles	S25	S06	Water production and distribution
S12	S02	Wearing apparel, leather, and related products	S26	S07	Construction
S13	S02	Sawmilling and furniture	S27	S08	Traffic, transport, storage and post
S14	S02	Paper and paper products, printing and reproduction of recorded media	S28	S09	Commerce and service

Source: Author.

Table 3.4
Final demand categories in the hybrid input–output table.

ID	Final demand categories	Energy deliveries to final demand categories
F1	Rural Household Consumption Expenditure	Rural Residential Consumption
F2	Urban Household Consumption Expenditure	Urban Residential Consumption
F3	Government Consumption Expenditure	
F4	Gross Fixed Capital Formation	
F5	Changes in Inventories	Stock Changes
F6	Exports	Exports
F7	Errors	Statistical Difference
F8	Imports	Imports

Source: Author.

Physical energy flows are reported in the energy balance table. The columns in this table describe the balance in the sources of supply for each type of energy and its uses. Similarly to the I–O table, five energy balance tables for 1992, 1997, 2002, 2007 and 2010

data) to this sector are replaced by physical energy flows available from energy statistics. In China's I–O table, there are no direct natural gas flows to households but via the "gas supply and production" sector. In a hybrid I–O table, natural gas directly flows to all other sectors, and "gas supply and production" covers coke gas only. The I–O table for 2010 places coking and refined petroleum products in the same sector, but I separate it based on the figures in benchmark I–O table of 2007.

[1]Because the benchmark I–O table for 1992 reports net export data only, I use the ratio data from Li and Xue [1998] to split them into exports and imports. Thanks to Youguo Zhang for providing these data.

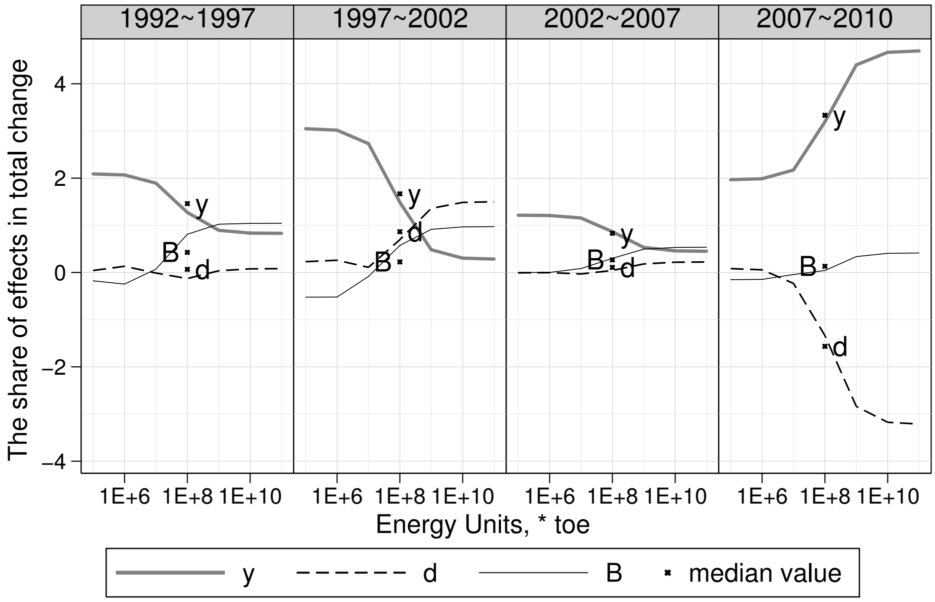


Figure 3.3: The share of effects in total energy use changes and energy units in China, 1992–2010.

Source: Author.

are used in this paper [NBS, 1998, 2010b, 2011b]. To combine the energy balance table with the I–O table, I aggregate energy types into six categories that correspond to the energy production sectors shown in Table 3.3. Making a transposition to this table, the rows of the new table present physical energy flows from the supply side to the demand side, which can be presented as an energy flow chart (see Figure 2.3 and Figure 2.4). In the hybrid I–O table, intermediate energy use covers energy flows to six energy sectors[1] and twenty–two non-energy sectors; energy consumption in the final demand sectors[2] includes energy deliveries to residences, stock exchanges, exports, statistical differences and imports. The relationship between the hybrid energy I–O table and the energy balance table is given in Table 3.3 and Table 3.4.

Dietzenbacher and Stage [2006] identified that the choice of monetary and energy

[1]Energy inputs to energy sectors are the sum of transformation inputs, energy sector own use and distribution losses.

[2]Direct energy use by the government is reported in the service sector according to NBS.

units would affect the estimation of level and mix effects when using the hybrid IO table. In order to overcome this problem, their proposed solution is based on using a sum of monetary units instead, which requires full information on the prices paid for the final demand energy. In this paper, I examine the impacts of the choosing different energy units on the decomposed effects (Figure 3.3). I found that the three effects — per capita level effect, distribution effect and mix effect — are determined by the choose of energy units. The shares of these effects in the change of total energy use follow a sigmoid function when energy unit shifting from 1E+5 to 1E+11 toe and monetary unit fixes on billion RMB(constant 2000 price). Most of these curves are symmetrical for the energy unit of 1E+8 toe, except in the period of 1992–1997, which might be caused by the inconsistency of energy statistics before and after 1996. The median values avoid the impacts from units on the decomposed effects. Thus, I choose "1E+8 toe" as the energy unit and "billion RMB" as the monetary unit in the calculation.

3.4 Results and discussions

3.4.1 Decomposition of total energy use

The energy flow chart provides a qualitative view of China's energy system. The energy I–O model proposed by Equation (3.14) allows us to quantitatively analyze China's energy use from the energy–demand side. In the energy I–O model, the total energy requirements are divided into household use and intermediate use. Intermediate energy use, $\hat{\boldsymbol{\varepsilon}}\mathbf{GF}^d$, measures the energy (in six energy types) embodied in domestically produced goods and services (from 28 sectors) that are consumed in seven final demand categories. It can be further broken down into direct use and indirect use or into domestic energy and imported if needed. The results are summarized in Figure 3.4, in which the total energy use by final demand categories, by energy types and by sectors is displayed. It should be noted that the energy figures displayed in Figure 3.4 are not from the energy supply side but from the energy demand side, so that the total coal use is not equal to its total primary supply.

The total energy use in terms of household consumption covers household use and energy embodied in the products that are consumed by households. It grew from 313 million toe in 1992 to 652 million toe in 2010, but its contribution to the total energy use fell from 42% in 1992 to 30% in 2010. This decreasing percentage is mainly due to a much faster growth in other final demand categories. Among the total energy use in household consumption, direct energy use, such as gas or coal for cooking, electricity for air conditioners, and gasoline for automobiles, accounts for only one–quarter, while more than three–quarters are embodied in the goods and services that are consumed by the household.

The energy embodied in the goods and services due to household consumption doubled between 1992 and 2010, 70 percent of which is attributable to indirect use, such as energy embodied in the materials employed to produce automobiles. With increasing household income, the composition of Chinese household expenditures shifted to energy–intensive products. Private expenditures on durable goods or energy–intensive goods, such as air conditioners and automobiles, has pushed household intermediate energy use growth but in small quantities. The increasing durable goods held by households caused the rising household use of secondary energy, such as electricity and petroleum products, which need more energy to produce in energy industries.

Increasingly, rural populations have migrated to urban areas due to urbanization, which is a result of modernization and industrialization. By the end of 2010, urban dwellers accounted for 50 percent of the total population for the first time in China's history [NBS, 2012b]. The gap of energy use between urban and rural households is getting wider. Compared to the relatively flat energy consumption in rural households, energy use in urban households tripled between 1992 and 2010. The recent Central Economic Working Conference underscored China's commitment to urbanization [Xin Hua News, 2013], which will boost domestic demand, thus advancing household energy use in the near future.

The energy use embodied in government consumption expenditures was kept nearly constant during 1992–2010. Its share in total energy use dropped to only four percent in 2010 from eight percent in 1992. In China's statistics, the direct energy use by the government is reported in the service sector, so only the intermediate energy use by the government is shown in Figure 3.4.

Investment activities — gross fixed capital formation and changes in inventories — are the main sources of China's current energy requirements. As Figure 3.4 shows, the energy embodied in gross fixed capital formation accounted for 39 percent of total energy use by 2010. It increased fourfold from 207 million toe in 1992 to 843 million toe in 2010, the highest growth rate in all final demand categories. The investment–led energy consumption boomed after 2002 when China became a member of WTO. The changes in inventories were responsible for less than five percent of total energy consumption. The increasing energy embodied in inventory after 2007 provided evidence of the overexpansion of investment in heavy industries, such as basic metals.

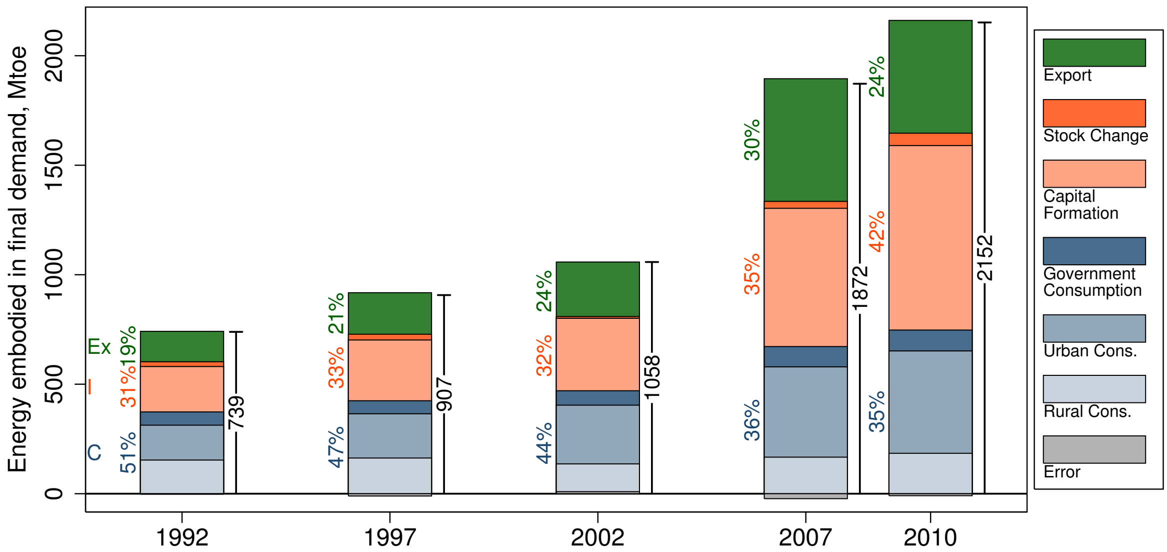
The boom in investment created a surge in industrial activity. As Figure 3.4 shows, the energy use for gross fixed capital formation mainly comes from construction (accounting for two–thirds) and equipment (accounting for one–fourth), two aggregated sectors. It should be noted that the energy required by the construction sector is not only direct energy use for construction itself but also indirect energy use for the material inputs to construction, such as the energy use in the production process of steel and cement, among others. The share of indirect energy use reached 93 percent of the total use due to investment activity (Figure 3.4), the highest in all final demand categories.

Exports — the demand from foreign countries — is the last final demand category that significantly affects the total energy demand in China. Since the 1990s, China has deeply participated in the international division to obtain a comparative advantage, such as cheap labor. Its total trade volume has experienced rapid expansion, at an average growth rate of 17 percent p.a. in the last three decades, accelerating to 22 percent p.a. after 2002[1] [NBS, 2010a, 2012b]. China's trade surplus expanded over the periods of 1994–1998 and 2003–2008 as a result of increasing foreign demand. It is interesting that the trade surplus soared after 2005, when RMB shifted to a managed floating exchange rate.

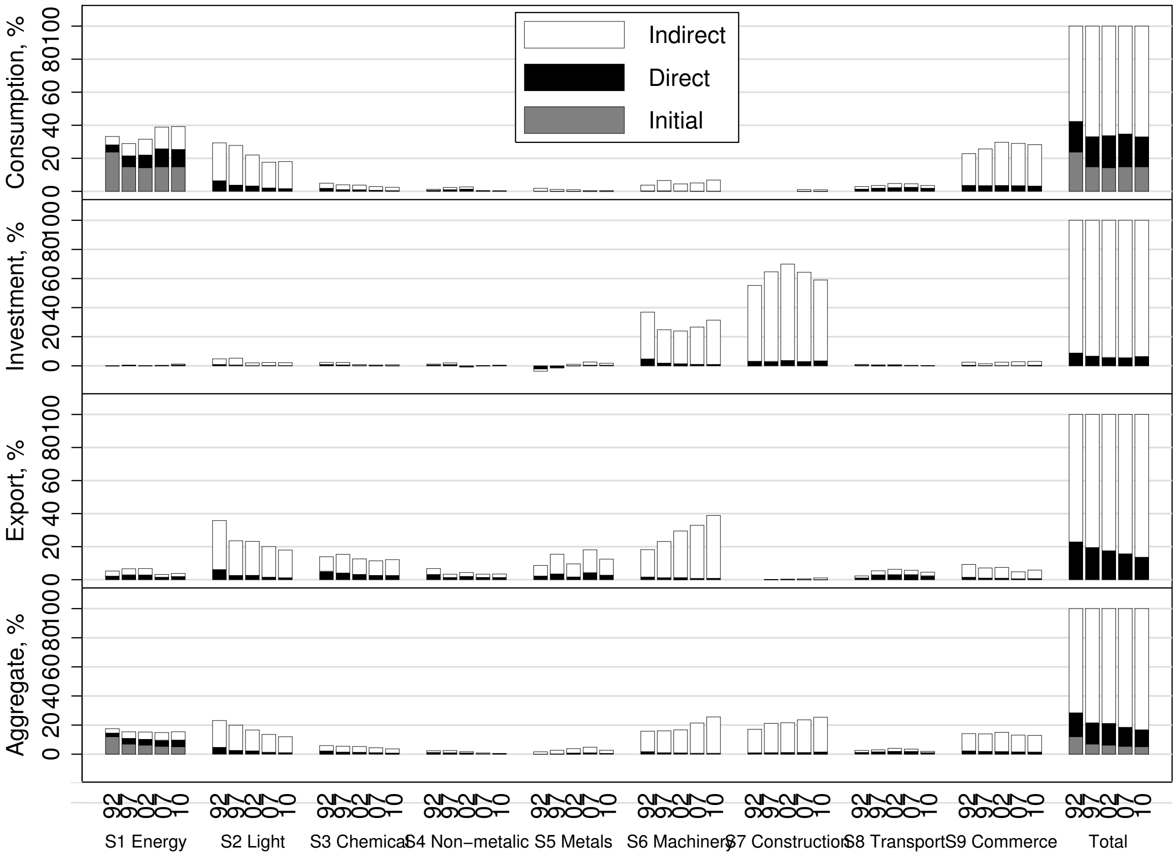
With exports expanding, the energy embodied in exported goods and services almost quadrupled during the period 1992–2010, only slightly slower than the gross fixed capital formation. During the period between 2002 and 2007, export–related energy use grew from 249 million toe to 560 million toe, doubling within five years. At the beginning, exports expanded mainly in light industries, such as textiles and apparel, later shifting to heavy industries, such as machinery and equipment. Exports now contribute to about one–quarter of the total energy use (24% percent in 2010). The "errors" in (Figure 3.4) represent the statistical difference in the I–O table.

As the discussion above, China's total energy use is embodied in the goods and services from the final demand categories of consumption, investment and export. From the import aspect, China avoids domestic energy use by imported goods and services. Under the assumption that imported goods and services are produced with the same technology as

[1] The growth rate is estimated based on trade in US dollars without considering the change in the foreign exchange rate.



(a) Embodied energy use by final demand category in China, 1992–2010.



(b) Embodied energy use by sector in China, 1992–2010.

Figure 3.4: Embodied energy use by final demand category and sector in China, 1992–2010.

Source: Author (*Notes*: See detailed industrial classification in Table 3.3).

domestic goods, the energy avoided by imports (EAI) can be estimated by the total energy use coefficient given in Equation (3.14). This EAI is a biased measure of embodied energy in imports, considering the difference of energy intensity between domestic and imported goods and services [Su and Ang, 2013; Weber et al., 2008]. According to the calculation, energy avoided by imports increased from 154 million toe in 1992 to 472 million toe in 2010 (Table 3.5). Imported goods and services mainly include raw materials and high–technology equipment, such as "Chemicals and chemical products", "Basic metals", "Machinery and equipment" and "Electric and telecommunication Equipment". The net effects of international trade activity on China's total energy use have climbed to 10 percent in 2007 from nearly balanced before 2002.

Table 3.5
Energy avoided by imports (EAI) in China, 1992–2010.

	Coal	Petro-leum	Natural Gas	Electricity Heat	Total	Share of TEU	Energy use by sector: Direct	Energy use by sector: Indirect
	M toe	M toe	M toe	M toe	M toe	%	M toe	M toe
1992 Energy Avoided by Imports	-104	-27	-4	-19	-154	-21%	-43	-110
1997 Energy Avoided by Imports	-116	-37	-5	-26	-185	-20%	-48	-137
2002 Energy Avoided by Imports	-152	-57	-10	-46	-264	-25%	-67	-197
2007 Energy Avoided by Imports	-251	-78	-18	-78	-425	-23%	-101	-324
2010 Energy Avoided by Imports	-264	-88	-26	-93	-472	-22%	-115	-357

Energy-Industry; Agriculture,Food, Textile, Wearing, Furniture, Paper; Chemical; Non-metallic; Metals; Machinery,equipment and other; Construction; Transport; Commerce and service

Source: Author.

3.4.2 Decomposition of energy use change

The differences of energy use in sub-periods provide the additive decomposition of total energy use changes by final demand category, energy type and sector, the result of which is displayed in Figure 3.5. Before 2002, China's total energy use increased at an almost uniform average annual growth rate[1] of four percent and three percent in the periods of 1992–1997 and 1997–2002, respectively. After 2002, however, it increased to twelve percent p.a. between 2002 and 2007 and slowed down to five percent p.a. during 2007–2010. The year 2002 is the break point for the trends of energy requirements in China.

[1]The average annual growth rate is defined as the geometric mean of percent change.

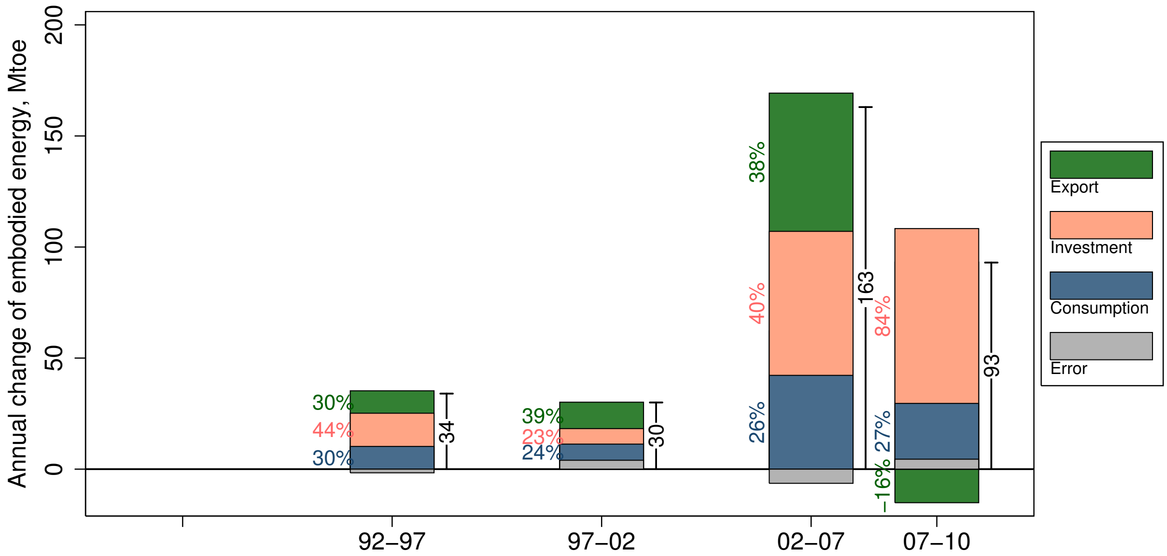
Similar to the total energy use indicated in the above subsection 3.4.1, the change in energy use in China mainly came from shifts in gross fixed capital formation, exports and household expenditures (mainly in urban areas). Before 2007, these three final demand categories each contributed to approximately one–third of the total energy use changes in China. After 2007, however, gross fixed capital formation shifts increased the total energy use by 211 million toe and accounted for up to 84% of the total change, while the energy embodied in exports decreased by 45 million toe. This is a result of the government's four trillion–RMB stimulus that was expected to offset the shrinking foreign demand caused by the global financial crisis in 2008 [Xin Hua News, 2008].

China's total energy use change is mainly due to indirect energy use. The "Gross fixed capital formation", for example, contributed to most of the total energy change, and over 90 percent of it came from indirect energy use, such as energy used to produce rebar. Before 2002, most energy increases in "Gross fixed capital formation" came from indirect energy use in construction. Since 2002, indirect energy use in machinery and equipment has become another major factor.

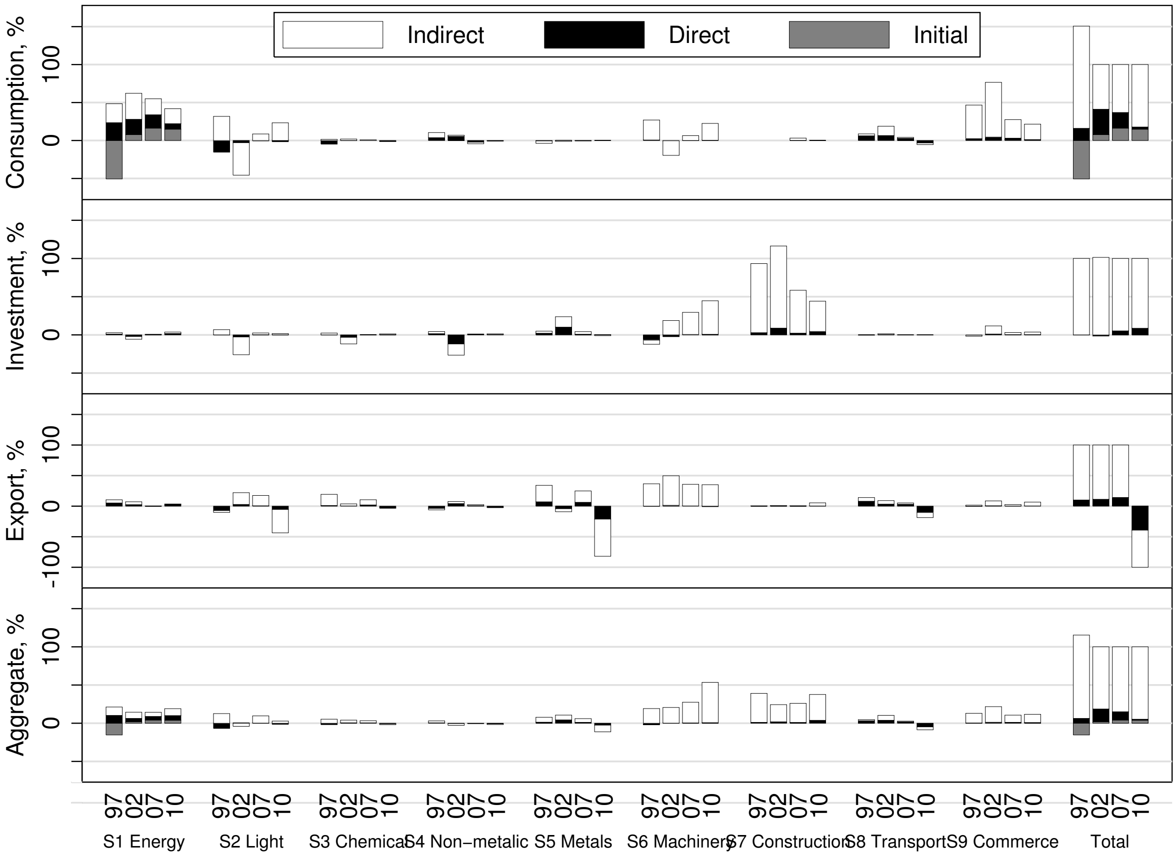
As mentioned above, the total energy use change can be decomposed into $6 \times 28 \times 7$ entries based on the energy I–O model, each of which is a product of technology coefficients ($\mathbf{G}$) (not included in household direct energy use change), product mix effects ($\mathbf{B}$), distribution effects ($\mathbf{d}$), final demand per capita level effects (y) and population effects (p). Using LMDI and the energy I–O model allows us to evaluate the impacts of the shift in each effect on the total energy use change. Table 3.6 displays the results of the SDA on China's energy use change by effects, by energy type and by sector.

