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Energy and Greenhouse Gas Emissions in China: Growth, Transition, and Institutional Change

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Abstract

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Global energy markets and climate change in the twenty first century depend, to an extraordinary extent, on China. China is now, or will soon be, the world's largest energy consumer. Since 2007, China has been the world's largest emitter of greenhouse gases (GHGs). Despite its large and rapidly expanding influence on global energy markets and the global atmosphere, on a per capita basis energy consumption and GHG emissions in China are low relative to developed countries. The Chinese economy, and with it energy use and GHG emissions, are expected to grow vigorously for at least the next two decades, raising a question of critical historical significance: How can China's economic growth imperative be meaningfully reconciled with its goals of greater energy security and a lower carbon economy?

Most scholars, governments, and practitioners have looked to technology — energy efficiency, nuclear power, carbon capture and storage — for answers to this question. Alternatively, this study seeks to root China's future energy and emissions trajectory in the political economy of its multiple transitions, from a centrally planned to a market economy and from an agrarian to a post-industrial society. The study draws on five case studies, each a dedicated chapter, which are organized around three perspectives on energy and GHG emissions: the macroeconomy; electricity supply and demand; and nitrogen fertilizer production and use.

Chapters 2 and 3 examine how growth and structural change in China's macroeconomy have shaped energy demand, finding that most of the dramatic growth in the country's energy use over the 2000s was driven by an acceleration of its investment-dominated, energy-intensive growth model, rather than from structural change. Chapters 4 and 5 examine efforts to improve energy efficiency and increase the share of renewable generation in the electric power sector, concluding that China's power system lacks the flexibility in generation, pricing, and demand to support further improvements in efficiency and scale up renewable generation at an acceptable level of cost and reliability. Chapter 6 examines energy use and GHG emissions from nitrogen fertilizer use, arguing that energy use and GHG emissions from nitrogen fertilizer use in China

are high relative to other countries because of China's historical support for small and medium-sized enterprises using domestic technology; its continued provision of energy subsidies to fertilizer producers; and its lack of a well-functioning agricultural extension system.

The case studies illustrate the limits of energy and climate policy in China without institutional reform. China's leaders have historically relied on economic growth to defer the difficult changes in political economy that accompany economic and social transition. However, many of the challenges of energy and climate policy require political decisions that reallocate resources among stakeholders. For instance, restructuring the Chinese economy away from heavy industrial investment and toward a higher GDP share of consumption will require financial sector reforms, such as interest rate liberalization or higher dividend payments for state-owned enterprises, that reallocate income from the industrial sector to households. Increasing power system flexibility will require price reforms that reallocate revenues and costs among generators, between generators and the grid companies, between producers and ratepayers, among ratepayer classes, and between and among provinces. Strong public interest institutions are needed to make these changes, which suggests that China's energy and GHG emissions trajectories will be determined, to a large extent, by the politics of institutional reform.

ACKNOWLEDGMENTS

This endeavor would never have been possible without the enduring love, support, patience, and faith of my wife Wendy Tao, who suffered me beyond all reason throughout my dissertation. My daughter, Kaia 睿蕾 Tao Kahrl, was conceived in the tail of the dissertation, and was an inimitable source of inspiration and motivation. I owe an enormous debt to my parents for their patient cultivation of my intellectual sensibilities. For that and their unconditional support I am forever grateful.

I had the great fortune of having a large, diverse, and instructive dissertation committee: David Zilberman, my chair, from whom I learned the importance of doing the things you believe in; Arpad Horvath, from whom I learned the joy of peeling back just one more layer; Dan Kammen, from whom I learned the value of balance between academic and applied research; David Roland-Holst, from whom I learned the importance of adding color to life; and Jim Williams, from whom I learned that a dash of creativity is always worth more than a cubic meter of rote analytics. A number of other professors at UC Berkeley provided indispensable guidance, most notably: Alex Farrell, scholar sans frontiers, who taught me that the best way to tackle new subjects is to go buy the textbook; John Harte, who taught me how to practice democratic science; and Margaret Torn, from who I learned that the most important questions are always the most basic. Nothing has so forged my identity as the ERG community, to whom I owe an existential debt. ERG is now such a core part of my values and method that I find it hard to imagine myself before it.

Over the course of my Ph.D I had the wonderful experience of working with staff at a joint Chinese Academy of Sciences – World Agroforestry Centre center in Kunming, China. For guidance and inspiration, I owe a debt of gratitude to Li Yunju, Su Yufang, Timm Tennigkeit, Horst Weyerhaeuser, and Xu Jianchu. I was also fortunate to work with staff at Energy and Environmental Economics, Inc., where I benefitted from the creativity of Ding Jianhua and the mentoring of Ren Orans, Snuller Price, and C.K. Woo. In understanding the Chinese, and indeed the U.S., electricity sector, Hu Junfeng has been a consummate colleague.

In undertaking and completing major intellectual endeavors it is the innumerable ghosts of past, present, and future to whom the greatest cumulative debt is owed — to the faceless authors, both long deceased and extant, of materials that have shaped the ideas in this dissertation; and to the faceless children, humanity's next generation, for whom the hope of a future more socially just and environmentally sustainable than our own has always been a tremendous, if amorphous, source of inspiration.

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Chapter 1

Introduction

发展才是硬道理 — 邓小平

Development is the only hard truth — Deng Xiaoping

In February of 2011 China officially surpassed Japan to become the world's second largest economy. The contrast with three decades prior could not have been more stark. In 1978, on the eve of reforms in agriculture that were to vault it into the modern world, China was a nation in economic, political, and social disarray, exhausted from a decade of violent revolution. In the following decades, economic growth on a scale and at a pace never witnessed in human history would indelibly but incompletely transform China's institutions and society, leaving it straddling the transient space between a planned and market economy, between an agrarian and a post-industrial society.

Like many other parts of its economy and society, China's energy consumption and greenhouse gas (GHG) emissions are products of this interplay between rapid economic growth and incomplete transition. An understanding of how energy and emissions are embedded in the political economy and social dynamics of China's transition process is essential context for more strategic and meaningful policy interventions, both domestic and international. However, this nexus remains poorly understood, in part because analyses of energy use and GHG emissions in China are often disciplinary and piecemeal. Transition is fundamentally a question of political economy and social change, but these are typically treated as exogenous in economic, energy, and earth systems modeling. Institutional and political analysis, which more explicitly addresses the role of transition in shaping policy, often downplays the physical roots of energy and earth systems. A more grounded understanding of how energy- and climate-related policymaking in China are shaped by transition requires an interdisciplinary perspective.

The future of energy consumption and GHG emissions in China has taken on a new, global sense of urgency over the past decade. China barreled into world energy markets in the 2000s, moving from a relative unknown to the world's second largest oil importer and, what most would have considered unimaginable a decade prior, a net coal importer in 2009.[1] The

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[1] China's rise up the crude oil import pecking order is nothing short of breathtaking. In 2000, China was the world's third largest oil importer, by virtue of its size, but its oil imports (1,401 thousand barrels per day [tbpd]) were just one-third of Japan's (4,242 tbpd). From 2000 to 2009, Japan's crude oil imports fell by 19% and China's grew 2.8 fold. Data are from the U.S. Energy Information Administration (EIA) website, "International Energy Statistics," http://www.eia.gov/countries/data.cfm (Accessed 11 October 2011). China had, throughout the 1980s, 90s, and

International Energy Agency (IEA) announced in 2010 that China had surpassed the U.S. as the world's largest energy consumer, a claim disputed by Chinese government agencies but nonetheless indicative of China's sudden emergence as a global energy consumer.[2] Just a decade earlier, the IEA had forecast that, by 2020, China's total primary energy consumption would still be 5% lower than U.S. 2000 levels.[3]

In response to rising energy, and particularly, coal consumption, China's central government set ambitious goals for energy efficiency and non-fossil fuel energy development during its 11th (2006-2010) and 12th (2011-2015) Five-Year Plans. These goals included nearer-term targets, such as reducing the economy's energy intensity by 20% below 2005 levels by 2010 and by 16% below 2010 levels by 2015, and longer-term term targets, such as increasing the share of non-fossil fuel energy to 15% of final energy consumption by 2020.[4] With strong central government support, China is now the world's largest manufacturer of solar photovoltaic (PV) modules and wind turbines (PEG, 2011).