The final demand changes[1] are the contributors that pushed the total growth in energy

[1] Here, the sub-level effects of the final demand for domestic products, $\mathbf{F}^d$, and of the final demand $\mathbf{F}$ are aggregated together, as Equation (3.19) shows.



(a) Changes of embodied energy use by final demand category in China, 1992–2010.



(b) Changes of embodied energy use by sector in China, 1992–2010.

Figure 3.5: Changes of embodied energy use by final demand category and sector in China, 1992–2010.

Source: Author (*Notes*: See detailed industrial classification in Table 3.3).

use. Keeping all other factors constant, the final demand changes, such as the level of economic activities or shifts toward more energy–intensive demands, increase the total energy use by nine percent, nine percent, fifteen percent and ten percent p.a. in the periods of 1992–1997, 1997–2002, 2002–2007 and 2007–2010, respectively. The impact of the final demand effect on energy requirement surged from 2002 to 2007, the first five years after China entered the WTO.

This rising pressure on energy demand associated with final demand shifts, however, was partly offset by changes in production technology, which reduced the total energy requirement per unit of goods and services. Holding all other factors unchanged, the improvement of production technology decreased the energy use at changeless annual rates of five percent, six percent, three percent and five percent in the periods of 1992–1997, 1997–2002, 2002–2007 and 2007–2010, respectively. The driving force of these energy savings was the improvement in the total energy use coefficients, especially for the final demands of energy–intensive goods and services from sectors such as "Construction", "Transport equipment", "Machinery and equipment", "Electric machinery and equipment" and "Chemicals and chemical products".

Between 2002 and 2007, the technological change in the construction sector abnormally increased the total energy use by 7 million toe, which caused the technology change effect to slow down to only three percent p.a. It should be highlighted again that the total energy savings are due to technological change not only from the final demand sector itself but also from those upstream sectors. Steel rebar, for example, which is produced by the sector of "Basic metals", is finally consumed in "construction", so that energy savings in "construction" cover the technological improvements in itself and also in "Basic metals".

The impact of final demand changes on the total energy requirements can be further decomposed into four different dimensions: the population effect (p), level per capita

Table 3.6
Changes in energy use by effects, energy type and sector in China, 1992–2010.

	Coal	Petro-leum	Natural Gas	Electricity Heat	Total	Change p.a.	Energy use change by sector	
							Direct	Indirect
	M toe	M toe	M toe	M toe	M toe	%	M toe	
Total change, 1992-1997	**81**	**50**	**2**	**36**	**168**	**4%**	**-2**	**170**
Final demand change	**246**	**70**	**7**	**48**	**371**	**9%**	**45**	**325**
Population effect	*29*	*8*	*1*	*5*	*42*	*1%*	*12*	*30*
Level per capita effect	*243*	*63*	*6*	*40*	*351*	*9%*	*98*	*254*
Distribution effect	*9*	*-1*	*0*	*1*	*9*	*0%*	*-2*	*10*
Products mix effect	*-36*	*1*	*0*	*3*	*-32*	*-1%*	*-62*	*31*
Technology change	-165	-20	-5	-13	-203	-5%	-48	-155
Total change, 1997-2002	**43**	**52**	**8**	**48**	**151**	**3%**	**48**	**103**
Final demand change	**274**	**103**	**9**	**66**	**452**	**9%**	**94**	**358**
Population effect	*24*	*7*	*1*	*5*	*37*	*1%*	*10*	*27*
Level per capita effect	*297*	*92*	*8*	*62*	*460*	*10%*	*122*	*338*
Distribution effect	*19*	*8*	*1*	*6*	*34*	*1%*	*4*	*30*
Products mix effect	*-66*	*-4*	*-1*	*-8*	*-79*	*-2%*	*-42*	*-37*
Technology change	-232	-51	-1	-17	-301	-6%	-46	-256
Total change, 2002-2007	**547**	**106**	**26**	**135**	**814**	**12%**	**177**	**637**
Final demand change	**653**	**182**	**24**	**164**	**1,022**	**15%**	**226**	**797**
Population effect	*25*	*8*	*1*	*6*	*40*	*1%*	*10*	*30*
Level per capita effect	*623*	*191*	*23*	*153*	*989*	*15%*	*251*	*738*
Distribution effect	*-17*	*2*	*1*	*8*	*-6*	*0%*	*-45*	*39*
Products mix effect	*23*	*-18*	*-1*	*-3*	*0*	*0%*	*10*	*-10*
Technology change	-106	-76	3	-29	-208	-3%	-48	-160
Total change, 2007-2010	**121**	**60**	**21**	**77**	**280**	**5%**	**40**	**240**
Final demand change	**353**	**92**	**16**	**98**	**560**	**10%**	**85**	**475**
Population effect	*18*	*5*	*1*	*5*	*29*	*1%*	*7*	*22*
Level per capita effect	*344*	*99*	*16*	*91*	*549*	*9%*	*131*	*418*
Distribution effect	*16*	*6*	*0*	*2*	*24*	*0%*	*-20*	*43*
Products mix effect	*-25*	*-17*	*0*	*0*	*-43*	*-1%*	*-34*	*-9*
Technology change	-232	-33	5	-21	-280	-5%	-45	-236

Energy-Industry; Agriculture,Food, Textile, Wearing, Furniture, Paper; Chemical; Non-metallic; Metals; Machinery,equipment and other; Construction; Transport; Commerce and service

Source: Author.

effect (y), distribution effect ($\mathbf{d}$) and products mix effect ($\mathbf{B}$). These effects are intercepts with each other and provide unique insights into the change in energy demand in China. An increasing population requires increased energy consumption. Between 1992 and 2010, the change in population caused around one percent of the total energy use growth annually, but this figure was in the process of being reduced. The per capita level effect caused almost all energy use growth that resulted from final demand shifts, which led China's total energy use growth at 9%, 9%, 15% and 9% annually in the periods of 1992–1997, 1997–2002, 2002–2007 and 2007–2010, respectively. The distribution effect has a minor but positive contribution to China's energy demand, which means the final demand has been shifting to energy intensive categories such as investment. In the periods of 1997–2002 and 2007–2010, especially, the distribution effect rose due to government fiscal stimulus that was expected to offset the weak export caused by financial crises in 1997 and 2008. The products mix effect has always cut the energy requirements since it in every final demand category is shifting to a lower energy intensive combination.

3.5 Limitations of this study

This study is based on the energy I–O model proposed in Equation (3.14), which assumes that a sector uses energy inputs in fixed proportions — the energy technical coefficient. As Miller and Blair [2009] noted, a Leontief production function is under the condition of constant returns to scale. This paper ignores the energy use change caused by shifts in the economies of production scale and the substitution of energy with other inputs such as labor or capital. Lin and Polenske [1995] suggest that the SDA should complement other types of analysis, such as econometric analysis.

This paper also ignores the effects of price change on total energy use in China. Since 2000, the international price of petroleum has risen from approximately 20 USD/bbl to currently approximately 100 USD/bbl. In the past three years, the international petroleum price (Brent) fluctuated around 100–120 USD/bbl, even though the commodity index (CCI) dropped by one–quarter. Given the negative real interest rate in most major economies, a higher oil price in the near future can be expected. Policymakers and consumers should pay attention to these rising oil price trends.

SDA requires a large amount of data; thus, the reliability of the statistics is crucial to the accuracy of the results. NBS began to publish China's energy balance table from 1980. The reliability of China's energy statistics (mainly coal) in the late 1990s and early 2000s has been questioned by many researchers [Sinton, 2001; Sinton and Fridley, 2002]. In 1998, China started to shut down small coalmines in order to cut the coalmine death toll and number of accidents, while many of those small coalmines reopened after this campaign.

NBS, however, did not report this part of coal production in its energy statistics. After China's second national economic census, NBS revised the energy statistics for the years between 1996 and 2007. Thus, there are changes in the definitions and coverage of energy data before and after 1996. These inconsistent energy statistics might cause the household use of coal to drop abnormally by 35 million toe from 1992 to 1997 (Figure 3.4).

Non-competitive import type I–O tables are required in this study. However, only competitive type I–O tables are available from the NBS. In section 3.2, I assume a fixed import ratio for each sector and non-direct export for imports when making non-competitive I–O tables, and a constant price index for both domestic and imported products when compiling I–O tables in constant prices. In addition, exports reported in China's I–O table cover not only normal exports but also processing/assembling fee. In the I–O table of 2007, for example, over 2% of total exports are processing fees. Different from normal exports, the processing fee does not cover any value of material. The energy embodied in the processing fee is very small, since it covers only direct energy use for processing/assembling. Thus, there is a slight overestimation in the energy embodied in exports in this analysis. Lau [2010] and Su and Ang [2013] provide detailed discussion on this topic. Although inaccuracies exist in China's statistics, these tables remain a starting point for this study.

The hybrid I–O tables used in this analysis are aggregated into 28 sectors, six of which are energy related sectors. The sector aggregation level affects the SDA results in some degree [Lin and Polenske, 1995; Su and Ang, 2012a; Su et al., 2010; Weber, 2009]. In general, a finer sector classification provides more detailed decomposition analysis on China's energy use changes. However, that detailed level of energy use, I–O and price index data is not available for every year and not compatible with each other. Here, I adopt a Monte Carlo simulation to examine the relationship between SDA results and sector numbers (Figure 3.6). This simulation is similar to the one designed by Weber

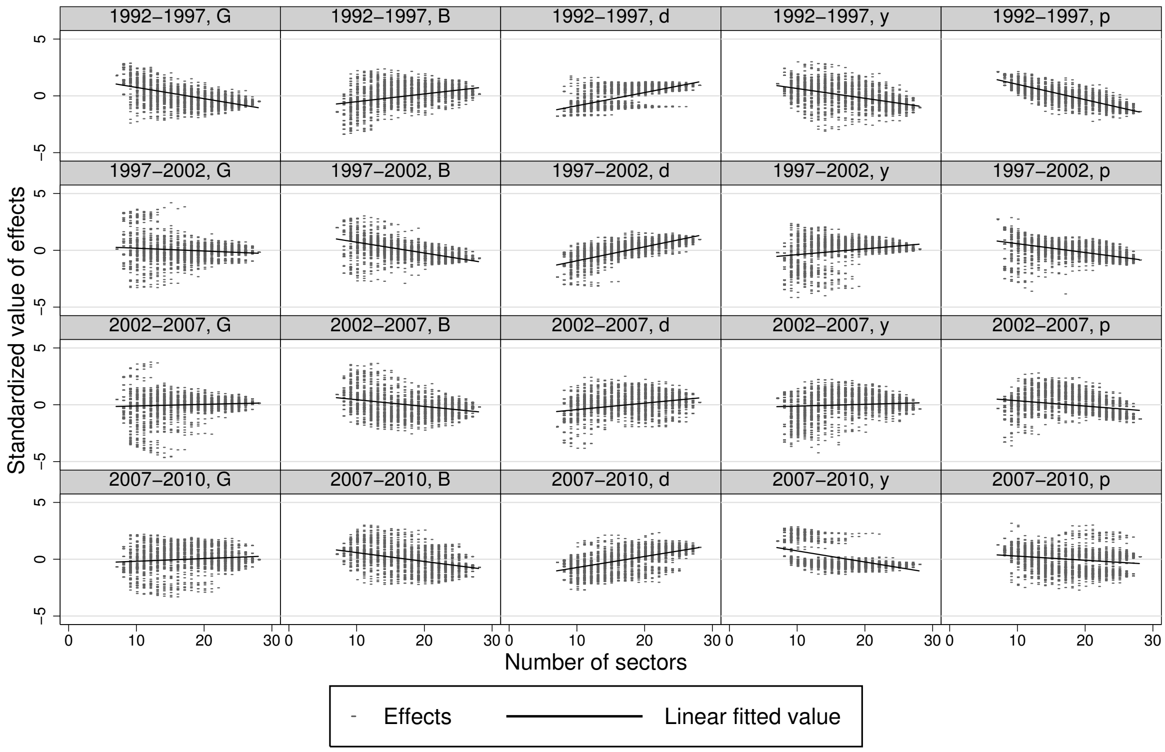


Figure 3.6: The standardized value of effects and sector aggregation levels.

Source: Author.

[2009]. The only modification I made is that the randomly chosen sector is aggregated with a sector directly before or after it, but not only directly after it. The effects that are displayed in Figure 3.6 are standardized values; and the sector number aggregated from 28 down to 7, considering only non-energy industries. As the simulation results shown in Figure 3.6, the linear fitted value of technology change effects (**G**) decrease with the increasing of sector disaggregation in the first two sub-periods, and keep almost constant during the periods of 2002–2007 and 2007–2010. The distribution effects (**d**) become more important with the increasing of sector numbers, and the variances of the SDA results are reduced with the increasing of disaggregation level, which might be determined by the possibilities of sector combinations. Let's keep these limitations and uncertainties of SDA in mind.

3.6 Conclusions and policy implications

This chapter analyzed the drivers of energy use in China from 1992 to 2010 by adopting the hybrid input–output model and structural decomposition analysis (SDA). The conclusions can be summarized from both the demand–side and the supply–side.

From the demand side (the rows of the I–O table), increasing final demand from private consumption, investment and exports are the main factors that drive economic growth. The demand for energy is derived from the final demand for goods and services. The energy I–O model allows us to investigate both the direct and indirect effects of final demand changes on total energy requirements. The results show that the main energy challenge for China is a structural adjustment in final demand. The final demand structure indirectly determined the industrial structure in China's economy. For example, final demand for investment indirectly pushed heavy industry growth, such as steel and cement production.

According to the calculation, gross fixed capital formation, household consumption expenditures and exports are three main sources of China's total energy requirements. The impacts of these factors on total energy use shifted with the development of the economy. In the early 1990s, China experienced a high inflation regime (up to 27.7 in September 1994), and the Chinese government adopted a range of policies to support the economy, such as devaluing the RMB by one–third in 1994, tax reform in 1994 and state–owned enterprise (SOE) reform since 1992. In the 1990s, China's energy use was still mainly driven by household consumption, which accounted for about two–fifths of the total energy use (Figure 3.4), but its contribution to energy use change decreased from 31 percent (1992–1997) to 20 percent (1997–2002) (Figure 3.5). In contrast, the contribution of exports to the changes in energy use increased from 30 percent (1992–

1997) to 39 percent (1997–2002). In other words, China was shifting toward becoming an export–oriented economy in the 1990s.

However, trade surplus fell in the late 1990s, early 2000s and 2009. To offset the weakened demand abroad and to reduce overproduction, the Chinese government boosted investment through the construction of public infrastructure, such as China Western Development in 1999, Revitalize the Old Northeast Industrial Bases in 2003, the Rise of Central China Plan in 2004, the New Rural Reconstruction Movement in 2005, and the Economic Stimulus Plan in 2009, among others. In other words, investment has been a major factor driving China's economic growth in the past decade. The contribution of gross fixed capital formation to China's total energy use increased from approximately 30 percent before 2002 to 39 percent in 2010 (Figure 3.4), and its contribution to the change of energy use swelled to three–quarters during 2007–2010 (Figure 3.5). However, this investment–led economic growth is unsustainable because the heavy dependence on investment not only created energy and environmental problems but also increased systematic risk, including surging local government debt. According to the Chinese National Audit Office [NAO, 2013], the local government debt rose to 17.7 trillion RMB at the end of June 2013, up 70 percent from two and a half years before. It is urgent for China to switch its economy from export– and investment–based growth to domestic consumption–oriented growth.

With exports and investment driving economic growth, the income of Chinese households has reached the level at which energy–intensive goods are affordable. For example, the average vehicle holdings per urban household reached 0.22 in 2012. According to the results in section 3.4, household consumption has contributed 30 percent of the total energy use (Figure 3.4) and to one–quarter of the change in energy use (Figure 3.5) in 2010. Given China's population, which is greater than 1.3 billion people, and accelerating urbanization, the commercial and transportation sectors should expect to surpass the industrial sector as the main energy demand drivers in the future.

From the supply side (the columns of the I–O table), both increasing inputs, such as labor, capital, energy and materials, and improving the total–factor productivity can boost economic growth. The improvement of total–factor productivity allows an economy to use less energy to produce the same amount of outputs, which can be defined as the total–factor energy efficiency considering energy inputs. The total–factor energy efficiency consists of two components: technical efficiency and allocative efficiency [Farrell, 1957]. Technical efficiency is simply defined as the ratio of energy inputs over total outputs, and allocative efficiency refers to how an economy allocates inputs by proportion and geography.

This study discusses technical efficiency only. In the energy I–O model, the technical energy efficiency is given by the direct energy use coefficients matrix. Elements of that matrix are in the unit of toe/toe for energy sectors (because their total outputs are energy fuels) and of toe/RMB for non-energy sectors. According to the results (Table 3.6), the improvement of technical energy efficiency saved around five to six percent of total energy use annually in the periods of 1992–1997, 1997–2002 and 2007–2010. In the period of 2002–2007, however, technological change only reduced three percent of the total energy use because of the increasing indirect energy use coefficient in the construction sector. Finally, I have to emphasize that energy issues are derivatives of economic and societal development. These systemic issues cannot be solved once and for all. Chinese policymakers should continue to deepen reform to build up a market–based economy and energy system. The government should play an important role in providing public goods, such as energy security and the environment. Let markets but not governments organize the use and distribution of energy resources.

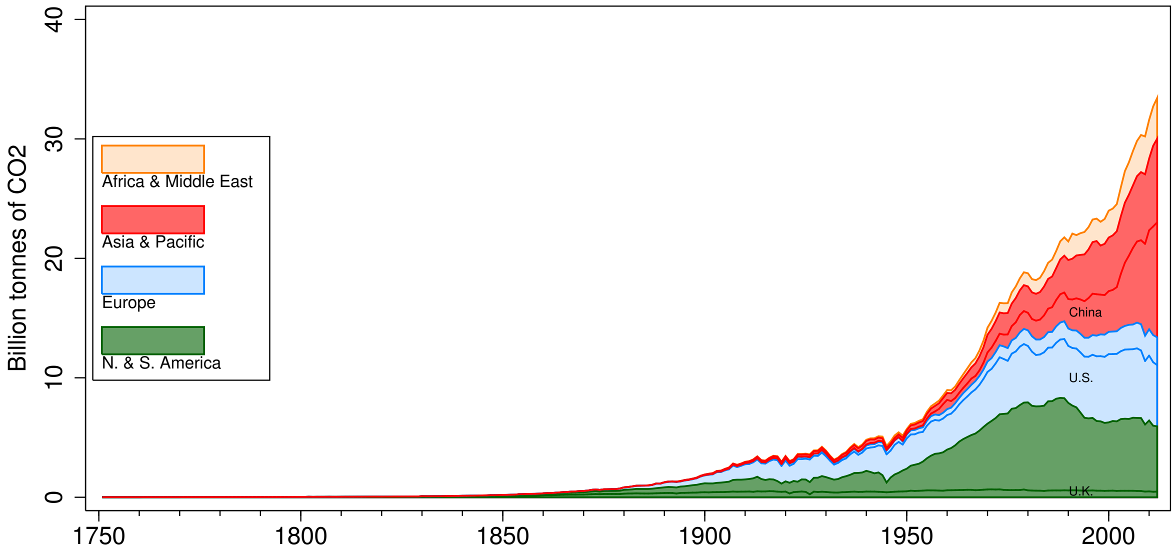
Chapter 4

Energy–related Carbon Embodied in Chinese Final Demand

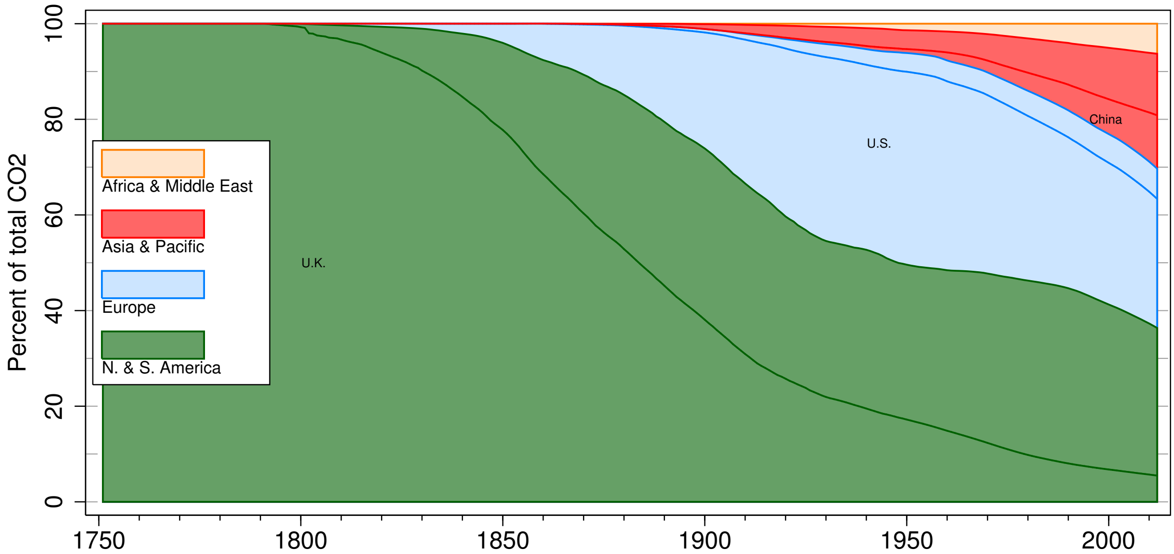
4.1 Introduction

The carbon dioxide (CO_2) concentration in the atmosphere reached 398 parts per million (ppm) in July 2014 [Dlugokencky and Tans, 2014], up to 44 percent from 277 ppm in 1750, the beginning of the Industrial Era [Joos and Spahni, 2008]. The carbon emissions from fossil-fuel combustion started before the Industrial Era and became the dominant source of anthropogenic emissions to the atmosphere up to the present [Le Quéré et al., 2014]. Global CO_2 emissions from the combustion of fossil fuels has reached a level unprecedented in human history — 35 billion tonnes for the year 2013 [BP, 2014]. The carbon emissions in China surged sharply since 2000, and it became the largest emitter in the world in 2006 and contributed 27% of global annual carbon emissions in 2012 [Le Quéré et al., 2014] (see Figure 4.1a). Its historical cumulative emissions climbed to 11% of the total in 2012, which is approximately 41% of the US [Le Quéré et al., 2014] (see Figure 4.1b). Though the Chinese government has committed itself to cut the CO_2 emission per unit of GDP in 2020 by 40 to 45% compared with the level of 2005 [Xin Hua News, 2009], its aggregate emissions are expected to rise further considering the projected sustained growth in economic output and household income.

CO_2 emissions are byproducts of energy consumption in economic activities. The emissions generated from construction, for example, are not only at the construction site, but also at the steel mill and cement plant. The emissions impacted by inter-industrial transactions or value chain can be described and explained by using the input–output model



(a) Annual emissions by region.