Rapid growth in fossil fuel energy consumption over the 2000s dramatically increased China's carbon dioxide (CO_2) emissions, almost single-handedly pushing the world onto a worst case emissions scenario for fossil fuel CO_2 emissions.[5] Methane (CH_4) and nitrous oxide (N_2O) emissions in China also rose, as growing incomes and changing diets led to greater consumption of meat and more nitrogen intensive crops.[6] At the same time, with growing recognition of the

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most of the 2000s, been a small net exporter of coal. In 2009, this situation suddenly changed, with net coal imports (imports minus exports) reaching 103 million tons and US$8.2 billion. Data are from China's National Bureau of Statistics, China Statistical Yearbook series, accessible in English from http://www.stats.gov.cn/english/statisticaldata/yearlydata/ (Accessed 11 October 2011).

[2] In July 2010, the IEA announced that China had surpassed the U.S. as the world's largest energy consumer. The Chinese government, sensitive to this label, disagreed with the IEA's analysis, and in particular how the IEA had calculated primary energy use from non-combustion sources. See International Energy Agency, "China overtakes the United States to become world's largest energy consumer," http://www.iea.org/index_info.asp?id=1479 (Accessed 11 October 2011); Leslie Hook, "China denies IEA claim on energy use," Financial Times, www.ft.com/cms/s/0/6ca47fa2-9402-11df-83ad-00144feab49a.html (Accessed 11 October 2011).

[3] The IEA's 2002 World Energy Outlook forecasted that China's total primary energy supply (TPES) would reach 2,133 million tons oil equivalent (Mtoe) by 2020 (IEA, 2002); in 2000, the IEA reports that U.S. TPES was 2,307 (IEA, 2007).

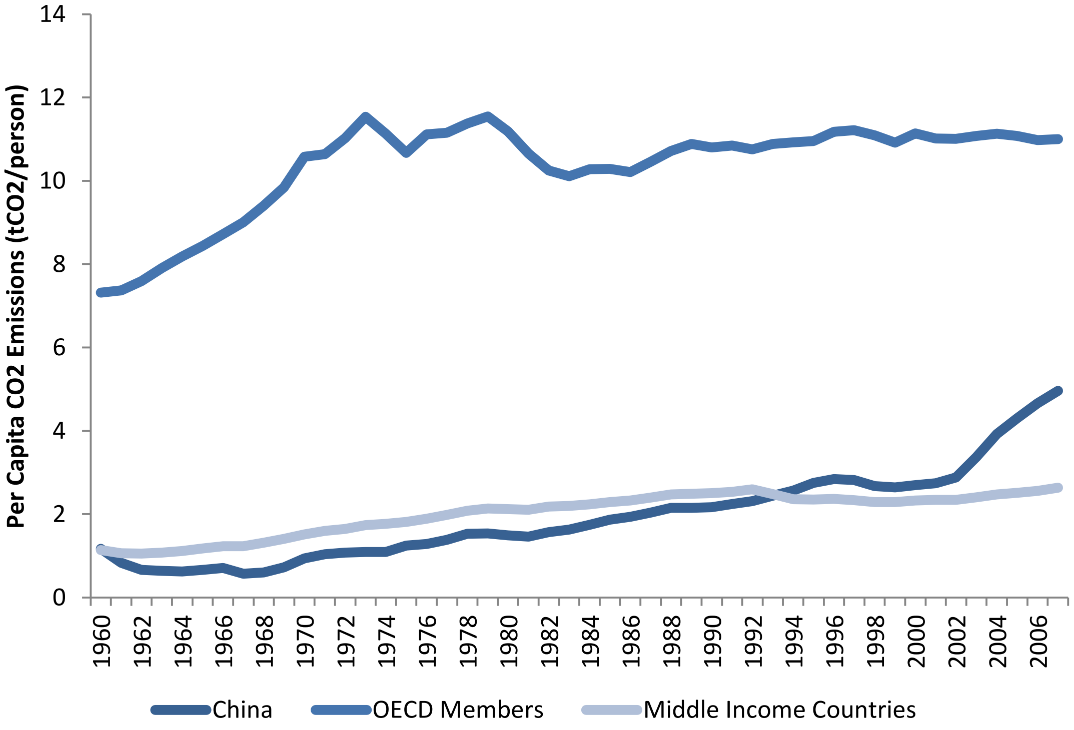
[4] The language for the energy intensity target in the 11th Five-Year was *about* 20% (单位国内生产总值能源消耗降低 20%左右), which means that these energy intensity targets, while binding, are also somewhat flexible. China's original alternative energy goal was to achieve 15% of primary energy consumption from renewables, including large hydropower, by 2020. In 2009, this target was changed to final energy consumption, and the qualifying energy sources were broadened to include nuclear. See Martinot (2010) for a description.

[5] From 2000 to 2009, China accounted for 75% of the 1.8 GtC increase in global, energy-related CO_2 emissions, which rose to 8.3 GtC by 2009. IPCC basic A1 and A2 scenarios (i.e., not including sub-scenarios) for fossil fuel CO_2 emissions in 2010 range from 7.8 GtC (A1 MARIA) to 10.0 GtC (A1 ASF), with an average of 8.6 GtC. CO_2 data are from EIA, "International Energy Statistics," http://www.eia.gov/countries/data.cfm (Accessed 18 October 2011). Emissions scenario data are from IPCC SRES Emissions Scenarios – Version 1.1, available at: http://www.grida.no/climate/ipcc/emission/data/allscen.htm (Accessed 18 October 2011).

[6] China has not conducted a national GHG inventory since 2000, which estimated emissions for 1994. Increased CH_4 and N_2O emissions are inferred from higher levels of meat production, which increased 27% between 2000 and 2009 (NBS, 2010) and nitrogen fertilizer use, which grew by 27% from 2002 to 2009. Nitrogen fertilizer data

risks to China, climate change has become a priority policy issue for China's central government. After the 2009 Copenhagen Climate Change Summit, China committed to reduce the CO_2 intensity of its economy by 40-45% below 2005 levels by 2020.

Figure 1. Per Capita CO_2 Emissions, China, Middle Income Countries, and OECD Members, 1960-2007



Notes and Source: China has been removed from "Middle Income Countries." Data are from the World Bank Development Indicators & Global Development Finance World databank, http://databank.worldbank.org (Accessed 20 October 2011).

Even with rapid growth in energy consumption and GHG emissions, per capita levels of energy consumption and emissions in China are still low relative to OECD countries (Figure 1). Economic growth remains the Chinese Communist Party and government's chief concern. In 2002, China's National Congress set a target of quadrupling the size of the country's 2000 gross domestic product (GDP) to reach three income milestones of a "well off" (小康 | xiaokang) society by 2020: GDP per capita of around 22,000 to 25,000 yuan, urban per capita disposable income of 22,000 yuan, and per capita net rural income of 6,860 yuan (Saich, 2009). This notion of a well off society, and what it represents historically and geopolitically, is hardwired into political discourse in China. As a result, China's energy and climate policy are both oriented around the notion of 'development space.'

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are from the FAOSTAT database, http://faostat.fao.org/default.aspx (Accessed 20 October 2011). FAO data have a discontinuity at 2002, which is why 2002, rather than 2000, is used as a base year.

The apparent contradiction between the growth imperative and the aims of energy and climate policy, raises a number of questions: What are the drivers of energy consumption and GHG emissions in China? When and how will China's energy consumption and emissions growth begin to slow? How meaningful are China's energy and climate goals? How likely are they to be met? What policy and political choices will determine whether they are met? Answers to all of these questions, many of which are open ended, depend on the resolutions to China's multiple transitions, from a centrally planned to a market economy, from a centralized to a more pluralistic polity, and from an agrarian to a post-industrial society.