(b) Cumulative emissions by region.

Figure 4.1: Global CO2 emissions from fossil fuel combustion and cement manufacture, 1751–2012.

Data source: Friedlingstein et al. [2010]; Le Quéré et al. [2014]; Marland et al. [2003].

[Miller and Blair, 2009]. The embodied analysis of CO_2 emission (or more popularly, the carbon footprint [Minx et al., 2009; Turner et al., 2007; Wiedmann, 2009]) can be applied to identify emissions associated with economic activities and thus provides substantial policy implication to mitigate CO_2 emission and to allocate the emission responsibility

Chen et al. [2010]. There are numerous studies using or extending the environmental input–output framework developed by Leontief [1970] for carbon emissions embodied in final demand [Baiocchi and Minx, 2010; Davis and Caldeira, 2010; Hertwich and Peters, 2009; Lenzen, 1998; Mäenpää and Siikavirta, 2007; Peters, 2008; Roca and Serrano, 2007; Statistisches Bundesamt, 2011; Wood, 2009] or in international trade [Machado et al., 2001; Mongelli et al., 2006; Okamura et al., 2009; Peters and Hertwich, 2008; Peters et al., 2011; Rhee and Chung, 2006; Wiedmann et al., 2007].

The input–output analysis of China's embodiment CO_2 emission is also widely studied by researchers, in particular during the last decade when its emission growth accelerated. Peters et al. [2007] analyze the impacts of changes in China's technology, economic structure, urbanisation, and lifestyle on CO_2 emissions by using China's input–output data and structural decomposition analysis. They found that infrastructure construction and urban household consumption are responsible for most of the CO_2 emission growth in China from 1992 to 2002. Guan et al. [2008] assessed the driving forces of China's CO_2 emissions from 1980 to 2030. Their scenarios show that household consumption, capital investment and growth in exports will largely drive the increase in CO_2 emissions and efficiency improvements alone will not stabilize China's future emissions. Guan et al. [2009] adopted structural decomposition analysis to investigate the drivers of China's CO_2 emission from 2002 to 2005. Their study revealed that the speed of efficiency gains in production sectors cannot cope with the growth in emissions due to growth in final consumption and associated production processes. Chen and Zhang [2010] revealed the greenhouse gas emissions embodied in final consumption and international trade by using input–output analysis. Minx et al. [2011] found that efficiency improvement have largely offset additional CO_2 emissions and the strong increases in emissions growth between 2002 and 2007 are instead explained by structural change in China's economy.

There are also many previous studies appling the input–output model to assess CO_2 emissions embodied in China's international trade. Wang and Watson [2007] estimated the net exports accounted for 23% of China's total CO_2 emissions in 2004. Weber et al. [2008] found that around one-third of Chinese emissions in 2005 (1700 Mt) were due to production of exports. Pan et al. [2008] estimated China's consumption-based CO_2 emission as 3840 Mt in 2006, which is lower than the production–based 5500 Mt. It indicated that a reliable consumption-based accounting methodology is feasible and could improve our understanding of which states are responsible for emissions. Yunfeng and Laike [2010] found that 10.03–26.45% of China's annual CO_2 emissions are embodied in China's exports, in contrast to only 4.40–9.05% in China's imports from 1997 to 2007. Lin and Sun [2009] showed that net exports were responsible for 1024 million tons of CO_2 emission in 2005. Zhang [2011] applied structural decomposition analysis to evaluate the scale, composition and technique effects of carbon emissions embodied in China's trade from 1987 to 2007. Xu et al. [2011] decomposed the increases of CO_2 emissions embodied in China's exports from 2002 to 2008 into four driving forces. They found that the change of the export composition was the largest driver, due to the increasing fraction of metal products in China's exports. The CO_2 emissions embodied in bilateral trade such as China–US [Du et al., 2011; Guo et al., 2010; Shui and Harriss, 2006; Xu et al., 2009], China–UK [Li and Hewitt, 2008] and China–Japan [Dong et al., 2010; Liu et al., 2010] were also studied.

This chapter adopts environmental input–output framework to analyze the CO_2 emissions embodied in Chinese final demand from 1992 to 2010. This study differs from the previous analyses by using the hybrid input–output approach to minimize the price variations in embodiment emissions and doing analysis for 2007–2010 with the latest 2010 China I–O table. The remainder of this chapter is organized as follows. Section 4.2

describes the methodology of hybrid environmental I–O model and introduces the data sources for this analysis. Section 4.3 addresses the embodiment analysis for China's CO_2 emissions. Finally, the conclusions are presented in the section 4.4.

4.2 Methodology and data

4.2.1 Environmental input–output model

The input–output model has been extended by many researchers to account for environmental pollution generation and abatement associated with interindustry activity. Miller and Blair [2009] classified the environmental input–output models into three categories. First, generalized input–output models are formed by augmenting the technical coefficient matrix with additional rows and/or columns to reflect pollution generation and abatement activities. Its most common model is known as the direct coefficients approach, which measures emissions by the products of total output and the emission coefficients. Second, the economic–ecologic models extend the interindustry framework to include additional "ecosystem" sectors, which require substantial data between economic and ecosystem sectors. Third, commodity–by–industry models express environmental factors as "commodities" in a commodity–by–industry input–output table, which is known as the hybrid units approach.

In this chapter, I extend the hybrid energy input–output model explained in chapter 3 to consider CO_2 emissions generated by fuel combustion. In the hybrid energy input–output model, the monetary energy flows are replaced by physical energy flows. The hybrid environmental input–output model converts the physical energy flows to corresponding CO_2 emissions. CO_2 emissions are estimated using the reference approach provided by IPCC [2006]. In general, CO_2 emissions are calculated by multiplying fuel consumption by the corresponding emission factor, $Emissions = \sum_{Fuel} Fuel\ Consumption_{Fuel} \cdot$

$Emission\ Factor_{Fuel}$.

Just the same as the accounting of total energy use in Equation (3.13), total CO_2 emissions equal the sum of emissions in intermediate sectors and in households, which is expressed as

$$\mathbf{c} = (\mathbf{J} - \mathbf{S}_c \hat{\boldsymbol{\eta}}_c) \circ \mathbf{C}_I \mathbf{i} + \mathbf{c}_H \tag{4.1}$$

The $m \times 1$ vectors of $\mathbf{c}$ and $\mathbf{c}_H$ are total CO_2 emissions and household CO_2 emissions respectively. $\mathbf{J}$ is a $n \times n$ matrix of ones; $\mathbf{S}_c$ is a $n \times n$ matrix, elements of which are share of carbon embodied in outputs over inputs for energy transformation sectors and zeros for all the other sectors; the $n \times 1$ vector $\boldsymbol{\eta}_c$ is introduced to avoid double accounting, elements of which are the carbon transformation efficiencies in corresponding energy sectors and zeros for all of the other sectors. The matrix $\mathbf{C}_I = \hat{\boldsymbol{\varepsilon}} \mathbf{A}_c \mathbf{x}_c$ refers to CO_2 emissions from combustible fuels and CO_2 embodied in electricity. Based on the non-competitive import type I–O model, the hybrid output can be expressed as the product of domestic Leontief inverse matrix and final demand of domestic goods, $\mathbf{x}_c = \mathbf{L}_c^d \mathbf{F}_c^d$. Therefore, $(\mathbf{J} - \mathbf{S}_c \hat{\boldsymbol{\eta}}_c) \circ \mathbf{C}_I$ refers to intermediate CO_2 emission that eliminates double accounting.

Similar to the total energy use in Equation (3.13), the total CO_2 emissions can be expressed as

$$\mathbf{c} = \hat{\boldsymbol{\varepsilon}}(\mathbf{J} - \mathbf{S}_c \hat{\boldsymbol{\eta}}_c) \circ \mathbf{A} \mathbf{L}_c^d \mathbf{F}_c^d \mathbf{i} + \hat{\boldsymbol{\varepsilon}} \mathbf{F}_c \mathbf{v} = \hat{\boldsymbol{\varepsilon}} \tilde{\mathbf{A}}_c \mathbf{L}_c^d \mathbf{F}_c^d \mathbf{i} + \hat{\boldsymbol{\varepsilon}} \mathbf{F}_c \mathbf{v} \tag{4.2}$$

where $\tilde{\mathbf{A}}_c = \hat{\boldsymbol{\varepsilon}}(\mathbf{J} - \mathbf{S}_c \hat{\boldsymbol{\eta}}_c) \circ \mathbf{A}_c$ is the $m \times n$ matrix of direct emission coefficients; $\hat{\boldsymbol{\varepsilon}} \mathbf{G}_c = \hat{\boldsymbol{\varepsilon}} \tilde{\mathbf{A}}_c \mathbf{L}_c^d$ is the $m \times n$ matrix of total emission coefficients; $\hat{\boldsymbol{\varepsilon}} \mathbf{G}_c \mathbf{F}_c^d \mathbf{i}$ represents intermediate emissions; $\hat{\boldsymbol{\varepsilon}} \mathbf{F}_c \mathbf{v}$ is the emissions from household; $\mathbf{v}$ is the $o \times 1$ vector consisting of ones for households and zeros for all of the other final demand categories.

The hybrid approach has a number of positive features compared to other environmental input–output models. First, the emissions by fuel types are explicitly identified. Second, the hybrid input–output model minimizes the price variations in energy supply. Third and most important, the direct coefficients input–output model assumes both direct and indirect emission coefficients are the same,

$$\mathbf{c} = \mathbf{ef}'\mathbf{L}^d\mathbf{F}^d = \mathbf{ef}'[\underbrace{(\mathbf{I})\mathbf{F}^d\mathbf{i}}_{Initial} + \underbrace{(\mathbf{A}^d)\mathbf{F}^d\mathbf{i}}_{Direct} + \underbrace{(\mathbf{L}^d - \mathbf{I})\mathbf{F}^d\mathbf{i}}_{Indirect}] \tag{4.3}$$

where $\mathbf{ef}'$ refers to carbon emission per unit of output. However, the hybrid I–O model maintains the original emission coefficients for each sector,

$$\mathbf{c} = \underbrace{\hat{\boldsymbol{\varepsilon}}\mathbf{F}\mathbf{v}}_{Initial} + \underbrace{\hat{\boldsymbol{\varepsilon}}\tilde{\mathbf{A}}\mathbf{F}^d\mathbf{i}}_{Direct} + \underbrace{\hat{\boldsymbol{\varepsilon}}\tilde{\mathbf{A}}(\mathbf{L}^d - \mathbf{I})\mathbf{F}^d\mathbf{i}}_{Indirect} \tag{4.4}$$

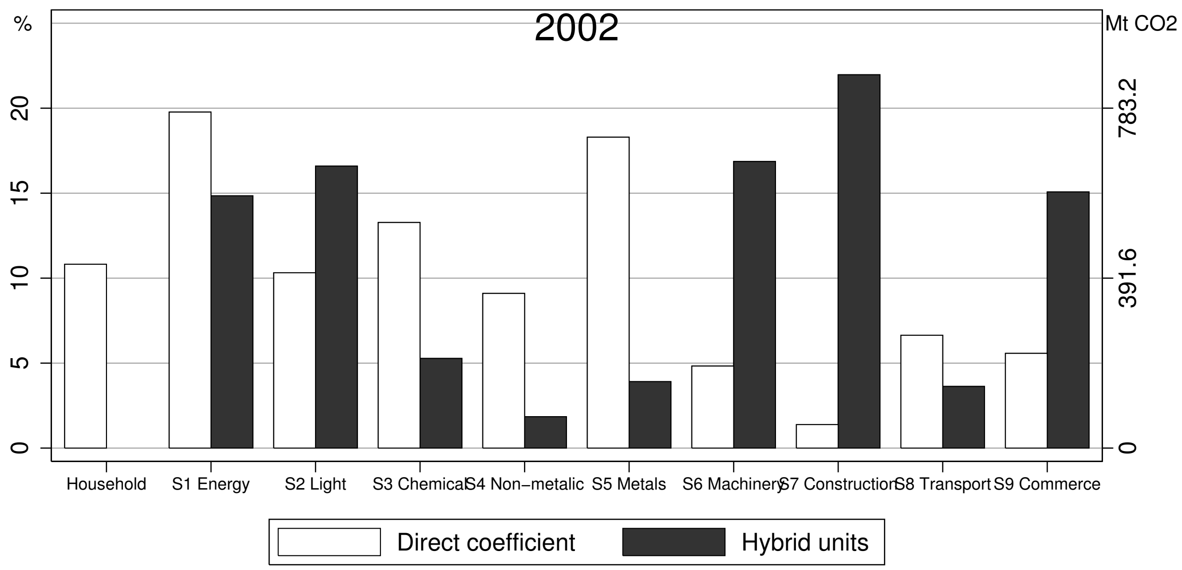


Figure 4.2: Embodied CO_2 emission by sector in 2002.

Source: Author (*Notes*: See detailed industrial classification in Table 3.3).

The CO_2 embodied in final demand is not only emitted from its producer but also from its upstream industries. For example, emissions associated with construction activity come not only from the construction site, but also the steel mill and cement plant. The hybrid environmental input-output model proposed in this study is able to account for all emissions associated with the final demand. However, as shown in Figure 4.2, the direct coefficient I-O model is still a producer–based CO_2 accounting model, although many previous studies adopt it to calculate the consumer–based CO_2 emission.

4.2.2 The data

Two main data sets are employed in this chapter: input–output tables and CO_2 emission data. I obtained the time-series I-O tables from the Chinese National Bureau of Statistics (NBS) for the years of 1992, 1997, 2002, 2007 and 2010 with 118, 122, 124, 135 and 65 sectors, correspondingly [NBS, 1996, 1999, 2006b, 2009, 2012e]. The first four I–O tables are benchmark tables with detailed sectors; the fifth table is extended from the year 2007 by NBS with aggregated sectors. The number of sectors for I–O tables are aggregated into 28, which are treated the same as the descriptions in section 3.3. The final demand category in the Chinese input–output table consists of rural and urban households' consumption, government expenditure, capital formation, inventory changes and exports. As this chapter adopts the hybrid I–O model to analyze the emissions embodied in final demand, it is not necessary to deflate these input–output tables to constant prices.

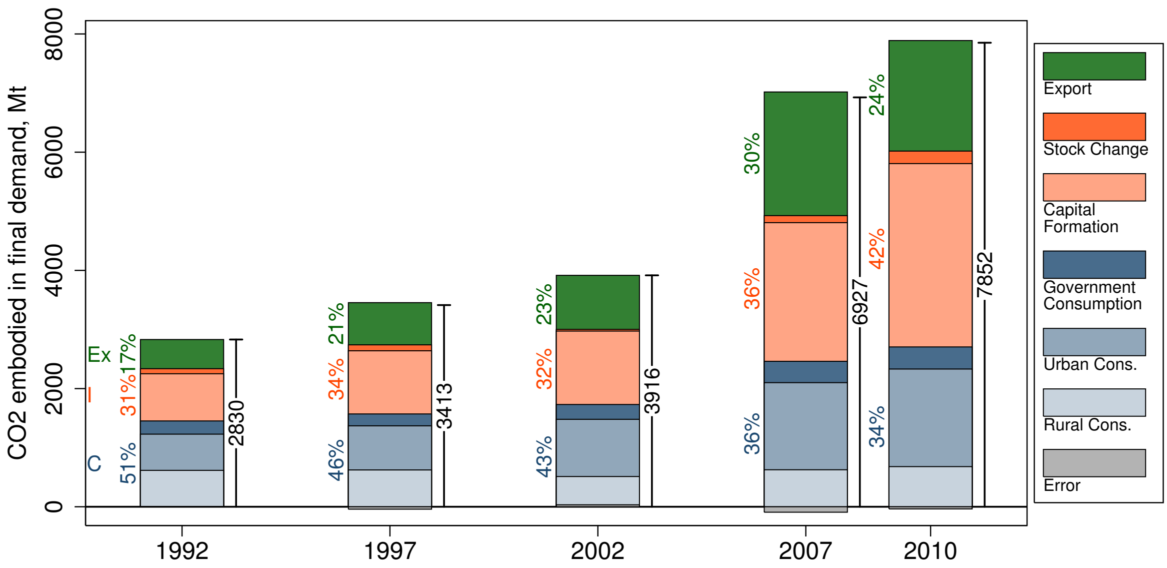
The calculation of energy related-CO_2 emission requires both fuel consumption data and the corresponding emission factors. The energy consumption data source from the energy balance table comes from the Chinese Energy Statistical Yearbook published by NBS [NBS, 1998, 2010b, 2011b]. The whole energy data set consists of 20 kinds of energies in both physical and net calorific units and is available at a 44-sectors level. The industrial energy use is aggregated into 28 sectors that are mapped to the input–output tables. Detailed treatments of the energy consumption data are provided in section 3.3. The emission factors are the default emission factors provided by IPCC [2006], which include the carbon contents (see Table B.1) and the carbon oxidation rate that is assumed to be one.

4.3 Results and discussions

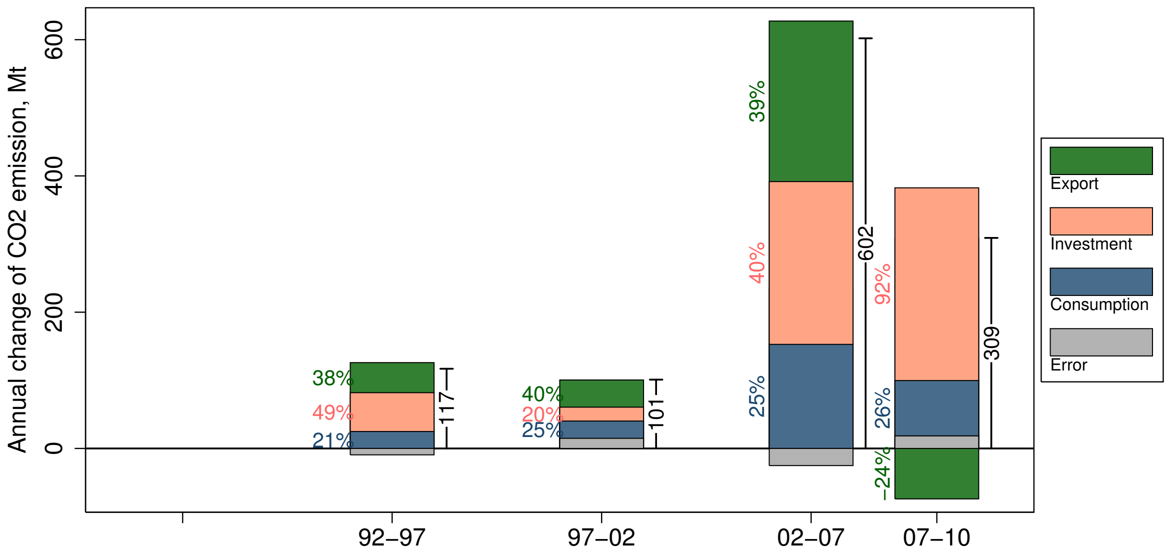
China's CO_2 emissions have increased by an exponential rate of 6% annually from 2,830 million tons (Mt) in 1992 to 7,852 Mt in 2010 (see Figure 4.3a,). The year of 2002 is the break point for Chinese CO_2 emissions. It grew at an exponential rate of 3% annually from 1992 to 2002, while its growth rate surged to 9% annually after 2002. Since the emissions are calculated by using the default emission factor, these estimated figures have differences from −5% to 6% comparing with the values provided by Le Quéré et al. [2014].

The total outputs of an economy consist of three major final demand categories: consumption, investment and exports. The production of the goods and services in final demand would directly or indirectly cause CO_2 emissions. Consumption, which includes the goods and services demand in rural households, urban households and government, was one of the most important final demand categories in the year of 1992, with a share of 51% of Chinese CO_2 emissions. In 2010, consumption was responsible for only 34% of total CO_2 emissions (see Figure 4.3a). Though the share of consumption in total emissions decreased, CO_2 emissions embodied in the consumption growth from 1,446 Mt in 1992 to 2,705 Mt in 2010, 3.5 percent per annual (exponential rate). The changes in consumption contributed around one-fourth (21% to 26%) to total CO_2 emission growth among each period from 1992 to 2010 (see Figure 4.3b).

Household consumption is responsible for approximately 85% of the consumption ac-



(a) Aggregate CO_2 emission by final demand category.



(b) Annual change of CO_2 emission by final demand category.

Figure 4.3: CO_2 emission and its changes embodied in Chinese final demand, 1992–2010. Source: Author.

tivity related CO_2 emissions. The key drivers behind the growth of CO_2 emissions embodied in the household consumption are typically income level, consumption patterns, population and household structure [Arvesen et al., 2010; Baiocchi et al., 2010; Feng et al., 2011; Hertwich, 2005; Hubacek et al., 2009; Minx et al., 2011]. Since the launch of the

Reform and Opening-up policy in 1978, the disposable income in Chinese households has grown at an average rate of 13% p.a. and reached a level at which energy-intensive goods are affordable. For example, the average possession of cellular telephones, computers, televisions, and vehicles per urban household reached 2.13, 0.87, 1.36, 0.22 in 2012, respectively [NBS, 2012b]. The utilization and production of these durable goods caused direct and indirect CO_2 emission. For example, gasoline consumed by household vehicles releases the initial CO_2 emissions in 'S1-Energy Sectors', and the electricity uses for household appliances would cause indirect CO_2 emission in 'S1-Enerrgy Sector' (Figure 4.4). Figure 4.4 displays the increasing shares of 'S1-energy related sectors' and 'S6-Machinery and Equipment' in total CO_2 emissions embodied in consumption.

The urbanization process in China is one important factor that needs to be considered. People migrating from rural to urban areas led to a 108% growth in the urban and a 19% reduction in the rural population. By the end of 2010, urban dwellers accounted for 50 percent of the total population for the first time in China's history [NBS, 2012b]. According to my calculations, emission increase of 1,038 Mt and 69 Mt related to urban and rural household consumption, respectively. The decline in household size (number of people per household) from 3.96 in 1990 to 3.10 in 2010 contributed to energy use and CO_2 emissions. For example, more energy is required and more CO_2 emitted if there are more households, since the smaller households cut the per capita energy use efficiency and push per capita emissions [LIU and RAVEN, 2010].