This study examines how these transitions have shaped, and will continue to shape, energy and climate-related policy in China. To gain the disciplinary breadth and substantive depth to address the questions posed here, case studies provide an ideal working material. I use three case study themes: 1) energy demand and the macroeconomy; 2) electricity supply and demand; and 3) nitrogen fertilizer production and use. Each theme illustrates different aspects of the relationship between transition and energy and climate policy in China.

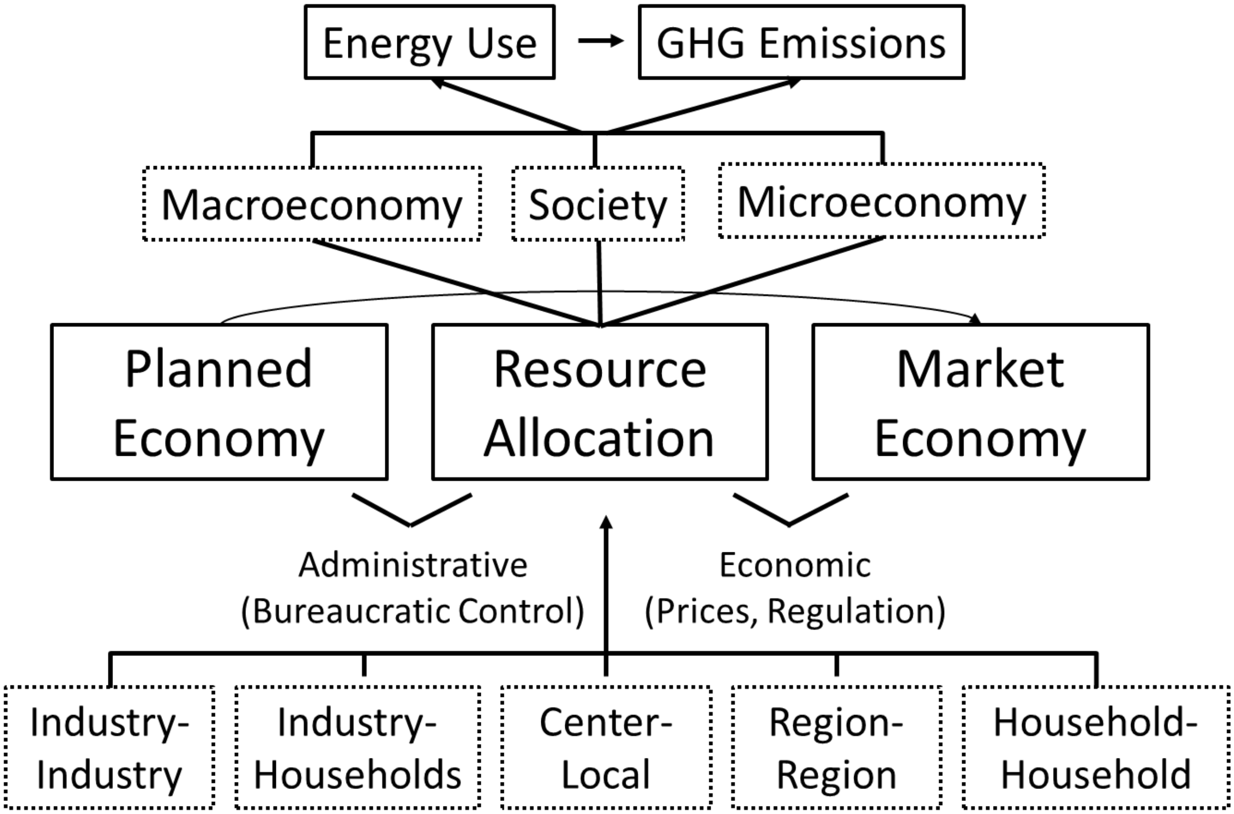
The study is organized into five parts. The remainder of this introduction unpacks the notion of 'transition' and traces its evolution in China's recent history, establishing a conceptual framework for the analysis. The core text includes five chapters, which are designed to be read as stand-alone pieces. The first two of these chapters (chapters 2 and 3) examine how growth and structural change in China's macroeconomy have shaped energy demand. The next two chapters (chapters 4 and 5) describe how the planned economy roots of China's electric power system constrain policies to improve power system efficiency and reduce the share of coal in electricity generation. The last chapter (chapter 6) examines why nitrogen fertilizer production and use in China are an important GHG source, and how a domestic offset program could be used to fund a fertilizer efficiency program. The final, concluding chapter draws from the individual case studies to address the study's hypotheses and make closing arguments.