Investment related CO_2 emission is the largest source for China's total emissions among the three major final demand categories, with a share of 42% in 2010 that rose from 31% in 1992 (see Figure 4.4). The average annual growth rate of emissions embodied in investment activity was 8% between 1992 and 2010, and surged to 13% p.a. after 2002, up 3.4 times from only 4% p.a. before 2002. The growing final demand for investment

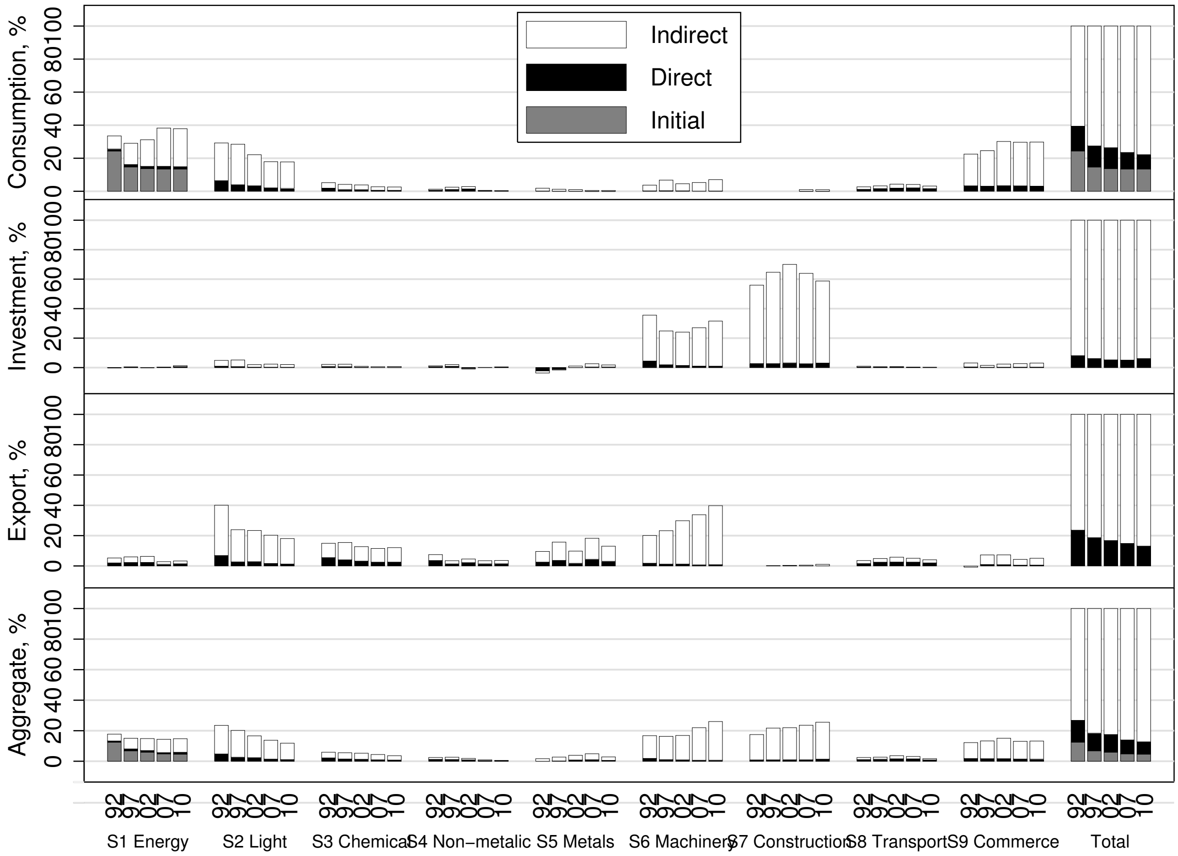


Figure 4.4: The initial, direct and indirect CO_2 emission, 1992–2010.

Source: Author (*Notes*: See detailed industrial classification in Table 3.3).

amounted to 2,430 Mt CO_2 between 1992 and 2010 (48% of total changes), of which 84% (2,043 Mt CO_2) occurred between 2002 and 2010. The period 2007–2010, especially, investment activity contributed 92% to total emission changes (see Figure 4.4).

As shown in Figure 4.4, around 56% – 70% of China's CO_2 emission embodied in investment between 1992 and 2010 are related to final demand for 'S7-Construction', 24% – 36% for 'S06-Machinery and equipment' and the remaining 6% – 10% for other sectors. The largest share for the sector of 'construction' in total emissions is primary due to its emission–intensive upstream industries, such as cement manufacturing, iron and steel production and electricity demand. Hence, one of the main sources for current embodied CO_2 emissions in China are the increasing final demand for construction services as a result of growing of 'Gross Fixed Capital Formation', such as, building of roads, rails, houses and other infrastructure.

The most rapidly growing final demand category is exports — the demand from the rest of the world. CO_2 emissions embodied in the goods and services that exported to the rest of the world increased from 494 Mt (17% of total emissions) in 1992 to 1,870 Mt (24% of total emissions) in 2010. The exports–related CO_2 emission growth rate reached 18% p.a. between 2002 and 2007, the period after China entered the WTO. As a result of the world finance crisis in 2008, the shrinking exports in China caused its embodied CO_2 emissions to drop by 11% between 2007 and 2010 from 2,092 Mt in 2007 (30% of total emissions).

The composition of exported goods and services is also changing. Energy–intensive and high–quality manufactured products grew strongly compared to the previous periods when the typically exported products were textiles, apparel and electrical devices. As Figure 4.4 shows, the share of emissions associated with the products in 'S2-Light Industries' and 'S3-Chemical' dropped slightly from 1992 to 2010, while it rose in 'S5-Metals' and 'S6-Machinery and Equipment'. This diversification of China's exported goods and services reveals the varying role of China in the global value chain, which has changed to high-end and more capital intensive products from being a producer of cheap, labor–intensive goods.

Equation (4.4) provides an estimate of initial, direct and indirect emissions. As shown in Figure 4.4, the share of indirect emissions grew from 73% to 87% in total CO_2 emissions in China. The growing indirect CO_2 emissions indicate the extending of the supply chain, which was one of three concepts used to describe the specialization of economics [Yang and Liu, 2008; Young, 1928]. The increasing of division and specialization of labor are associated with the growth of productivity and the capital deepening process. The changes of indirect emissions are also associated with economic structure change, which is the combination of the distribution effect across final demand categories and the product mix within each final demand category. As presented in Figure 4.4, both distribution effect and product mix pushed the growth in carbon-intensive industries, the supply chain of which requires more energy use and CO_2 emissions.

4.4 Conclusions and policy implications

This chapter adopted the environment input–output framework by using the hybrid units approach to investigate the energy–related carbon embodied in Chinese final demand between 1992 and 2010. The hybrid input–output model provides the estimate of emissions embodied in the industrial chain, which accounts for the consumption–based emissions on sectoral level.

This study shows that the year 2002 is the break point of the carbon emission trends in China. China's carbon emission accelerated after 2002 when China became a member of the WTO. The energy–related carbon embodied in the final demand category of consumption accounted for 51% of total carbon emission in 1992 and dropped to 34% in 2010. On the contrary, the carbon embodied in investment activity increased from 31% in 1992 to 42% in 2010. Exports contributed about one–fifth to overall emission. The trends of carbon embodied in Chinese final demand is similar to the embodied energy, which is determined by the change of economic structure.

The indirect energy use and carbon emission indicate the length of the roundabout production chain, or the roundaboutness of production, which describes the specialization of economics. The increasing of division and specialization of labor are associated with the growth of productivity and the capital deepening process. The calculation shows that the share of indirect CO_2 emission rose from 73% in 1992 to 87% in 2010, since the deepening division and specialization of labor coinciding with China's economic development. The changes of indirect CO_2 emissions are also determined by economic structure shifts, such as increasing dependence on investment activity and growing demand for carbon-intensive goods and services.

The increasing emission rate is equivalent to the increasing input of the environment. Given the scarcity of resources and technology, the emission abatement is the substitution between the environment and alternative inputs, such as labor, capital and energy. For example, if we upgrade incandescent light bulbs to LED, we can save electricity and thus reduce emissions. Hence, this is a substitution of energy and environment by capital since LED bulbs are much more expensive than incandescent bulbs. However, environmental resources are public goods that are non-exclusive and non-competitive. There are no private incentives to provide the public good — the environment. Economists describe this activity — emissions, which impose involuntary costs on others, as negative externality. Cheung [1970] pointed out that the externality is a fate concept. The nature of this problem is the transaction cost, which is the tradeoff between the exogenous transaction cost to a clearly delineated environmental property right and the endogenous transaction cost provoked by ambiguously defined environmental property rights. Coase [1960] perceptively noted that the institution does not matter in a world with zero transaction cost, where property rights are clearly delineated. However, when the cost of transactions is significant, institutions evolve endogenously to achieve efficient outcomes. The policies that can be used to reduce emissions include command–and–control regulations, emission taxes and tradable emissions permits. The proper policy should be one with minimum transaction costs. Finally, it should be noted that the CO_2 emission problem is derived from economic and social development. There is no once–and–for–all solutions for this social problem.

Chapter 5

Total–Factor Productivity and Energy–Saving Potential

5.1 Introduction

5.1.1 Economic growth and energy

What makes one country wealthier than another? The question of economic growth is one of most important questions concerning economists. The theory of economic growth, correspondingly, is the oldest yet most fashionable subject in economics. Economic growth can be driven by either growth in inputs, such as human resources, capital stock and natural resources (such as energy), or growth in productivity (the output per unit of input), such as technology and entrepreneurship [Samuelson and Nordhaus, 2009].

In classical economics, Smith and Nicholson [1887] systematically investigated the implications of the division of labor for wealth creation and the prosperity of nations. Smith pointed out that the division of labor is limited by the extent of the market and the extent of the market is affected by transportation efficiency. He also proposed that capital is a vehicle for increasing the division of labor in roundabout productive activities.

In neoclassical economics, Schumpeter [1934] pointed out that "new combination of means of production" is the fundamental phenomenon of economic development. It is vertical innovations that lead to the replacement of incumbent firms through a process of creative destruction. Harrod [1939] and Domar [1946] developed exogenous growth models involving both capital stock and labor. The Harrod–Domar model is at best balanced on a knife–edge of equilibrium growth, since three key parameters — the savings ratio, the investment coefficient (for each unit of increase in income) and the rate of increase of labor are exogenously given. Solow [1956] specified a Cobb–Douglas production function, in addition to the saving equation, income and investment identities, and market clearing condition for investment. Due to the diminishing marginal returns in neoclassical production function, long–term per capita income in the Solow model will converge to a steady state and stay there forever if the parameters are fixed. According to the hypothesis that technical change can be ascribed to experience, Arrow [1962] provided a so–called "learning by doing" model, in which technological progress is given as an endogenous parameter. Since the mid of 1980s, researchers such as Romer [1986] and Lucas [1988] developed the new or endogenous growth theory which holds that economic growth is primarily the result of endogenous forces, such as the investment in human capital, innovation, and knowledge. The theory also focuses on positive externalities and spillover effects of a knowledge–based economy that will lead to economic development.

Although there are a large number of studies that focus on economic growth, the importance of energy in economic growth was not present in economic studies until the 1973 oil crisis. Since the 1973 oil crisis, many studies have focued on the constraint on the economic growth potential in the long run due to the limited availability of fossil fuels. The seminal articles by Dasgupta and Heal [1974], Solow [1974] and Stiglitz [1974] (the DHSS model) introduced natural resources and the environment into the neoclassical economic growth model. They pointed out that the limitations imposed by natural resources can be offset by at least three economic forces: technical change, the substation of man–made capital for natural resources, and returns to scale. The DHSS model investigated the feasibility of sustained growth in consumption per capita given limited natural resources. Rasche and Tatom [1977] were the first to use a Cobb–Douglas production function accounts explicitly for not only labor and capital but also energy resources.

5.1.2 China's economic growth and energy

China's economy has sustained an average growth rate of 10 percent annually over the last three decades since the launch of the reform and opening–up policy in 1978. This growth is unprecedented in world history. There are plenty of debates on the sources of China's miraculous economic growth.

Krugman [1994] pointed out that Asia's miraculous growth in output could be fully explained by rapid growth in inputs: expansion of employment, increases in education levels [Young, 1995], and massive investment in physical capital.

Woo [1996] also claimed that China's economic growth is mainly driven by the expansion of inputs, among which capital accumulation contributes over half of aggregate growth. He pointed out that the total factor productivity (TFP) growth in China, which accounted for only 12–14 percent of aggregate growth in the period of 1979–1979 and for 3–6 percent of aggregate growth in 1985–1993, is the result of the reallocation of surplus agriculture labor to industry and service sectors.

Borensztein and Ostry [1996] compared the performance of the Chinese economy in the pre- and post- reform periods, and examined the durability of the contribution of efficiency gains that flowed from the reforms and from labor reallocation, as well as the feasibility of attempts to maintain rapid growth by boosting fixed investment. They found that the growth rate of TFP rose to an average 3.8 percent per year in the post-reform period from negative before reform. They also argued that true underlying productivity growth, in the sense of technological progress, was substantially lower.

Chen [1997] investigated the technological change or TFP as one source of economic growth in East Asian countries. He argued that the conclusions drawn by [Young, 1995] and Krugman [1994] are mainly based upon the assumption that TFP covers all technological change. He also discussed the prospects for East Asian economic growth and pointed out that East Asian economic growth is the result of hard work and good policies, but not a miracle.

Wu [2000] applied a stochastic frontier method to estimate provincial productivity growth in China during the period 1981–1995. He found that the pattern of TFP growth resembles a J-shaped curve, and that the main contributors to Chinese economic growth have changed from efficiency improvement and growth in inputs in the 1980s to technological progress in the 1990s. His study also showed that technical efficiency performance in China's regional economies has converged rapidly since the early 1980s.

Chow and Li [2002] extended the work of Chow [1993] to account for the economic growth in China as labor, capital and TFP by using a Cobb–Douglas production function and official Chinese data. They found that China's TFP grew at t about 3% annually during the period 1978–1998. Due to the expected high rate of capital formation of over 30% of GDP and the high capital elasticity of about 0.6, they also pointed out that the Chinese economy in the first decades of 21st century would still manage to grow at a substantial rate of at least 7%.

The investigation of Zheng et al. [2009] on China's sustained growth showed that reform measures often resulted in one–time level effects on total factor productivity. They said that China's growth strategy since the mid-1990s has emphasised capital formation at the expense of efficient allocation and utilization of production factors, which has led to a slowdown in TFP growth. They pointed out that China needs to adjust its reform program toward sustained increases in productivity.

Lee and Hong [2012] examined the factors that contributed to rapid economic performance in developing Asian countries from 1981 to 2007. They also found that the robust growth in capital accumulation generally marked the regions' economic expansion. While the contribution of labor input, education, and total factor productivity to GDP growth have been more moderate, they also have been positive on the whole as well.

However, the contribution of energy to China's economic growth that considers both labor and capital is rarely studied, with the exception of Hu and Wang [2006], who used the non-parametric method (data envelopment analysis, DEA) to estimate the index of total–factor energy efficiency in China. This chapter attempts to estimate a parametric econometric model — the stochastic frontier analysis (SFA) and translog production function, which is applied to panel data sets of labor, capital and energy at the provincial level over the period of 1990–2011. In addition, this study estimates the total–factor energy efficiency and the energy saving potential in China.

5.2 Total–factor energy efficiency and the translog stochastic production model

5.2.1 Efficiency and productivity

5.2.1.1 Total–factor energy efficiency

Energy efficiency is one of widely discussed energy policies at the forefront of energy and environmental issues. It reveals the relationship between energy input and economic output and between energy input and alternative inputs. The most widely used definition of energy efficiency is the energy:GDP ratio, also called energy intensity, which measures the relative change between energy and GDP. A systematic discussion on the definitions of energy efficiency can be found in the study by Patterson [1996]. According to the theory of dematerialization, energy intensity follows a bell–shaped pattern. It is determined by three fundamental factors: changes in the structure of final demand, increases in the efficiency of energy use, and the substitution of alternative inputs [Bernardini and Galli, 1993]. Chapter 3 provided the analysis of drivers of energy use from the demand–side by adopting the hybrid energy input–output model. The present chapter discusses the energy input from the supply–side by using the stochastic frontier analysis and translog production function.

This chapter addresses the total–factor energy efficiency (TFEE) as the consideration of multiple inputs — labor, capital and energy. Farrell [1957] was the first to measure efficiency which incorporates multiple inputs and yet avoids index number problems. The basic idea of Farrell's measurement on efficiency is the relative distance from the observed firm to production frontier. It is very difficult to specify a theoretically efficient production frontier, which is therefore estimated from observations of the inputs and outputs of a number of firms. Farrell [1957] proposed that the production frontier can be estimated by either a nonparametric method, such as total factor efficiency indices and data envelopment analysis (DEA), or a parametric method, such as least–squares econometric production model and stochastic frontier. This chapter adopts the translog production model and stochastic frontier analysis. Farrell [1957] proposed that economic efficiency consists of two components: technical efficiency and allocative efficiency, which reflects the ability of an economy to obtain maximum output from a given set of inputs and to use the inputs in optimal proportion if their respective prices are given, corresponding [Coelli, 1996].

Farrell's idea can be illustrated by using a simple example concerning firms that use two inputs to produce a single output. The SS' in Figure 5.1 represents the unit isoquant for firms with fully efficient, which allows us to measure technical efficiency. The point P defines a given firm that uses two inputs to produce a unit of single output. Technical inefficiency of the firm P, therefore, could be measured by the distance of QP, which is the quantity of two inputs that could be proportionally saved without a decrease in output

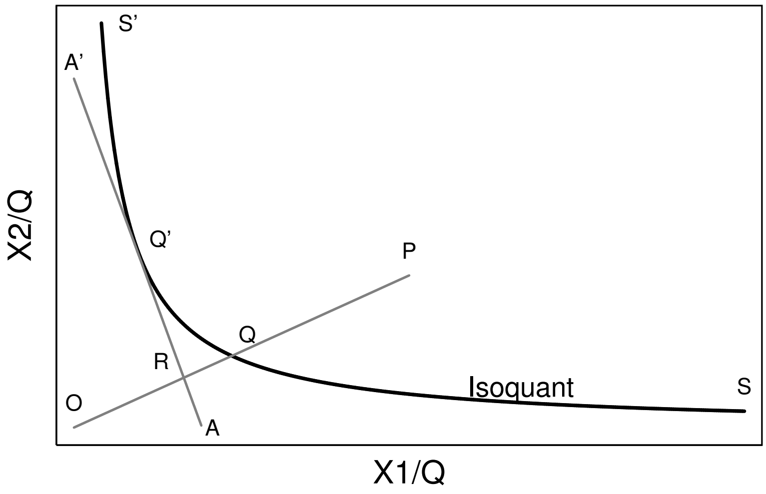


Figure 5.1: Technical and allocative efficiency.

Source: Coelli [2005].

[Coelli, 2005]. Hence, *technical efficiency (TE)* of P can be calculated by the ratio of

$$TE = OQ/OP \tag{5.1}$$

where the value of TE lies between zero and one, and evaluates the degree of the firm's technical efficiency. The fully technically efficient firm has a value of one for its TE. For example, the firm Q is technically efficient as it lies on the efficient isoquant.

If the price ratio of the two inputs, which is represented by the slope of the isocost line AA' in Figure 5.1, is known, then the *allocative efficiency (AE)*[1] of Q and also of P (because both of them are using factors in the same proportion) can be expressed as

$$AE = OR/OQ. \tag{5.2}$$

The distance of RQ represents the reduction of production costs if the production occurs in the firm Q', which is fully technically efficient and allocatively efficient, instead of in

[1] Farrell [1957] calls it as price efficiency

the firm Q, which is technically efficient but allocatively inefficient.

Given the measure of technical efficiency, the *total economic efficiency* of point P can be expressed as a product of allocative efficiency and technical efficiency:

$$EE = OR/OP = (OR/OQ) \times (OQ/OP) = AE \times TE. \tag{5.3}$$

Note that all three measures are bounded by zero and one. As opposed to the input–orientated measures discussed above, efficiency can be also calculated from output–orientated measures if there are multiple outputs. The output–oriented efficiency equivalent to the input–oriented efficiency for the production with constant returns to scale, but will be unequal for increasing or decreasing returns to scale [Farrell, 1957].

Besides the technology and allocative inputs discussed above, the operation scale also affects a firm's efficiency if the firm is using a variable–returns–to–scale (VRS) technology. As shown in Figure 5.2, the firm operating at point C is unable to become more productive by changing its operation scale. The point C is defined as the technical optimal production scale (TOPS) [Coelli, 2005]. The *scale efficiency (SE)* indicates the productivity that can be improved by moving to the operation scale at the point of TOPS. As Figure 5.2 shows, that the productivity of the firm operating at point D (as presented by the slope of the ray from the origin) could be improved by moving to point E on the VRS frontier (removing the technical inefficiency), and it could be further improved by moving to point B (removing scale inefficiency). Hence, the scale efficiency of firm D relating to the distance of EF is given by

$$SE = \frac{GF}{GE} = \frac{GF/GD}{GE/GD} = \frac{TE_{CRS}}{TE_{VRS}}. \tag{5.4}$$

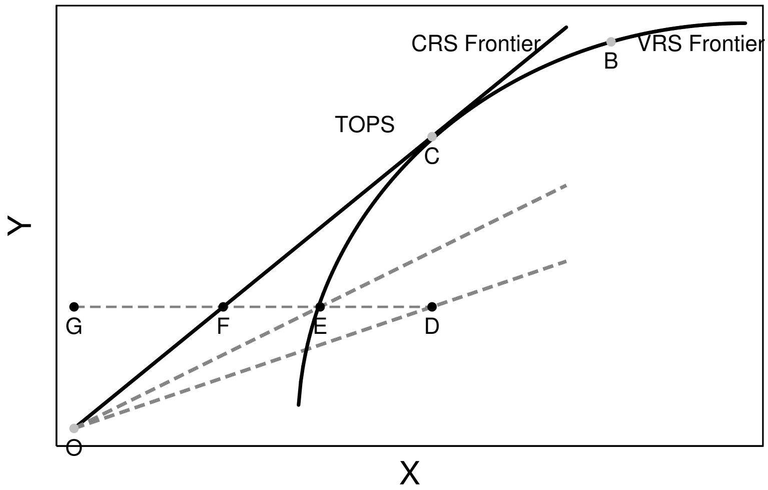


Figure 5.2: Scale efficiency.

Source: Coelli [2005].

5.2.1.2 *Total–factor productivity*

Productivity and efficiency are different concepts in economics. Total–factor productivity (TFP) growth is a residual, often called the Solow residual [Hulten, 2001; Solow, 1957], which accounts for the effects in total output not caused by inputs, such as labor, capital and energy. If all inputs are accounted for, then TFP growth can be taken as a measure of an economys long–term technological change.

Total–factor productivity growth as the Solow residual, which is the residual growth rate of output not explained by the growth in inputs, is given by

$$T\dot{F}P = \dot{y} - \sum \eta_i \dot{x}_i \tag{5.5}$$

where TFP, y, η and x_i refer to total factor productivity, output, output elasticity of input x_i and i-th input (labor, capital and energy), correspondingly. The dot $\dot{}$ over a variable indicates its growth rate, which can be approximated with either annual percentage change or first difference of log level variables, for example, $\dot{y} = (dy/dt)(1/y) = d\ln y/dt$.

Alternatively, the TFP growth can also expressed as a conventional Divisia index as

$$T\dot{F}P = \dot{y} - \sum \frac{w_i x_i}{C} \dot{x}_i \tag{5.6}$$

where w_i is the price of the i-th input, and C is the observed cost.

Bauer [1990] decomposed TFP growth into a technical change component, a technical efficiency change component, and a scale component:

$$T\dot{F}P = T\Delta + TE\Delta + \sum_i [\eta_i - s_i]\dot{x}_i \tag{5.7}$$

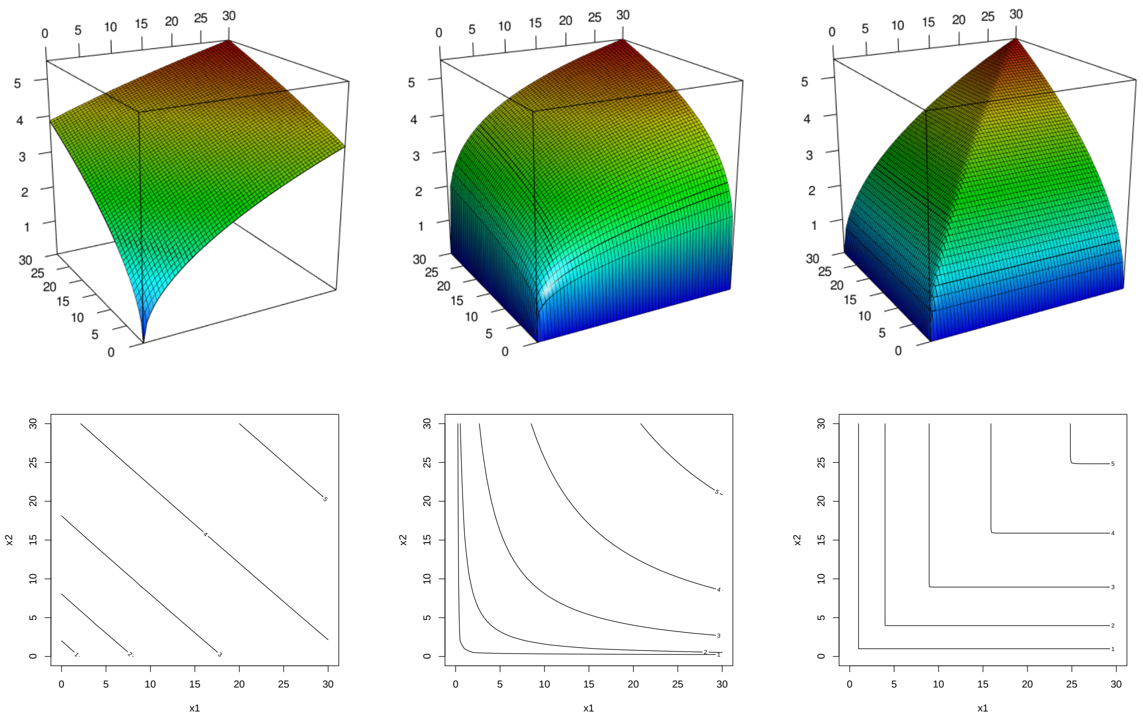
where $T\Delta = \partial \ln Y/\partial t$ refers to technical change; TE refers to technical efficiency and $TE\Delta$ refers to technical efficiency change; $\eta_i = (\partial y/y)/(\partial x_i/x_i) = \partial \ln y/\partial \ln x_i$ refers to the output elasticity of the i-th input; $s_i = \dfrac{w_i x_i}{C}$ is the observed share of the i-th input. Kumbhakar and Lovell [2000] provided a similar study on TFP growth decomposition.

5.2.2 Translog production function and stochastic frontier

5.2.2.1 Translog production function

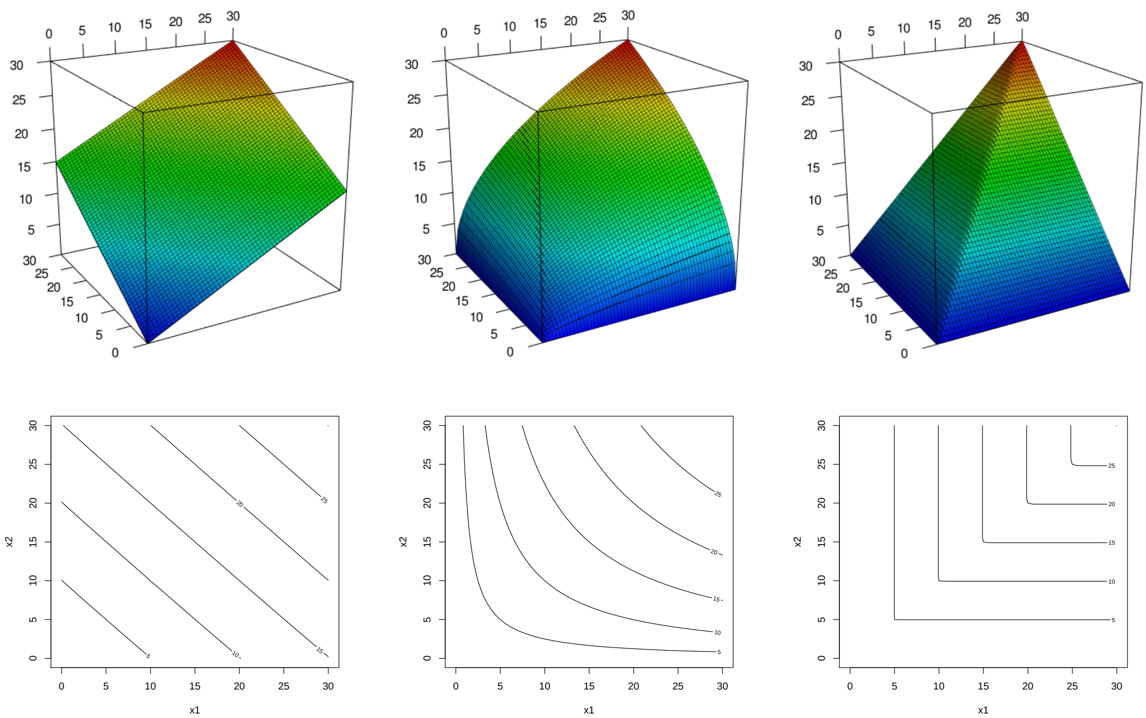
Since the 1950s, Samuelson's economics textbook included microeconomics, that is, Marshall's marginal analysis of demand and supply and macroeconomics incorporating Keynes economics which tries to explain phenomena that cannot be predicted by Marshall's marginal analysis [Yang et al., 2001]. Modern microeconomics is based on an unrealistic dichotomy between pure consumers and pure producers. Utility functions are used to describe individuals' preferences, and production functions and production sets are used to describe production conditions.

If Q represents output and $\mathbf{x}$ represents the vector of inputs in "physical" units, then the production function can be written as $Q = f(\mathbf{x})$. There are several properties asso-



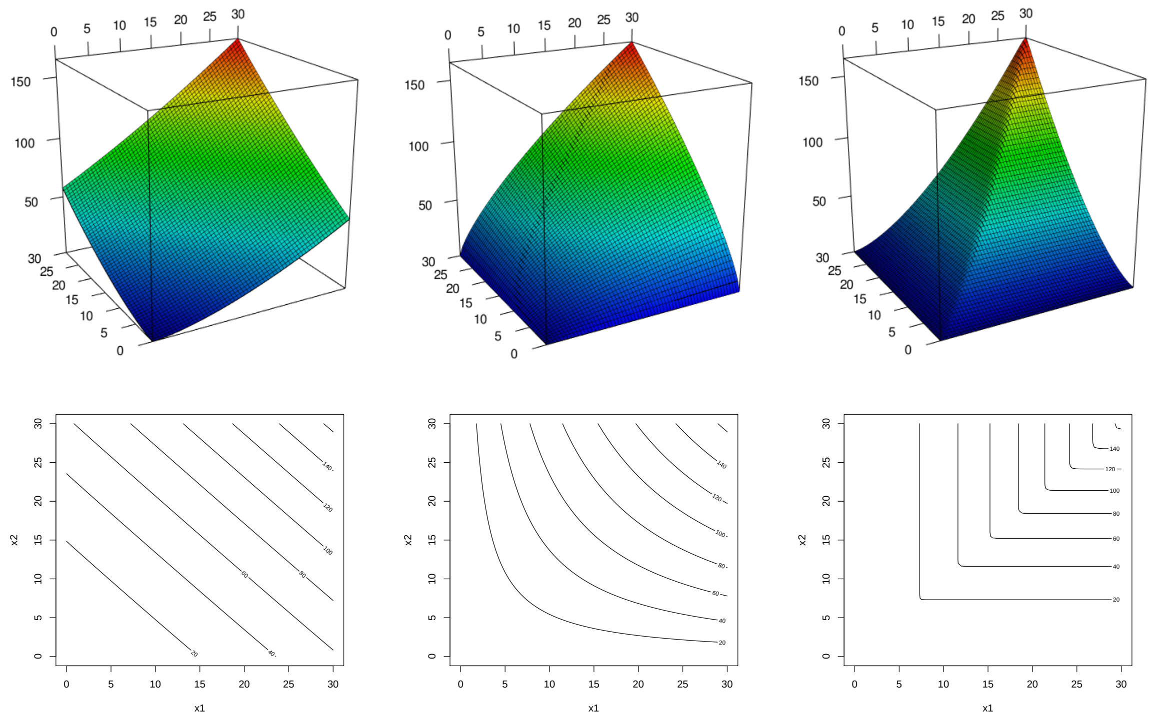
(a) $\rho = 0.99$ or $\sigma = 100$ (b) $\rho = 0.01$ or $\sigma \approx 1$ (c) $\rho = -100$ or $\sigma \approx 0.01$

Figure 5.3: Decreasing returns to scale: $\nu = 0.5$ (Strongly concave).



(a) $\rho = 0.99$ or $\sigma = 100$ (b) $\rho = 0.01$ or $\sigma \approx 1$ (c) $\rho = -100$ or $\sigma \approx 0.01$

Figure 5.4: Constant returns to scale: $\nu = 1$ (Weakly concave).



(a) $\rho = 0.99$ or $\sigma = 100$ (b) $\rho = 0.01$ or $\sigma \approx 1$ (c) $\rho = -100$ or $\sigma \approx 0.01$

Figure 5.5: Increasing returns to scale: $\nu = 1.5$ (Quansi concave).

Source: Author.

ciated with the production function: 1) non-negativity, which means the value of output is a finite, non-negative, real number; 2) weak essentiality, which means the production of positive output is impossible without the use of at least one input; 3) nondecreasing or monotonicity in inputs, which means additional units of an input will not decrease output; 4) concave in inputs, which means that any linear combination of the vectors $\mathbf{x}_0$ and $\mathbf{x}_1$ will produce an output that is no less than the same linear combination of $f(\mathbf{x}_0)$ and $f(\mathbf{x}_1)$.

The most widely used production function is the constant elasticity of substitution (CES) production function, which assumes that elasticity of substitution must be constant for all pairs of inputs. The two factor (labor and capital) CES production function introduced by Solow [1957] and later made popular by Arrow et al. [1961] is given by

$$Q = A\left(\alpha L^{\rho} + (1-\alpha)\, K^{\rho}\right)^{\nu/\rho} \tag{5.8}$$

The change of parameter A refers to the Hicks–neutral technical change. The parameter α is the share of the contribution of labor to aggregate output. The parameter ν is a measure of the economic scale. The Figure 5.3–Figure 5.5 illustrate the 3D production possibility frontier and isoquant curve of two factor CES production with decreasing returns to scale when $\nu < 1$, constant returns to scale when $\nu = 1$ and increasing returns to scale when $\nu > 1$, correspondingly. The parameter ρ yields the elasticity of substitution: $\sigma = \dfrac{1}{1-\rho}$. The Subfigures of (a)–(c) in Figure 5.3–Figure 5.5 illustrate the 3D production possibility frontier and isoquant curve with perfect substitution when $\rho \to 1$ or elasticity of substitution $\sigma \to +\infty$, unitary elasticity of substitution (Cobb–Douglas function) when $\rho \to 0$ or $\sigma \to 1$ and perfect complementarity (or Leontief function) when $\rho \to -\infty$ or $\sigma \to 0$, correspondingly.

This chapter requires three factors (labor, capital and energy) production function. However, Uzawa [1962] has demonstrated that constancy of elasticities of substitution and transformation is highly restrictive for more than two factors of production. There are many empirical studies that use the nested constant elasticity of substitution production function to incorporate energy into the economic model, such as the GTAP-E model combining energy with capital to produce an energy–capital composite [Burniaux and Truong, 2002]. This study adopts the translog production function[1], which was proposed by Christensen et al. [1973], to estimate the three–factor production function of China's

[1] It is short for the transcendental logarithmic production function

economy,

$$\begin{aligned}\ln y_{rt} =& \alpha + \sum_i \beta_i \ln x_{irt} + \beta_t t + \sum_i \beta_{irt} t \ln x_{irt} + \\ & \frac{1}{2}\left(\sum_i \sum_j \beta_{ij} \ln x_{irt} \ln x_{jrt} + \beta_{tt} t^2\right) + \varepsilon\end{aligned} \tag{5.9}$$

where y_{rt} refers to output in region r and time t; x_{irt} and x_{jrt} refer to inputs of labor, capital or energy $(i, j = 1, 2, 3)$ in region r and time t; t refers to time component which represents the technical change. The translog production function maintains the additivity and homogeneity hypothesis as CES production function. It has a flexible functional form permitting the partial elasticities of substitution between inputs to vary and the Hicks–neutral technical assumption to relax.

5.2.2.2 Stochastic Frontier

The production function specifies the maximum possible output obtainable from a given set of inputs and technological knowledge. The modern microeconomics paradigm assumes that producers actually operate on these production functions, apart from randomly distributed statistical noise. However, there is much empirical evidence suggesting that not all producers always succeed in optimizing their production and utilizing the minimum inputs. In addition, even if they are technically efficient, not all producers succeed in allocating their inputs in a cost–effective manner given the input prices [Kumbhakar and Lovell, 2000] (see Figure 5.6). Therefore, the symmetrically distributed error terms with zero means in traditional production functions are no longer appropriate when analysing producer behaviour. This chapter adopts the stochastic frontier production function, in which the error term in traditional production function is replaced by two components, one to account for random effects and another to account for one–side inefficiency.

The stochastic frontier production function model was independently proposed by

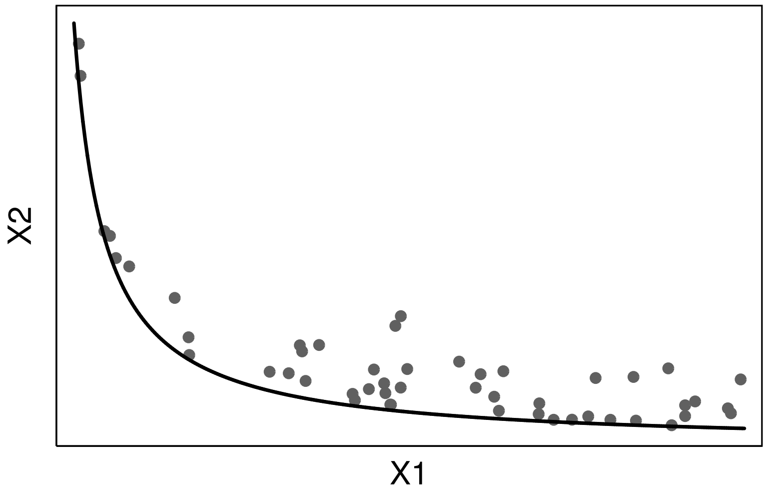


Figure 5.6: Stochastic production frontier.

Source: Author.

Meeusen and van Den Broeck [1977] and Aigner et al. [1977]. Reviews of this research can ben found in Førsund et al. [1980], Battese [1992] and Kumbhakar and Lovell [2000]. This chapter adopts the Battese and Coelli [1995] model for panel data, which can be expressed in the following form:

$$\ln y_{rt} = f(\mathbf{x}_{rt}; \boldsymbol{\beta}) + (v_{rt} - u_{rt}) \tag{5.10}$$

where y_{rt} is a scalar of output in the r-th region and t-th period; $\mathbf{x}_{rt}$ is a vector of logarithm inputs and time in the r-th region and t-th period; $\boldsymbol{\beta}$ is a vector of unknown parameters, which is estimated from the translog production.

The first error component v_{rt} is intended to capture the effects of statistical noise. It is assumed to be independent and identically distributed (i.i.d.) as normal distribution $v_{rt} \sim \mathcal{N}(0, \sigma_v^2)$. The second error component $u_{rt} \geq 0$ is intended to capture the effects of technical inefficiency. It is assumed to be i.i.d. truncation (at zero) of normal distribution $u_{rt} \sim \mathcal{N}^+(\mu_{rt}, \sigma_u^2)$. The mean of the one–side inefficiency error is assumed to be a linear function of observable variables,

$$\mu_{rt} = \mathbf{z}'_{rt}\boldsymbol{\delta} \tag{5.11}$$

where $\mathbf{z}_{rt}$ is a vector of explanatory variables associated with technical inefficiency of production of regions (r) over time (t); $\boldsymbol{\delta}$ is a vector of unknown coefficients. The explanatory variables associated with technical inefficiency includes economic region dummy, share of state–owned enterprises in industrial production (indicator of marketization degree), share of government expenditure in GDP (indicator of government behaviours), and share of exports in GDP (indicator of economy openness).

Battese and Coelli [1995] adopt a single–stage approach that simultaneously estimates the parameters of the stochastic frontier and the model for the technical inefficiency effects by using the method of maximum likelihood. The log-likelihood function of this model is given in the appendix in the working paper by Battese and Coelli [1993]. The likelihood function is expressed in terms of the variance parameters, $\sigma^2 = \sigma_v^2 + \sigma_u^2$ and $\gamma = \dfrac{\sigma_u^2}{\sigma^2}$ [Battese and Corra, 1977].

Given the three–factor translog production function with stochastic frontier (5.9–5.11), the measure of technical efficiency and its rate of change of the r-th region and the t-th period are expressed as

$$TE_{rt} = \exp(-u_{rt}) \tag{5.12}$$

$$TE\Delta_{rt} = \frac{\partial \ln TE_{rt}}{\partial t} = -\frac{\partial u_{rt}}{\partial t} \tag{5.13}$$

where $TE_{rt} \in [0, 1]$ according as u_{rt} shifts from infinity (completely inefficient) to zero (completely efficient). $TE\Delta_{rt} \gtreqless 0$ according as technical efficiency increases, remains unchanged, or declines through time.

The measure of rate of technical change is given by

$$T\Delta_{rt} = \frac{\partial \ln y_{rt}}{\partial t} = \beta_t t + \beta_{tt} t + \beta_{Lt} \ln L_{rt} + \beta_{Kt} \ln K_{rt} + \beta_{Et} \ln E_{rt} \tag{5.14}$$

where $\beta_t t + \beta_{tt} t$ stands for the net technical change, which is the technical change in all regions due to technical spillover effect; $\beta_{Kt} \ln K_{rt} + \beta_{Lt} \ln L_{rt} + \beta_{Et} \ln E_{rt}$ refers to non-neutral technical change, because of the technical accumulation in the process of learning by doing and the difference in learning ability for different regions. $T\Delta \gtreqless 0$ according as technical change shifts the production frontier up, leave it unchanged, or shifts it down. In general cases, the production frontier of an economy is shifting outward as a result of technological progress.

The measure of output elasticities of inputs are expressed as

$$\eta_{L_{rt}} = \frac{\partial \ln y_{rt}}{\partial \ln L_{rt}} = \beta_L + \beta_{LL} \ln L_{rt} + \beta_{LK} \ln K_{rt} + \beta_{LE} \ln E_{rt} + \beta_{Lt} t \tag{5.15}$$

$$\eta_{K_{rt}} = \frac{\partial \ln y_{rt}}{\partial \ln K_{rt}} = \beta_K + \beta_{KK} \ln K_{rt} + \beta_{LK} \ln L_{rt} + \beta_{KE} \ln E_{rt} + \beta_{Kt} t \tag{5.16}$$

$$\eta_{E_{rt}} = \frac{\partial \ln y_{rt}}{\partial \ln E_{rt}} = \beta_E + \beta_{EE} \ln E_{rt} + \beta_{LE} \ln L_{rt} + \beta_{KE} \ln K_{rt} + \beta_{Et} t \tag{5.17}$$

where the elasticities provide measure of percentage change in output resulting from one percent change in the input, holding all else constant. The returns to scale provide the measure of the effects of scale increase of inputs (or of increasing all inputs) on the output, which is given as

$$\nu_{rt} = \eta_{L_{rt}} + \eta_{K_{rt}} + \eta_{E_{rt}} \tag{5.18}$$

The measure of elasticity of substitutions are given by

$$\sigma_{LK} = \frac{d\ln L/K}{d\ln MRTS_{KL}} = \left(1 + \frac{-\beta_{LK} + \dfrac{\eta_L}{\eta_K}\beta_{KK}}{-\eta_L + \eta_K}\right)^{-1} \tag{5.19}$$

$$\sigma_{LE} = \frac{d\ln L/E}{d\ln MRTS_{EL}} = \left(1 + \frac{-\beta_{LE} + \dfrac{\eta_L}{\eta_E}\beta_{EE}}{-\eta_L + \eta_E}\right)^{-1} \tag{5.20}$$

$$\sigma_{KE} = \frac{d\ln K/E}{d\ln MRTS_{EK}} = \left(1 + \frac{-\beta_{KE} + \dfrac{\eta_K}{\eta_E}\beta_{EE}}{-\eta_K + \eta_E}\right)^{-1} \tag{5.21}$$

where $MRTS_{KL} = \dfrac{\partial y}{\partial K}/\dfrac{\partial y}{\partial L}$ is the marginal rate of technical substitution; σ refers to elasticity of substitution; β refers to corresponding coefficients in Equation (5.7), β_{KL}, for example, is the coefficient of cross term of capital and labor; η refers to elasticity. The proofs of elasticity of substitution in translog production function are given in the Appendix E.

Based on the total–factor efficiency and translog stochastic production function described above, we can define the total–factor energy efficiency (TFEE) [Hu and Wang, 2006] and energy saving potential (ESP) as

$$TFEE_{rt} = \frac{TEI_{rt}}{AEI_{rt}} \tag{5.22}$$

$$ESP_{rt} = \frac{AEI_{rt} - TEI_{rt}}{AEI_{rt}} = 1 - TFEE_{rt} \tag{5.23}$$

where AEI_{rt} refers to observed actual energy input of r-th region in t-th period. The target energy input of TEI_{rt} represents a practical minimum input of energy when performing at fully technical efficiency. I estimate the target energy input via translog stochastic production function with the technical inefficient component u_{rt} replaced by $(1 - \dfrac{\eta_E}{\nu_{rt}})u_{rt}$.

5.3 The data

Data on provinces and their aggregates are considered for this empirical study. From the perspective of the economic development stage, provinces are classified into three main areas: east, central, and west (see Table 5.1). The east area covers the coastal provinces: Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Guangxi and Hainan. Hainan is excluded from the data set because of missing energy data in the sample period. The central area covers nine inland provinces: Shanxi, Inner Mongolia, Jilin, Heilongjiang, Anhui, Jiangxi, Henan and Hubei. The West area covers the provinces of Sichuan, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang. Tibet is excluded from the data set due to unavailable energy data. Since Chongqing was promoted as one of the municipalities in China only after 1997, it is regarded as one part of Sichuan. Thus, a total of 32 regions (28 provinces and 3 aggregates between 1953 and 2011, national between 1990 and 2011) for each year are provided to estimate the stochastic production function.

The panel dataset employed in this study includes two different parts: (1) the output and input factors (see Table 5.1) and (2) the technical inefficiency explanatory variables (see Table 5.2). Data of nominal GDP and GDP deflator are collected from the "China Compendium of Statistics 1949–2008" [NBS, 2010a] and the "China Statistical Yearbook" [NBS, 2012b]. Nominal GDP have been deflated to constant 2000 prices by using the GDP deflator published by NBS.

As with GDP, data of labor employment is also collected from the "China Compendium of Statistics 1949–2008" [NBS, 2010a] and the "China Statistical Yearbook" [NBS, 2012b]. There are inconsistent definitions of labor employment. From 1990 to 2000, the data of labor employment have been adjusted in accordance with the data obtained from the 5th

Table 5.1
Summary statistics of output and input factors by region, 1953–2011 (for China) 1990–2011 (for provinces).

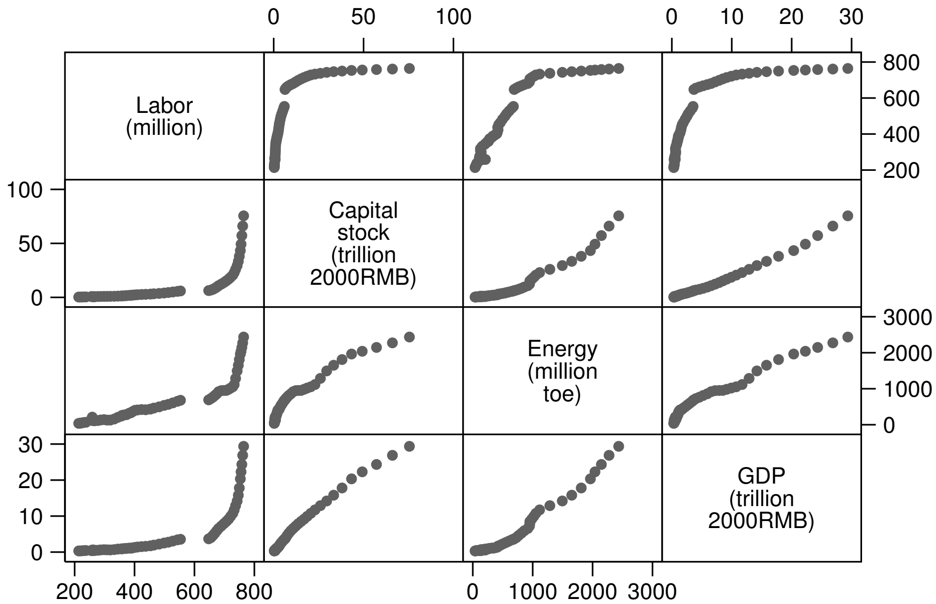
Region		Output factor		Input factors					
		GDP (billion RMB)		Labor (million)		Capital stock (billion RMB)		Energy (million toe)	
		Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.
Beijing	E	429	290	8	2	997	759	32	10
Tianjin	E	265	217	5	0	641	593	25	11
Hebei	E	664	452	34	3	1,411	1,233	102	54
Shanxi	C	262	181	15	1	566	554	68	31
Inner Mongolia	C	274	246	11	1	674	815	49	38
Liaoning	E	654	450	21	1	1,746	1,211	86	32
Jilin	C	272	194	12	0	676	722	35	12
Heilongjiang	C	420	264	16	1	782	521	51	15
Shanghai	E	638	436	9	1	1,359	927	46	19
Jiangsu	E	1,222	922	45	1	2,461	2,146	89	50
Zhejiang	E	855	619	30	5	1,755	1,541	60	35
Anhui	C	386	266	34	3	788	609	39	16
Fujian	E	505	367	17	3	962	864	32	21
Jiangxi	C	279	190	21	2	580	525	23	12
Shangdong	E	1,188	883	53	6	2,487	2,289	118	73
Henan	C	689	481	52	7	1,498	1,468	77	41
Hubei	C	475	327	33	2	911	854	57	27
Hunan	C	480	329	36	3	903	772	52	28
Guangdong	E	1,521	1,128	43	9	2,368	1,978	92	55
Guangxi	E	285	197	26	2	612	658	26	15
Hainan	E	70	46	4	0	162	107	-	-
Sichuan	W	795	560	17	1	1,627	1,357	97	44
Guizhou	W	138	89	20	3	356	275	34	14
Yunnan	W	253	153	23	3	1,115	608	32	17
Tibet	W	16	12	1	0	-	-	-	-
Shaanxi	W	258	192	18	1	704	598	31	16
Gansu	W	138	88	14	1	270	227	25	9
Qinghai	W	38	25	3	0	121	105	9	6
Ningxia	W	40	26	3	0	150	138	12	8
Xinjiang	W	175	104	7	1	489	369	31	16
East		8,225	5,957	290	31	16,799	14,155	708	373
Central		3,537	2,475	231	18	7,380	6,825	453	217
West		1,836	1,238	106	8	4,833	3,640	272	129
China		5,466	7,332	490	194	11,145	17,225	664	624

Notes: (1) E: east area, C: central area, and W: west area. (2) *: excluding from the corresponding aggregate area. (3) -: missing or unavailable of data in the sample period. (4) All monetary values are in constant 2000 prices.

Source: Author.

National Population Census. Since 2001 these data have been calculated by the annual population sampling survey. The inconsistent statistical definitions caused the abnormal change in labor employment before and after 1990 (see Figure 5.7a).

There are plenty of previous empirical studies that provide an estimate of China's capital stock [Chow, 1993; Chow and Li, 2002; Li, 2003; Shan, 2008; WANG and YAO, 2003; Zhang et al., 2004]. I update the real capital stock published by Zhang et al.



(a) Scatterplot matrix.

	Labor	Capital	Energy	GDP
Labor	1.0000			
Capital	0.7362	1.0000		
Energy	0.8822	0.9600	1.0000	
GDP	0.7981	0.9929	0.9809	1.0000

(b) Correlation matrix.

Figure 5.7: The relationship between the output and inputs factors of China, 1953–2011.

Source: Author.

[2004] using the perpetual inventory method (PIM). The PIM can be expressed as $K_t = K_{t-1}(1-\delta_t)+I_t$, where K_t, δ_t and I_t are the capital stock, depreciation rate and investment in the year of t, correspondingly; K_{t-1} is the capital stock in the year of $t-1$. The investment series are the gross fixed capital formation at current prices, which are collected from the the "China Compendium of Statistics 1949–2008" [NBS, 2010a] and the "China Statistical Yearbook" [NBS, 2012b]. Nominal investments are deflated to constant 2000 prices using the implicit deflator constructed by Zhang et al. [2004]. I adopt an overall depreciation rate of 9.6% and the initial capital stock of the 1952 investment divided by 10% [Young, 2000; Zhang et al., 2004].

Data of energy consumption are collected from the "China Energy Statistical Yearbook" [NBS, 2012a] and the "China Compendium of Statistics 1949–2008" [NBS, 2010a]. The term energy here refers to commercial energy only. According to IEA [2013a], around 10 percent of total primary energy supply to China is sourced by biomass. This study doesn't consider biomass due to the unavailability of data.

Table 5.1 presents the descriptive statistics of both national and provincial output and input factors in China. As the table shows, the east or coastal area has the highest level of economic output and also inputs compared to the central and west areas. Figure 5.7 provides the relationship between each of the output and inputs factors. This scatterplot matrix has similar function as the correlation matrix but provides much more information. These two matrices shown that GDP, capital and energy have strong positive correlations among each other, while these three factors are weakly correlated with labor due to capital deepening in the last decade.

The variables that are used to explain technical inefficiency include: (1) the dummy variable of economic region which is defined as one for provinces in the eastern area and zero for the remainders; (2) share of state–owned enterprises in industrial production that is an indicator of the degree of marketization; (3) share of government expenditure in GDP that is an indicator of government behaviours; and (4) share of exports in GDP that is an indicator of economic openness.

Table 5.2 displays the describe statistical of the technical inefficiency explanatory variables. As Table 5.2 shows, the eastern areas have lower Gov.Exp./GDP and SOE/IP but higher Export/GDP compared with the other two areas. The trends of technical inefficiency explanatory variables of China from 1953 to 2011 are given in Figure 5.8. The

Table 5.2
Summary statistics of technical inefficiency explanatory variables by region, 1953–2011 (for China) 1990–2011 (for provinces).

Region		Gov.Exp./GDP (%)		Export/GDP (%)		SOE/IP (%)	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Beijing	E	14%	3%	36%	10%	59%	7%
Tianjin	E	12%	2%	37%	12%	39%	8%
Hebei	E	9%	2%	8%	2%	39%	11%
Shanxi	C	14%	4%	6%	2%	62%	11%
Inner Mongolia	C	17%	3%	5%	2%	58%	18%
Liaoning	E	13%	3%	21%	4%	56%	14%
Jilin	C	15%	3%	7%	4%	65%	12%
Heilongjiang	C	14%	4%	7%	3%	73%	11%
Shanghai	E	14%	4%	53%	21%	45%	10%
Jiangsu	E	8%	2%	30%	18%	21%	8%
Zhejiang	E	8%	2%	30%	14%	18%	6%
Anhui	C	13%	5%	7%	1%	47%	14%
Fujian	E	10%	2%	32%	6%	23%	10%
Jiangxi	C	13%	4%	6%	2%	52%	18%
Shangdong	E	8%	1%	16%	4%	32%	9%
Henan	C	10%	3%	3%	1%	40%	12%
Hubei	C	11%	3%	6%	1%	50%	13%
Hunan	C	12%	3%	5%	1%	46%	15%
Guangdong	E	10%	1%	76%	9%	22%	8%
Guangxi	E	13%	4%	8%	2%	51%	13%
Hainan	E	17%	6%	15%	7%	50%	18%
Sichuan	W	14%	5%	5%	2%	48%	12%
Guizhou	W	23%	8%	4%	1%	69%	9%
Yunnan	W	23%	4%	6%	1%	68%	9%
Tibet	W	70%	22%	6%	3%	66%	13%
Shaanxi	W	15%	4%	6%	2%	67%	9%
Gansu	W	21%	7%	4%	1%	75%	10%
Qinghai	W	30%	11%	1%	1%	78%	9%
Ningxia	W	23%	6%	8%	2%	65%	11%
Xinjiang	W	19%	7%	11%	7%	80%	5%
East		10%	2%	35%	8%	31%	9%
Central		13%	3%	5%	1%	52%	13%
West		17%	5%	6%	1%	61%	10%
China		23%	7%	12%	10%	62%	22%

Notes: (1) E: east area, C: central area, and W: west area. (2) *: excluding from the corresponding aggregate area.

Source: Author.

share of export in GDP has grown since the launch of the reform and opening–up policy in 1978. Export is the demand of foreign economies; thus, its value fluctuated during the financial crises around 2000 and 2008-2009. The share of government expenditure in GDP dropped after the early 1980s, while it climbed up since the end of 2000s. Because of the project of Great Leap Forward in 1958, the share of state–owned enterprise surged during the First Five–Year Plan based on a Soviet–style centrally controlled economy. After that, the share of SOE in total industrial production decreased from the late 1970s, which represents the increasing degree of marketization in China.

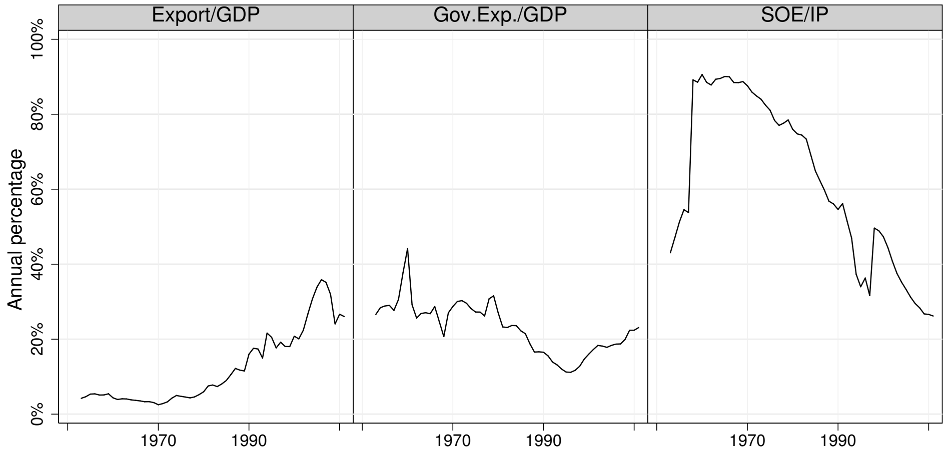


Figure 5.8: Trends of technical inefficiency explanatory variables of China, 1953–2011. Data source: NBS [2010a, 2014] (calculated by author).

5.4 Results and discussion

5.4.1 Estimates of translog stochastic production function

Maximum likelihood estimates of the coefficients in the translog stochastic production function are obtained using *sfpanel* command in Stata that is provided by Belotti et al. [2012]. The translog stochastic production function with these estimated parameters and standard errors are given as follows:

L-K-E Translog Stochastic Production Function:

$$\begin{aligned}
\ln y_{rt} = &+ \underset{[0.052]^{*}}{0.3227} + \underset{[0.000]^{***}}{0.5509} \ln L_{rt} + \underset{[0.000]^{***}}{0.8506} \ln K_{rt} - \underset{[0.021]^{**}}{0.2721} \ln E_{rt} + \underset{[0.533]}{0.0068t} \\
&+ \underset{[0.001]^{***}}{0.0803} (\ln L_{rt})^2 - \underset{[0.026]^{**}}{0.0600} (\ln K_{rt})^2 - \underset{[0.131]^{**}}{0.0551} (\ln E_{rt})^2 + \underset{[0.000]^{***}}{0.0008} t^2 \\
&- \underset{[0.001]^{***}}{0.1253} \ln L_{rt} \ln K_{rt} + \underset{[0.000]^{***}}{0.2267} \ln K_{rt} \ln E_{rt} - \underset{[0.169]}{0.0692} \ln L_{rt} \ln E_{rt} \\
&+ \underset{[0.002]^{***}}{0.0114} t \ln L_{rt} - \underset{[0.877]}{0.0007t} \ln K_{rt} - \underset{[0.000]^{***}}{0.0140} t \ln E_{rt} \\
&+ v_{rt} - u_{rt}
\end{aligned} \tag{5.24}$$

Inefficiency Model:

$$\begin{aligned} u_{rt} = &+ \underset{[0.000]^{***}}{0.3318} - \underset{[0.758]^{**}}{0.0059} East - \underset{[0.000]^{***}}{0.7226}\, Export/GDP \\ &+ \underset{[0.000]^{***}}{1.9649}\, Gov.Exp/GDP + \underset{[0.077]^{*}}{0.0838} SOE/IP \end{aligned} \tag{5.25}$$

Variance Parameters:

$$\sigma_u^2 = \underset{[0.000]^{***}}{0.1451} \qquad \sigma_v^2 = \underset{[0.024]^{**}}{.0204}$$

where p-values below parameters $^{*}p < 0.1,^{**} p < 0.05,^{***} p < 0.01$.

Log likelihood $= 397.2180$.

As Equation (5.24) shows, most coefficients of energy related terms have negative signs, with the exception of the cross term energy–capital which has a positive coefficient. It means that energy consumption is complementary with the increase of capital stock. The output elasticity of energy in the Chinese aggregate economy slightly rises along with the capital deepening process since the 1990s. Its overall average since 1978 is 0.4 (see Figure 5.9), which means that one percent increase of energy input causes about 0.4 percent increase of output.

The output elasticity of capital stock in the Chinese aggregate economy has decreased from 0.53 in 1978 to 0.43 in 1997 and then stabilized at around 0.42. I also provide the output elasticity of capital estimated by previous empirical studies (see Figure 5.9) [Chow, 1988, 1993, 2008; Chow and Li, 2002; Guo and Jia, 2005; Lau and Brada, 1990; Wang and Meng, 2001]. Most of these estimates of output elasticity of capital are larger than this study because they didn't consider energy inputs.

The output elasticity of labor was steady around 0.17 in the two and a half decades

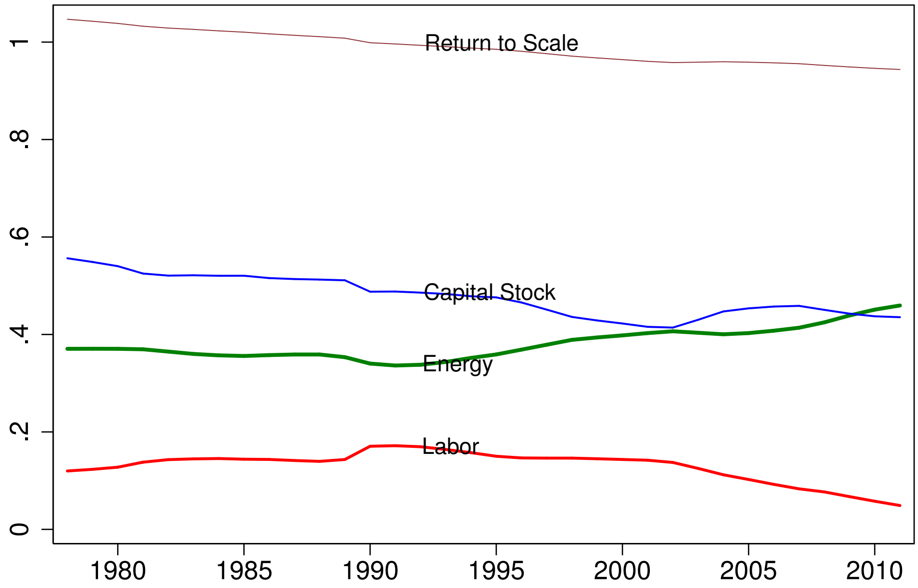


Figure 5.9: Elasticity of labor, capital and energy and returns to scale of China, 1978–2011.

Source: Author.

after 1978 and dropped to only 0.06 in 2011. As a result of the decreasing elasticity of capital before the 2000s and the decreasing elasticity of labor after 2000s, the returns to scale of China's economy dropped from 1.06 to the current 0.96. In other words, the Chinese economy has changed from an economy with increasing returns to scale (IRS) to decreasing returns to scale (DRS).

Based on the estimated translog production function, I also provide the empirical estimates of elasticity of substations in the aggregate Chinese economy (see Figure 5.9). The elasticity of substitution measures the curvature of an isoquant and thus, the substitutability between any pair of inputs. Formally, the elasticity of substitution measures the percentage change in factor proportions due to a change in the marginal rate of technical substitution. In general, the value of elasticity of substitution ranges from 0 to $+\infty$, with 0 being perfect complementarity (or Leontief function) and $+\infty$ being perfect substitution (see Figure 5.1–Figure 5.3). If there are more than two inputs available, the degree of

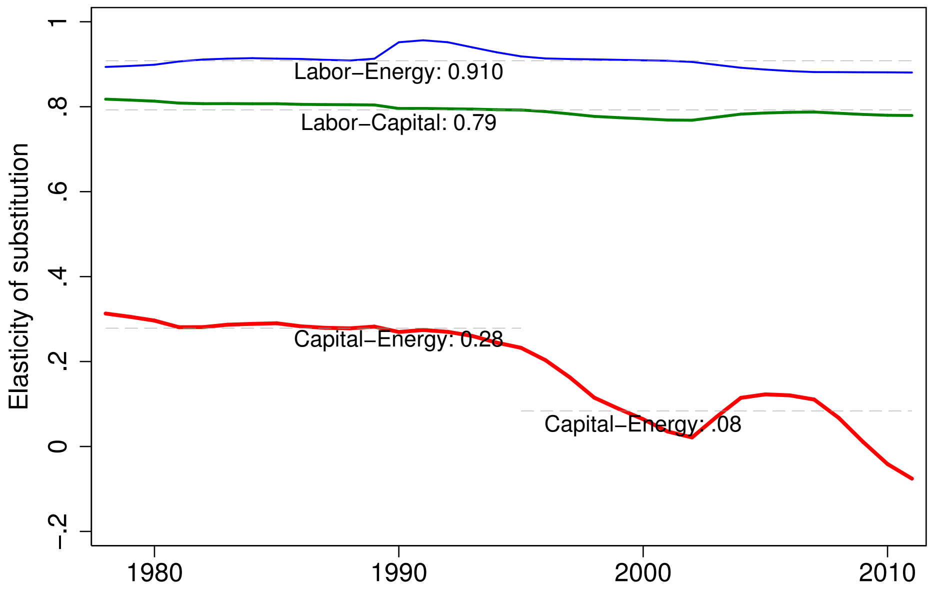


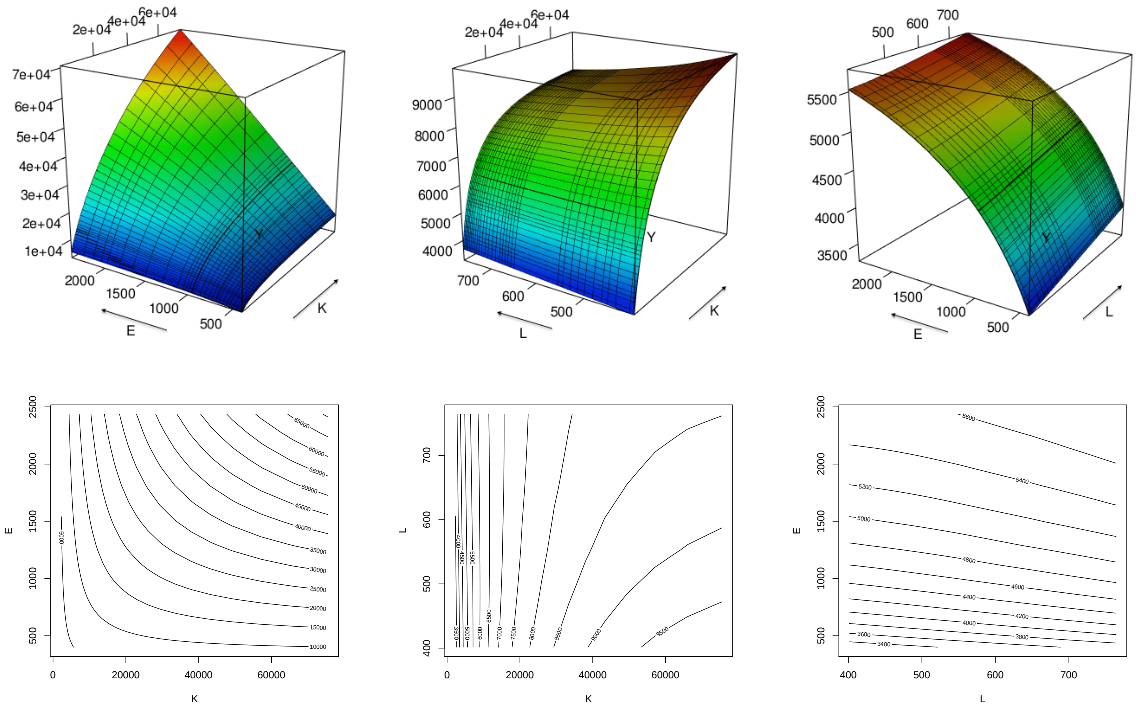
Figure 5.10: Elasticity of substitution of Capital–Energy, Labor–Capital and Labor–Energy of China, 1978–2011.

Source: Author.

complementarity may be such that the elasticity of substitution is negative.

The elasticity of substitution of capital–energy stabilized at around 0.23 before the middle of 1990s and then decreased to the current −0.26. It shows that the pair inputs of capital–energy have almost perfect complementarity in the last decades in China. The energy–capital complementarity happens in the short to medium term due to capital constraint. In the long–term, the energy–capital relationship turns into substitutability considering the capital renewal process. The elasticity of substitution of labor–energy is about 0.90 and of labor–capital is about 0.78 since 1978. It should be noticed that the flexible elasticity, returns to scale and elasticity of substitution are estimated by using translog production function, while CES production function is unable to provide that information.

Figure 5.10 displays the 3D diagrams and isoquants curve of L-K-E translog production function of the aggregate Chinese economy, where one of three inputs in natural logarithm



(a) K-E ($L = L_{1978}$, $t = 1$) (b) L-K ($E = E_{1978}$, $t = 1$) (c) L-E ($K = K_{1978}$, $t = 1$)

Figure 5.11: 3D diagram and isoquant of translog production function of China, 1978–2011.

Source: Author.

and the time component are fixed to the corresponding value in 1978. The isoquant of capital–energy is similar to the one of Leontief production function with nearly perfect complementarity. As the isoquants shown in Figure 5.11b and Figure 5.11c, I can found that the contribution of labor to Chinese aggregate economic output is smaller than the contribution from capital and energy, which echoed the output elasticity of labor display in Figure 5.9.

The signs of the coefficients of the inefficiency model Equation (5.25) are as expected. The region dummy and the share export in GDP coefficients are negative, which indicate that the coastal and liberal provinces are less technically inefficient or more technically efficient than the others. On the contrary, the share of government expenditure in GDP and share of state–owned enterprise in industrial production are positive, which mean that a provincial economy that relies on fiscal expenditure and SOE are technically inefficient. Although the coefficient for these explanatory variables are significant for the interpretation of sources of technical inefficiency, the share of unexplained inefficiency error, which is the constant in the technical inefficiency model, grew from 36% in 1978 to 84% in 2002 and then dropped to the current 64%.

5.4.2 Total–factor productivity

In the last three and half decades, China has achieved a miraculous economic development. Chinese per capital income has increased eight–fold since the launch of the reform and opening-up policy in 1978. In the following, China's aggregate economic growth can be decomposed into factor accumulation and TFP growth. As the Figure 5.12 shows, China has three major business cycles since 1978. The first business cycle is between 1978 and 1988, when China applied the reform on collective farming with the household–responsibility system and the upward price adjustment for some agricultural products. In this period, China's growth was reliant on productivity growth, which accounted for 22–44% of aggregate growth. My estimates are similar with the empirical study by Hu and Khan [1997] who found the growth of TFP explained more than 40% of China's aggregate economic growth in the early reform period.

Hu and Khan [1997] explained this productivity boom as the result of reforms on property rights in the countryside, decollectivization, and higher prices for agriculture products, economic freedom of production, welcoming foreign investment and price liberalisation. Zheng et al. [2009] pointed out that industrial reforms gave individual firms, managers, and workers greater incentives to improve efficiency. The economic reform transferred labor out of agriculture, improved the educational attainment and increased labor force participation rates. However, some of those factors only had a one–time effect on TFP.

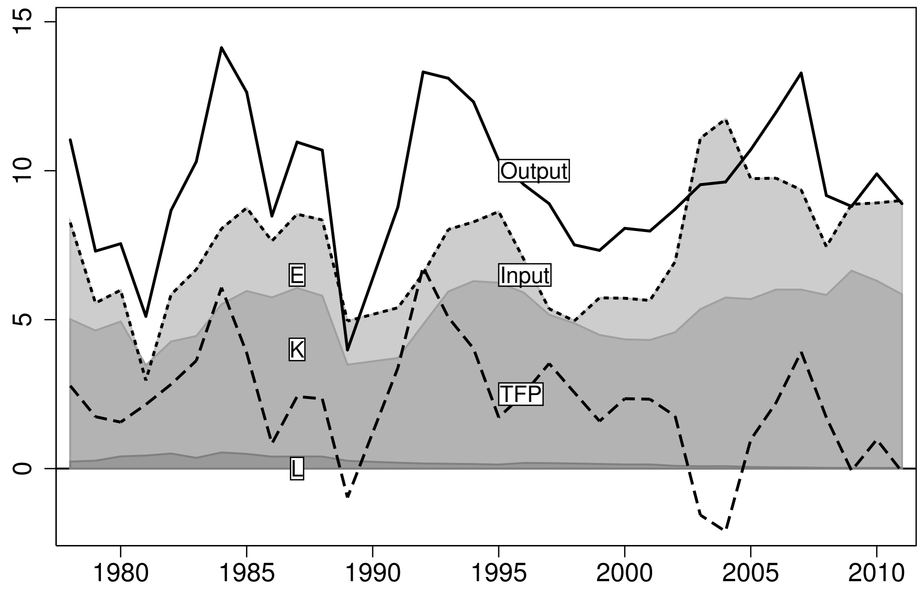


Figure 5.12: Growth in output, inputs, and TFP of China, 1978–2011.

Source: Author.

A two–digit inflation triggered by the investment boom in the early 1990s peaked at 27.7% in September 1994. In addition, the Chinese government faced a serious fiscal deficit and low foreign currency reserves during the early 1990s. In order to stimulate the economy and solve the problems of high inflation, fiscal deficit and low foreign reserves, the Chinese government applied a range of reforms, such as devaluing the RMB by one–third, tax reform and state–owned enterprise reform. Since then, exports have become one important source of economic growth. Those reforms pushed the TFP growth at an average of 3.4 percent per annum and explained around 33% of overall economic growth during the decade since 1991.

From the late 1970s to the mid 1990s, China's growth depended more on productivity growth less on increased capital. However, since the late 1990s, growth in capital inputs has exceeded GDP growth substantially. To offset the shrinking export market as a result of financial crises in 1997 and 2008, investment picked up speed when the government increased spending on large–scale infrastructure projects. For examples, China Western Development in 1999, Revitalize the Old Northeast Industrial Bases in 2003, the Rise of Central China Plan in 2004, the New Rural Reconstruction Movement in 2005, and the Economic Stimulus Plan in 2009, among others. Hosting the 2008 Olympic Games in Beijing further encouraged government spending on construction projects. The government fiscal expenditure, China entering the WTO in 2001 and the real estate boom also stimulate both foreign and domestic investments in China. As investment in manufacturing and construction reached unprecedented levels, capital stock accounted for an average of 55% of China's aggregate growth from 1997 to 2011, while the contribution of TFP growth to China's aggregate growth dropped to only 16% during the same period. As with the surging of investment, energy growth provided around 30% of China's aggregate growth. Here we need to point out that labor measure in this empirical study is not adjusted for quality change, which underestimates the contribution of labor input to China's GDP growth.

5.4.3 Energy–saving potential

Based on Equation (5.23), I am able to estimate the provincial energy–saving potential (ESP) during 1990–2011. The ESP is the opposite of total–factor energy efficiency (TFEE), and reveals the difference between the actual energy use and the target energy use when performing at full technical efficiency. The total factor energy efficiency is estimated from a regional comparison of energy efficiency. Guangdong province is identified as always producing on the production frontier, or with fully efficiency. In other words, Guangdong province has the lowest energy–saving potential.

The regional energy–saving potential ranking from low to high are the eastern, central and western area. The ranking order is as expected, that energy efficiency is proportional to energy development. My estimates are different from the study by Hu and Wang [2006],

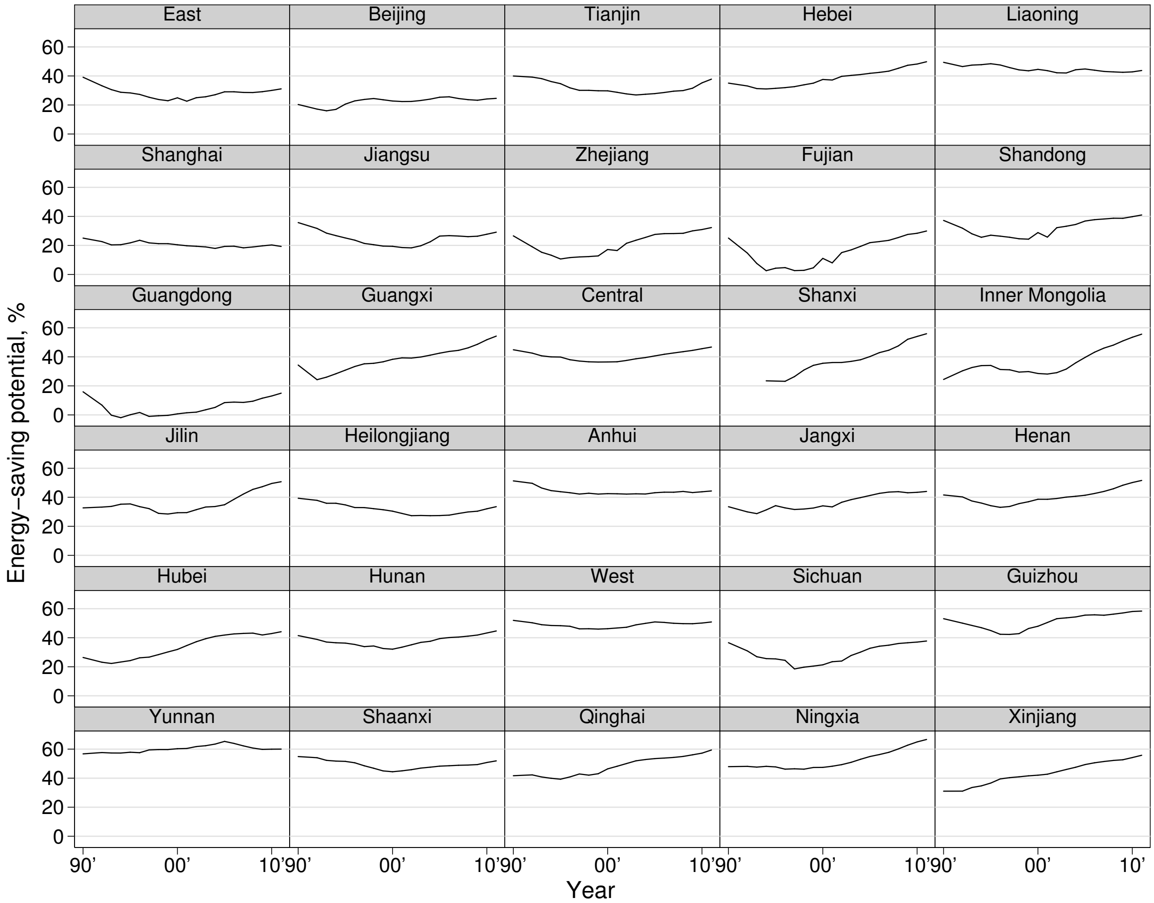


Figure 5.13: Provincial energy–saving potential, 1990–2011.

Source: Author.

who found a U-shape relation between an area's TFEE and per capita income in China. As Figure 5.13 shows, the energy–saving potential is diverse among provinces. The coal-rich areas, such as Shanxi and Inner Mongolia, and have an ESP over 60%, which means these provinces waste over 60% of their energy input compared with the fully technically efficient province of Guangdong.

We can see that the trends of ESP in most provinces displayed in Figure 5.13 are following a U-shape pattern, for example in Tianjin, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Jilin, Heilongjiang, Henan, Sichuan, Guizhou, and Shaanxi. The U-shape pattern of ESP trends is determined by the economic development of the last two decades.

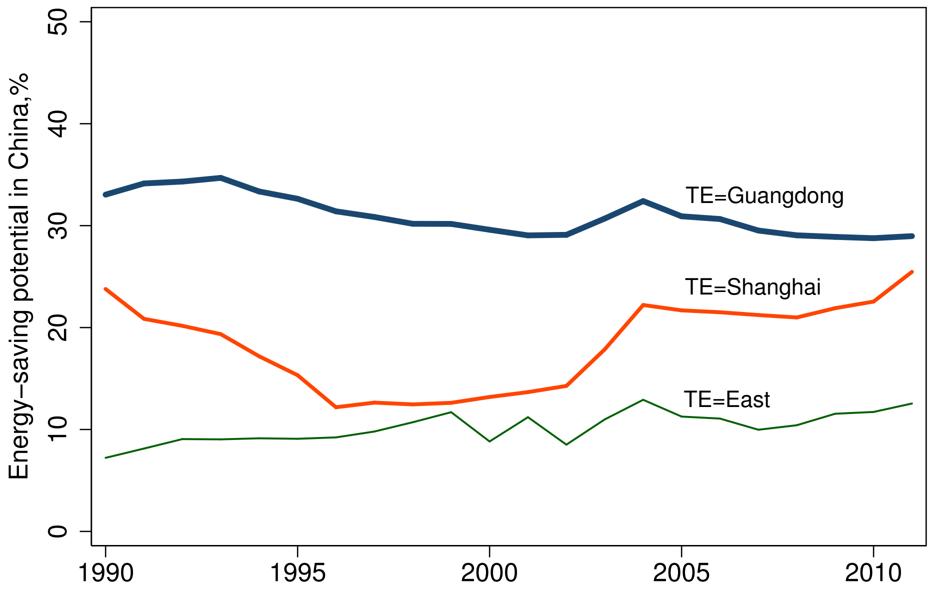


Figure 5.14: Scnarios of energy–saving potential of China, 1978–2011.

Source: Author.

The increasing contribution of investment to energy input is surging and energy efficiency is also decreasing.

Figure 5.14 provides the scenario analysis of China's aggregate energy–saving potential when the overall technical efficiency is assumed to be performing as the efficiency in the eastern area, Shanghai, and fully efficient. I are able to found that China would save approximately 11 percent of total energy use if it operated as the same technical efficiency as the average of the eastern area, 20 percent at Shanghai's technical efficiency and 36 percent at full efficiency.

5.5 Conclusions

This study constructed a three–factor translog stochastic production function for China's economy. Based on the L-K-E translog stochastic production function, I estimated the total–factor productivity of China's aggregate economy. As we known, energy is not the only input to economic production, and it has to be accompanied by other inputs such as labor and capital for production. The energy–saving potential index is, therefore, calculated for the evaluation of energy efficiency among provinces.

The translog production function identified the production frontier of China's economy or the fully efficient province, and also explained the relationship between alternative inputs. The output elasticity of energy input is approximately 0.4 in China since 1978, which means one percent growth in energy input would lead to about 0.4 percent of aggregate economic growth. The elasticity of substitution of capital–energy is about 0.23 before mid-1990s, and then dropped to only -0.02. The negative elasticity of substitution reveals the perfect complementarity between capital and energy input in China. The inefficiency model was provided to explain the sources of economic inefficiency. I found that the provinces located in the coastal regions and with more liberal economies have lower economic inefficiency, while the share of fiscal expenditure in GDP and SOE in industrial production are positively correlated with the technical inefficiency.

The calculated TFP index illustrated the sources of economic growth in China. Since the launch of the reform and opening-up policy in 1978, China's economic growth can be divided into three periods. In the first period between 1978 and the late 1980s, total factor productivity contributed to about 22–44% of China's growth. This productivity boom resulted from a series of reforms, such as the household–responsibility system and price reform. In second period, between the early 1990s and late 1990s, China's economy was supported by the devaluation of RMB, SOE and tax reform. Since the late 1990s, China's growth has been mainly driven by investment activity, such as government spending on large–scale infrastructure projects, and both foreign and domestic investment in manufacturing. Together with the increasing investment, energy use surged in the last decade in China.

As Miller [2014] illustrated, the trade freedom index improved significantly in China during the last two decades. There are still huge potential to upgrade the freedom in the fields of investment, finance and labor. The 'decision' of the third Plenary Session of the 18th CPCCC for deeper reforms in a large range of issues, such as the basic economic system, the fiscal and taxations system, the socialist democratic system, law and ecology, will open one window for the future of the Chinese economy and energy [Xin Hua News, 2014]. The market will playing a more and more important role in the allocation of resources.

I also made a regional comparison on the total–factor energy efficiency, which revealed the difference between actual energy use and the optimal energy input. I provided the energy–saving potential index among the provinces in China. I found that energy–saving potential is inversely proportional with the economic development stage. In other words, the more developed provinces have higher energy efficiency. Scenario analysis on provincial energy–saving potential was provided to describe the potential for energy conservation in China. Given the current technology and knowledge, China can reduce about 31 percent of its energy input if it operates at the same technical efficiency as Guangdong province.

Chapter 6

Conclusions

6.1 Summary of the results and policy implications

Energy consumption, energy-related CO_2 emission and economic growth are three interrelated issues at the forefront of public attention. This dissertation aims to investigate the driving forces of China's energy use and carbon emissions, to analyze their roles in the economic growth and to provide the policy implications for energy conservation and carbon emissions reduction in China.

Chapter one discussed the research background, research objective and questions, and the organization of this study.

Chapter two provided a brief overview of energy use in history. Energy flow charts were provided to describe China's energy supply and use system and its changes, and to make a comparison of the international energy systems among the main economies in the world.

Energy is always an important factor to the improvement of social and economic welfare in human history. The transitions of power source divide human history into four distinct energy eras: biomass fuels, draft animals, waterwheels and windmills, fossil fuels and electricity. The energy transition from animal power and biomass fuels to engines and fossil-fuels has driven productivity growth significantly. In the long term, technological innovation, which is the new capital stock in economics jargon, is the primary source of productivity growth.

The demand for energy is a derived demand from the utilization of capital stocks. Coal and petroleum used as fuels, for example, started with the diffusion of steam engines in textile manufacture from the mid-1700s and the diffusion of internal combustion engines in transportation from the late 1800s. From the 1800s to the 1910s, the share of coal in the global total primary energy supply (TPES) climbed from single digits to 50%. From the 1900s to the 1970s, the share of hydrocarbon fuels (crude oil and natural gas) increased from almost zero to approximately 60% within seven decades. Meanwhile, coal dropped to only 25% from 50%. After the oil crisis in the 1970s, the world energy structure has been largely stable throughout the last forty years. In this period, hydrocarbon fuels have accounted for approximately 55% of the world's TPES, coal for around 25%, biofuels for around 10% and primary electricity (hydro- and nuclear-) for the last 10%.

In China, the energy used in rural areas differed little from hundreds of years ago until the end of the imperial era in 1911, while coal was widely adopted as the main energy source for many European countries by the 1900s. Even in the 1950s, biomass fuels, such as wood and crop straw etc., still accounted for more than one half of China's TPES. In 2010, the Chinese economy relied on coal for two-thirds (67%) of its TPES, petroleum for one-sixth (17%), natural gas for 4% and primary electricity for another 9%. The coal–based energy supply system has been stable for more than four decades.

During the past few decades, the most significant changes in China's energy system include the following three points. First, Chinese energy supply structure has been relatively stable throughout the last few decades. China now relies on international markets for more than half of its petroleum consumption (53% in 2010), while it remained an oil net exporter between 1970 and 1992. Second, the direct use of coal in final demand has been significant substituted by electricity, decreased from more than half (57% in 1992) to a quarter (28% in 2010). Third and most important, the total energy consumption in China has accelerated since the early 2000s, and China became the largest energy consumer in the world in 2010. It is critical to understand the driving forces of China's energy use for the design of energy policy on both national and global scales.

In *chapter three* a structural decomposition analysis (SDA) was conducted based on hybrid input–output tables, and discussed the driving forces of total energy use in China from 1992 to 2010. The energy intensity of Chinese economy resembles an inverted U-shape across increasing levels of income per capita. As the explanation of the theory of dematerialization, this pattern relationship arises from economic structural and technological change. The technique of SDA was adopted to gauge the effects of the driving forces of China's energy use.

As shown in the results, China's energy use is embodied in three final demand categories: gross fixed capital formation, household consumption expenditures and exports. The impacts of these factors on total energy use have shifted with the development of the economy. In the 1990s, China's energy use was still mainly driven by household consumption, which accounted for about two-fifths of the total energy use, but its contribution to the energy use change decreased from 31 percent (1992–1997) to 20 percent (1997–2002). In contrast, the contribution of exports to the changes in energy use increased from 30 percent (1992–1997) to 39 percent (1997–2002). In other words, China became an export–oriented economy in the 1990s.

However, investment has been a major factor driving China's economic growth in the past decade. The energy use embodied in gross fixed capital formation increased from approximately 30 percent of total energy use before 2002 to 39 percent in 2010, and its contribution to the change of energy use swelled to three-quarters during 2007–2010. This investment–led economic growth is unsustainable because the heavy dependence on investment not only has created energy and environmental problems but also increased systematic risk, including surging local government debt. It is imperative for China to switch its economy from export– and investment–based growth to domestic consumption–

oriented growth.

With exports and investment driving economic growth, the income of Chinese households has reached the level at which energy–intensive goods are affordable. Household consumption has contributed 30 percent of the total energy use and to one-quarter of its change in 2010. Given China's population and accelerating urbanization, the commercial and transportation sectors should expect to surpass the industrial sector as the main energy demand drivers in the future.

From the supply side (the columns of the I–O table), this study evaluated the technical energy efficiency by the direct energy use coefficients matrix in the hybrid energy input–output model. The improvement of technical energy efficiency saved around five to six percent of total energy use annually in the periods of 1992–1997, 1997–2002 and 2007–2010. In the period of 2002–2007, however, technological change reduced total energy use by three percent because of the increasing indirect energy use coefficient in the construction sector.

Carbon emissions in China have surged sharply since 2000. Emission grew at an exponential rate of 3% annually from 1992 to 2002, while the growth rate surged to 9% annually after 2002. China has become the largest emitter in the world since 2006 and contributed 27% of global annual carbon emissions in 2012. Its historical cumulative emissions climbed to 11% of global total emission in 2012, which is approximately 41% of the US. Though the Chinese government has committed itself to cut the CO_2 emission per unit of GDP in 2020 by 40 to 45% compared with the level of 2005, its aggregate emissions are expected to rise further considering the projected sustained growth in economic output and household income. CO_2 emissions are byproducts of energy consumption in economic activities. The emissions generated from construction, for example, come not only from construction sites, but also its upstream industries such as steel mill and cement plant. The emissions impacted by inter-industrial transactions or supply chain can be described and explained by using the input–output model. *Chapter four* adopted the hybrid environmental input–output model to investigate the energy–related CO_2 emission embodied in Chinese final demand.

The results show that the final demand category of consumption was responsible for 51% of Chinese CO_2 emission in 1992 and decreased to 34% in 2010. The changes in consumption contributed around one-fourth (21% to 26%) of total CO_2 emission growth among in each period from 1992 to 2010. The key drivers behind the growth of CO_2 emissions embodied in the household consumption are typically income level, consumption patterns, population and the household structure.

In contrast to the decreasing share of consumption, investment activity–related CO_2 emissions increased from 31% in 1992 to 42% in 2010. The growing final demand for investment amounted to 2,430 Mt CO_2 between 1992 and 2010 (48% of total changes), of which 84% occurred between 2002 and 2010. In the period 2007–2010, especially, investment activity constituted 92% of total emission changes. Around 56% to 70% of emissions embodied in investment between 1992 and 2010 are related to final demand for 'Construction', which is due to its emission–intensive supply chains, such as cement manufacturing, iron and steel production and electricity generation.

Exports–related emissions have grown most rapidly compared to all the other final demand categories. Emissions from the production of goods and services destined for exports increased from 494 Mt (17% of total emissions) in 1992 to 1,870 Mt (24% of total emissions) in 2010. The composition of exported goods and services is changing, which indicates the shifting role of China in the global economy from a producer of cheap, labor–intensive goods toward high–end and more capital–intensive products.

Indirect energy use and carbon emissions indicate the length of the roundabout production chain, or the roundaboutness of production, which was one of three concepts used to describe the specialization of economics. The increasing of division and specialization of labor are associated with the growth of productivity and the capital–deepening process. My calculations show that the share of indirect carbon emissions rose from 73% in 1992 to 87% in 2010, since labor has increasing experienced division and specialization concurrent with China's economic development.

The increase of emissions is equivalent to the increasing input of the environment. Given the scarcity of resources and technology, emission reduction is the substitution between the environment and alternative inputs, such as labor, capital and energy. However, the environmental resources are public goods that are non-exclusive and non-competitive. There are no private incentives to provide the public good of the environment. Economists describe emissions, which imposes involuntary costs on others, as a negative externality. The nature of the externality problem is the transaction cost, which is the tradeoff between the exogenous transaction cost to clearly delineated environmental property right and the endogenous transaction cost provoked by ambiguously defined environmental property right. According to the Coase theorem, an institution does not matter in a world with zero transaction cost where property rights are clearly delineated. However, when the transaction costs are significant, institutions evolve endogenously to achieve efficient outcomes. The policies that can be used to reduce emissions include command and control regulations, emission taxes and tradable emissions permits. The proper policy should be the one with minimum transaction costs.

Chapter three and four provide the demand side analysis of the energy and emission in China by using a hybrid input–output model. In *chapter five* a supply side analysis was conducted by constructing a three–factor translog stochastic production function for China's economy. The translog production function identifies the production frontier of

China's economy, and also explains the relationship between alternative inputs. According to my calculations, the output elasticity of energy input is approximately 0.4 in China since 1978, which means one percent growth in energy input would lead to about 0.4 percent of aggregate economic growth. The elasticity of substitution of capital–energy was about 0.23 before mid-1990s, and then dropped to only -0.26. The negative elasticity of substitution reveals the perfect complementarity between capital and energy input in China. An inefficiency model was provided to explain the sources of economic inefficiency. I found that the provinces located in coastal regions and with higher degree of liberal economy have lower economic inefficiency. Also, the shares of fiscal expenditure in GDP and SOE in industrial production are positive correlated with technical inefficiency.

The calculated TFP index illustrates the sources of economic growth in China. Since the launch of the reform and opening policy in 1978, China's economic growth can be divided into three periods. In the first period between 1978 and the late 1980s, total factor productivity contributed to about 22% to 44% of China's growth. This productivity boom was the result of a series of reforms, such as the household–responsibility system and price reform. In the second period from the early 1990s to the late 1990s, China's economy was supported by the policies such as devaluation of RMB, SOE and tax reform. Since the late 1990s, China's growth has mainly been driven by investment, such as government spending on large–scale infrastructure projects and both foreign and domestic investment in manufacture. Accompanied by increasing investment, energy use surged in the last decade in China.

The trade freedom index improved significantly in China during the last two decades. There are still huge potential to upgrade the economic freedom in the fields of investment, financial and labor. The decision of the third Plenary Session of the 18th CPCCC for deeper reforms will open one window for the future of Chinese economic development and energy use. The market will play a more and more important role in the allocation of resources.

A provincial comparison on the total–factor energy efficiency reveals the difference between actual energy use and optimal energy input. I provided the energy–saving potential index among the provinces in China. It was also found that the higher developed provinces have higher energy efficiency. Scenario analysis was provided to describe the potential for energy conservation in China. Given the current technology and knowledge, China can reduce about 31 percent of its energy input if it operates as the same technical efficiency as Guangdong province.

Finally, I have to emphasize that energy and environment issues are derivatives of economic and societal development. The energy and emissions would be one of more and more important factor for the designing economic policies in China. This study proposed policy implications from both the demand-side and the supply-side. From the demand-side, Chinese economy should switch from investment- and export-based growth to domestic consumption-oriented growth. It should also concern the future challenges on the energy use and emissions of the final demand of consumption, such as transportation and building energy use. From the supply-side, the substitution between energy and capital due to their perfect complementarity, and between alternative fuels, such as coal and natural gas, are important for the energy conservation and carbon emission abatement. More specifically, the policies should incentive the promotion and innovation of new technologies, such as the subsidization on IGCC power plant and hybrid vehicle etc, the pricing on the environment via emission tax or tradeable emissions permits. The international cooperation is also important for the issues of energy and emissions. These systemic issues cannot be solved once and for all. Chinese policymakers should continue to deepen reform to build up a market–based economy and energy system. Let markets, not governments, organize the use and distribution of energy resources and the environment.

6.2 Limitations and extensions of the study

There are three main contributions in this dissertation compared with previous studies. First, energy flow charts were provided to trace the energy flows throughout the Chinese economy and to visualize the complete picture of the energy system and its changes in China. Second, hybrid energy and environmental input–output models were proposed to analyze the driving forces of China's energy use and CO_2 emission and to illustrate the embodied energy use and emission in China. This hybrid I–O model presented China's consumption-based energy use and CO_2 emission, while the direct coefficient I–O model is still a producer-based energy and CO_2 accounting model. Third, this study constructed a parametric econometric model — the translog stochastic production model — to estimate the energy saving potential in China, differing from the non-parametric model widely adopted in other studies.

The limitations of this study include the problems related to the data and the methodologies. This dissertation was a data–intensive analysis. Hence, the reliability of the statistics is crucial to the accuracy of the estimation results. Statistical datasets required for this study included energy data, input–output tables, and macroeconomic data. China's energy statistics (mainly for coal) in the late 1990s and early 2000s have been questioned by many researchers. Although NBS revised the energy statistics for the years between 1996 and 2007, uncertainties regarding the quality of energy data still exist. NBS did not provide the data of biomass uses in China, which account for around 10% of China's TPES according to IEA.

Non-competitive import type input–output tables were required in this study. However, only competitive type I–O tables were available from the NBS. I assumed a fixed import ratio and non-direct export for imports to make non-competitive I–O tables. The price indexes were industry based but not commodity based. Therefore, there were inaccuracies when deflating the input–output tables to constant price. An energy balance table is a commodity by industry based data set, which does not match with the commodity by commodity based input–output table. This does not mean that all analyses should be rejected. Rather, the statistics should be treated as a starting point.

This study adopts methodologies from both demand-side, the hybrid input–output model, and supply-side, the translog stochastic production model, to analyze the energy use and CO_2 emissions. However, this dissertation did not provide the supply side analysis on Chinese energy system. The translog production function adopted in chapter 5 contains three input variables — labor, capital and energy, but the output variable is value added but not total production. I will finish the energy–emission–economic model by using general equilibrium models in my future research. Though a qualitative study on super cycles in energy prices was provided, the impacts of price change on energy use and emissions were ignored in this study due to the limitations of the method. I will conduct fuel prices forecasting via the time series model and the fuel price shock on the economy via CGE model. I will also consider the framework of inframarginal analysis to study Chinese energy system in my future research.

Appendix A

Energy units and prefixes

Table A.1
Energy units.

Energy Units	Symbol	Definition	J
1 Joule	J	=1 m·N=1 C·V=1 W·s	1
1 Kilowatt hour	kWh	=1 kW×h	3.6×10^{6}
1 Kilocalorie	Cal	=kcal=1000 cal	4187
1 British thermal unit	Btu		1055
1 Pound-force foot	lb_f ft	=g×1 lb×1 ft	1.36
1 Electron volt	eV	=e×1V	1.6×10^{-19}
1 Horsepower×second	hp s	=1 hp×1s	745.7
Energy equivalents	**Symbol**	**Definition**	**J**
1 Barrel (42 gal) of oil equivalent	boe	=5.8×10^{6} Btu	6.12×10^{9}
1 Ton of coal equivalent	tce	=7 Gcal	29.307×10^{9}
1 Ton of oil equivalent	toe	=10 Gcal	41.868×10^{9}
1000 Cubic feet of natural gas		=10^{6} Btu	1.09×10^{9}
1 Gallon of gasoline			1.32×10^{8}
1 Gram of uranium 235			8.28×10^{10}
1 Gram of deuterium			2.38×10^{11}
2000 Dietary food calories		=2000 kcal	8.3774×10^{6}
1 Solar constant×cm^2×sec			8.374

Data source: Mandil [2004].

Table A.2
Metric prefixes.

Prefix	Symbol	Definition	Prefix	Symbol	Definition
yotta	Y	1E+24	deci	d	1E−1
zetta	Z	1E+21	centi	c	1E−2
exa	E	1E+18	milli	m	1E−3
peta	P	1E+15	micro	μ	1E−6
tera	T	1E+12	nano	n	1E−9
giga	G	1E+9	pico	p	1E−12
mega	M	1E+6	femto	f	1E−15
kilo	k	1E+3	atto	a	1E−18
hecto	h	1E+2	zepto	z	1E−21
deca	da	1E+1	yocto	y	1E−24

Data source: Mandil [2004].

Appendix B

Default net calorific values and carbon contents

Table B.1
Default net calorific values (NCVs) and carbon contents of fossil fuels.

Fuel type		Net calorific value	Carbon Content
		kJ/kg, kJ/m^3	kg/GJ
Coal	Coal Raw	20,908	26.8
	Coal Cleaned	26,344	25.8
	Coal Washed	15,392	25.8
	Coal Briquettes	17,795	26.6
	Gangue	5,861	26.6
	Coke	28,470	29.2
	Coke Oven Gas	16,746	12.1
	Blast Furnace Gas	3,770	12.1
	Converter Gas	7,954	12.1
	Coal Gas not Coke Source	5,234	12.1
	Coke Other Products	33,820	22.0
Petroleum	Crude Oil	41,868	20.1
	Gasoline	43,122	18.9
	Kerosene	43,122	19.5
	Diesel Oil	42,703	20.2
	Fuel Oil	41,868	21.1
	Naphtha	43,961	20.0
	Lubricants	41,450	20.0
	Petroleum Waxes	40,000	20.0
	White Spirit	43,000	20.0
	Bitumen Asphalt	38,392	22.0
	Petroleum Coke	30,772	26.6
	Liquid Petroleum Gas	50,241	17.2
	Refinery Gas	46,053	15.7
	Petroleum Other Products	38,978	20.0
Natural Gas	*Natural Gas*	38,100	15.3
	LNG	51,500	17.5

Data source: IPCC [2006]; NBS [2014].

Appendix C

Energy flow charts of Japan, U.K. and U.S. in 2010

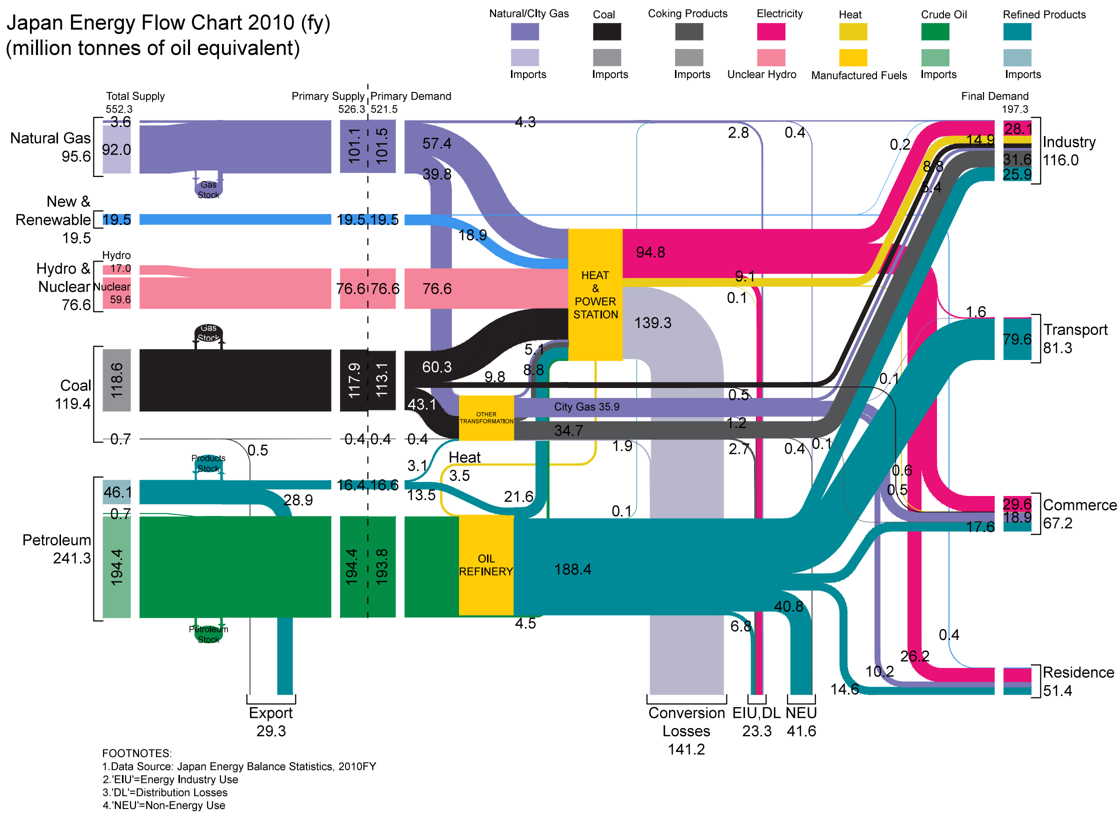


Figure C.1: Japan's energy flow chart 2010.

Data source: ANRE [2012].

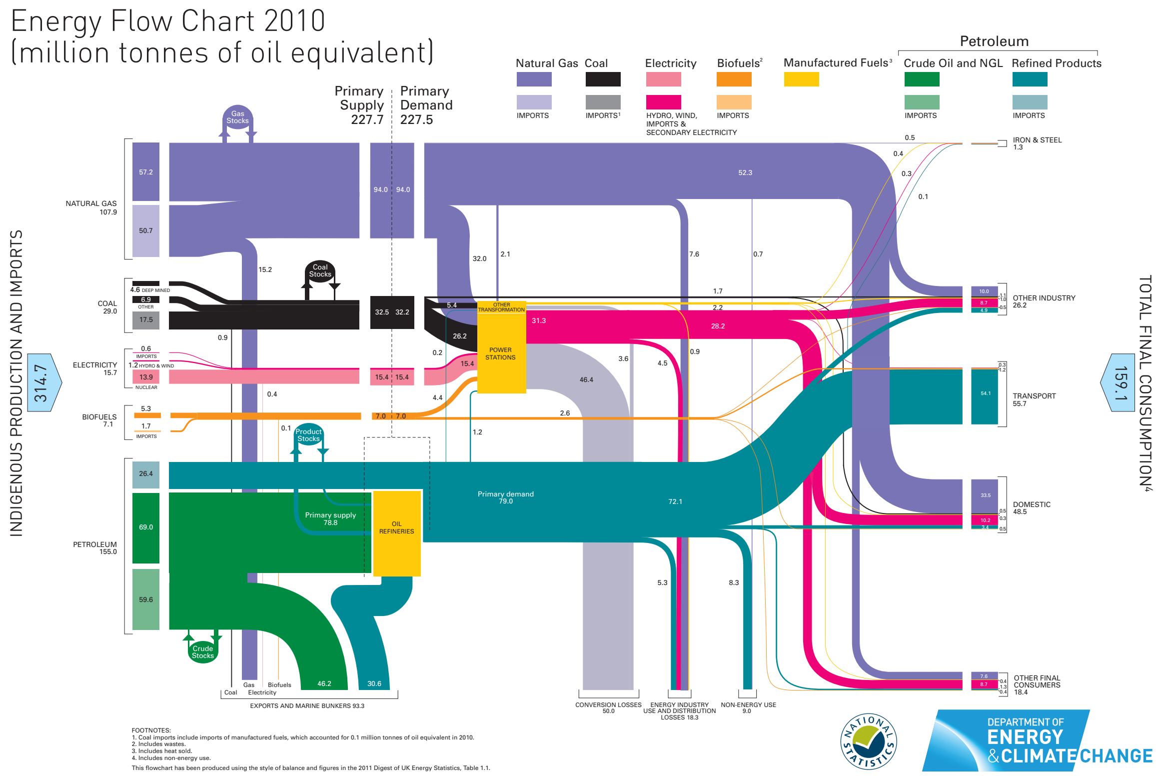


Figure C.2: U.K.'s energy flow chart 2010.

Source: DECC [2013].

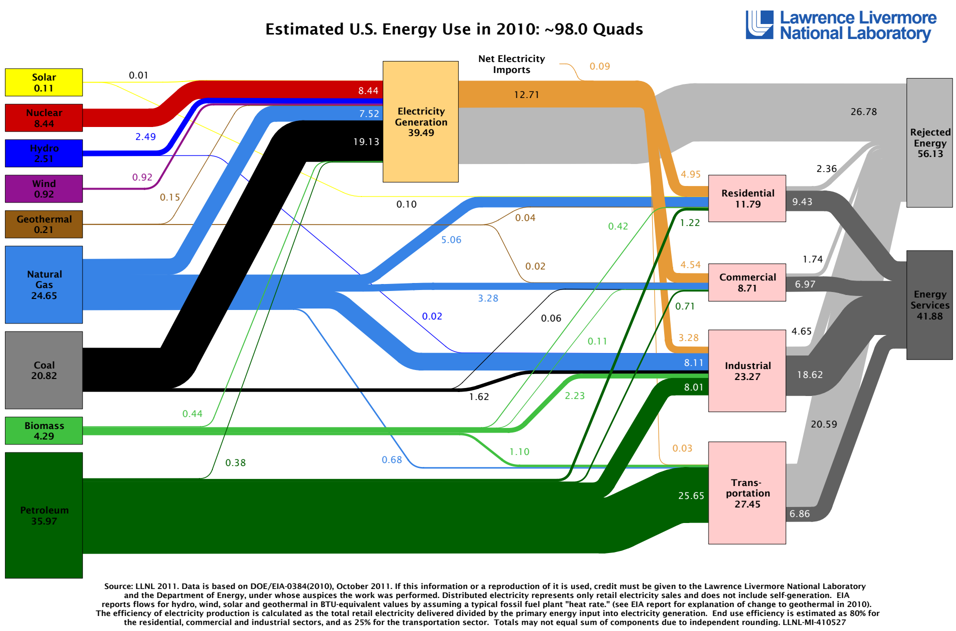


Figure C.3: U.S.'s energy flow chart 2010.

Source: LLNL [2011].

Appendix D

LMDI decomposition formulations

Based on Equation (3.14), assuming the aggregate (total energy use in this paper) is a function of n factors, $y = f(x_1, x_2, \cdots, x_n) = x_1 \cdot x_2 \cdots x_n$. The additive decomposition of the aggregate is through the total differential (total changes from all sources)

$$dy = \frac{\partial y}{\partial x_1}dx_1 + \frac{\partial y}{\partial x_2}dx_2 + \cdots + \frac{\partial y}{\partial x_n}dx_n = \sum_{i=1}^{n}\frac{\partial y}{\partial x_i}dx_i.$$

Suppose the kth factor changes from $x_{k,0}$ to $x_{k,T}$ and keeping all else factors constant, its impact on the aggregate can be expressed as

$$\Delta y_{x_k} = \int_{x_{k,0}}^{x_{k,T}} \frac{\partial y}{\partial x_k}dx_k = \int_{x_{k,0}}^{x_{k,T}} \frac{f(\cdots, x_k, \cdots)}{x_k}dx_k = \int_{x_{k,0}}^{x_{k,T}} f(\cdots, x_k, \cdots)dlnx_k$$

Using the weight function — the logarithmic mean divisia formulation, $\overline{y}^D = \Delta y/\Delta ln(y)$, the integral value is estimated by

$$\Delta y_{x_k} = \overline{f(\cdots, x_k, \cdots)}^D \Delta lnx_k.$$

Appling LMDI to Equation (3.20), the technological change effect is given by

$$\Delta \mathbf{e_G} = \sum_{m,n,o} \overline{\hat{\boldsymbol{\varepsilon}}\mathbf{G}\mathbf{B}^d\hat{\mathbf{d}}^d y^d p}^D \Delta ln\mathbf{G};$$

the products mix effect is given by

$$\Delta \mathbf{e_B} = \sum_{m,n,o} \overline{\hat{\boldsymbol{\varepsilon}}\mathbf{G}\mathbf{B}^d\hat{\mathbf{d}}^d y^d p}^D \Delta ln\mathbf{B}^d + \sum_{m,n,o} \overline{\hat{\boldsymbol{\varepsilon}}\mathbf{B}\hat{\mathbf{d}}yp\mathbf{v}}^D \Delta ln\mathbf{B};$$

the distribution effect is given by

$$\Delta \mathbf{e_d} = \sum_{m,n,o} \overline{\hat{\boldsymbol{\varepsilon}}\mathbf{G}\mathbf{B}^d\hat{\mathbf{d}}^d y^d p}^D \Delta ln\mathbf{d}^d + \sum_{m,n,o} \overline{\hat{\boldsymbol{\varepsilon}}\mathbf{B}\hat{\mathbf{d}} yp\mathbf{v}}^D \Delta ln\mathbf{d};$$

the level per capita effect is given by

$$\Delta \mathbf{e}_y = \sum_{m,n,o} \overline{\hat{\boldsymbol{\varepsilon}}\mathbf{G}\mathbf{B}^d\hat{\mathbf{d}}^d y^d p}^D \Delta ln y^d + \sum_{m,n,o} \overline{\hat{\boldsymbol{\varepsilon}}\mathbf{B}\hat{\mathbf{d}} yp\mathbf{v}}^D \Delta ln y;$$

and the population effect is given by

$$\Delta \mathbf{e}_p = \sum_{m,n,o} \overline{\hat{\boldsymbol{\varepsilon}}\mathbf{G}\mathbf{B}^d\hat{\mathbf{d}}^d y^d p}^D \Delta ln p + \sum_{m,n,o} \overline{\hat{\boldsymbol{\varepsilon}}\mathbf{B}\hat{\mathbf{d}} yp\mathbf{v}}^D \Delta ln p.$$

Appendix E

Elasticity of substitution in translog production function

Proof. Consider the LKE translog production function without time component

$$\begin{aligned}\ln y =&\alpha + \beta_L \ln L + \beta_K \ln K + \beta_E \ln E + \\ &\frac{1}{2}\beta_{LL}(\ln L)^2 + \frac{1}{2}\beta_{KK}(\ln K)^2 + \frac{1}{2}\beta_{EE}(\ln E)^2 + \\ &\beta_{LK}\ln L \ln K + \beta_{KE}\ln K \ln E + \beta_{LE}\ln L \ln E.\end{aligned} \tag{E.1}$$

The marginal rate of technical substitution of capital-energy, for example, is given by

$$MRTS_{EK} = \frac{MP_E}{MP_K} = \frac{\partial y/\partial E}{\partial y/\partial K} = \frac{\partial y/\partial \ln E}{\partial y/\partial \ln K}\cdot\frac{K}{E} = \frac{\eta_E}{\eta_K}\cdot\frac{K}{E}. \tag{E.2}$$

Then, the elasticity of substitution of capital-energy is

$$\begin{aligned}\sigma_{KE} &= \frac{d\ln K/E}{d\ln MRTS_{EK}} = \frac{d\ln K/E}{d\ln(\eta_E/\eta_K\cdot K/E)} = \frac{d\ln K/E}{d\ln \eta_E/\eta_K + d\ln K/E} \\ &= \left(1+\frac{d\ln\eta_E/\eta_K}{d\ln K/E}\right)^{-1} = \left(1+\frac{d\ln\eta_E - d\ln\eta_K}{d\ln K - d\ln E}\right)^{-1} \\ &= \left(1+\frac{d\ln\eta_E/d\ln E - d\ln\eta_K/d\ln E}{d\ln K/d\ln E - 1}\right)^{-1}.\end{aligned} \tag{E.3}$$

The elasticity of capital and energy are

$$\eta_K = \frac{\partial \ln y}{\partial \ln K} = \beta_K + \beta_{KK}\ln K + \beta_{LK}\ln L + \beta_{KE}\ln E \tag{E.4}$$

$$\eta_E = \frac{\partial \ln y}{\partial \ln E} = \beta_E + \beta_{EE}\ln E + \beta_{LE}\ln L + \beta_{KE}\ln K. \tag{E.5}$$

Taking the partial derivative of elasticity respect to energy, we have

$$\frac{\partial \eta_K}{\partial E} = \frac{\beta_{KE}}{E} \tag{E.6}$$

$$\frac{\partial \eta_E}{\partial E} = \frac{\beta_{EE}}{E}. \tag{E.7}$$

Rewriting Equations (E.6) and (E.7) we have

$$\frac{\partial \ln \eta_K}{\partial \ln E} = \frac{\beta_{KE}/\eta_K}{E/E} = \frac{\beta_{KE}}{\eta_K} \tag{E.8}$$

$$\frac{\partial \ln \eta_E}{\partial \ln E} = \frac{\beta_{EE}/\eta_K}{E/E} = \frac{\beta_{EE}}{\eta_E}. \tag{E.9}$$

Dividing elasticity of capital (Equation (E.4)) over elasticity of energy (Equation (E.5)) we have

$$\frac{\eta_K}{\eta_E} = \frac{\partial \ln y/\partial \ln K}{\partial \ln y/\partial \ln E} = \frac{\partial \ln E}{\partial \ln K}. \tag{E.10}$$

Substituting Equations (E.8), (E.9) and (E.10) into Equation (E.3), we obtain the elasticity of substitution of capital-energy as follows

$$\begin{aligned}
\sigma_{KE} &= \left(1 + \frac{d \ln \eta_E/d \ln E - d \ln \eta_K/d \ln E}{d \ln K/d \ln E - 1}\right)^{-1} \\
&= \left(1 + \frac{\beta_{EE}/\eta_E - \beta_{KE}/\eta_K}{\eta_E/\eta_K - 1}\right)^{-1} \\
&= \left(1 + \frac{-\beta_{KE} + \beta_{EE}\dfrac{\eta_K}{\eta_E}}{-\eta_K + \eta_E}\right)^{-1}.
\end{aligned} \tag{E.11}$$

The same procedure may be easily adapted to obtain the elasticity of substitution of labor-capital and labor-energy as follows

$$\sigma_{LK} = \left(1 + \frac{-\beta_{LK} + \dfrac{\eta_L}{\eta_K}\beta_{KK}}{-\eta_L + \eta_K}\right)^{-1} \tag{E.12}$$

$$\sigma_{LE} = \left(1 + \frac{-\beta_{LE} + \dfrac{\eta_L}{\eta_E}\beta_{EE}}{-\eta_L + \eta_E}\right)^{-1} \tag{E.13}$$

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