Transition: Concepts and History

The word 'transition' is perhaps most often associated with transition economies, those countries that, from different degrees of central planning in the middle of the 20th century, began to implement market-oriented reforms toward the century's end. Yet transition also describes the process of socioeconomic development, from agrarian to industrial and finally to post-industrial societies, as well as the demographic and geographic shifts that accompany this development transition. In China, the lines between reform and development were often blurred (Naughton, 1999), and the word transition is used here to refer to both the gradual dismantling of the planned economy and the process of socioeconomic development.

While some of its elements may occur as a matter of course, transition is primarily an outcome of active reform. Seen from this perspective, transition outcomes are neither predetermined nor inevitable, depending instead on the scale and direction of reforms with regard to how resources are allocated. Resource allocation mechanisms are the most fundamental difference between planned and market economies, and as such are the hinge of transition. In planned economies, the state allocates most resources — capital, labor, land, natural resources — through administratively determined output quotas, credit allocation, and prices. In market economies, prices and, in natural monopoly industries, regulators, allocate most resources. China's incomplete reforms have left it straddling plan and market, with a significant portion of the economy exposed to market forces and an equally significant portion under administrative control.

Figure 2. A Framework for Transition, Energy, and Emissions in China



Changes in resource allocation that accompany transition reforms influence energy demand and GHG emissions primarily through their impact on changes in the macroeconomy (e.g., the balance of consumption and investment), the microeconomy (e.g., price subsidies, regulation), and society (e.g., urbanization) (Figure 2). GHG emissions can either be a direct outcome of these changes (e.g., N_2O emissions from nitrogen fertilizers as a result of urbanization and changing diets), or an energy byproduct of them (e.g., a rising share of investment in energy-intensive sectors increases fossil fuel energy consumption, which produces CO_2 emissions).

As in all countries, the political economy of resource allocation in China is characterized by five primary resource conflicts, between: industry and industry; industry and households; central and local governments; region and region; and between households, rural and urban and younger and older generations. These five conflicts are the undercurrents of China's transition process, at times facilitating and at times obstructing reforms.

Contrary to most analyses of energy and climate policy in China, which focuses only on the top, and at most the top two, layers of Figure 2, this study posits that energy demand and GHG emissions are embedded in the political economy of China's transition process. Within this framework, technology is an outcome of deeper changes in political economy rather than a starting point for analysis. Because energy and emissions are bound up in larger processes of political economy, I argue that China's transition to a low carbon economy will be determined more fundamentally by politics and institution building than by technology. The conclusions address and expand on this hypothesis.

Transition, like all change, is path dependent. Elucidating China's transition path requires tracing its roots back to the planned economy. The historical narrative that follows is organized around three themes that capture four of the five resource conflicts in Figure 2: industrial organization and policy (industry-industry and industry-households); center-local dynamics (center-local); and urbanization, household economics, and demography (household-household). This narrative provides critical context for understanding the discussion in the individual chapters, and the synthesis in the conclusion.[7]

Industrial Organization and Policy

Government ownership of the means of production is at the core of central planning, and in that sense the industrial economy is the most important element of both the planned economy and its reform. Almost all the elements of a modern economy in China, including its financial system and regulatory apparatus, have emerged from within the planned economy. Although corporatization and downsizing of state-owned enterprises (SOEs), privatization, and the emergence of regulatory institutions have fundamentally changed China's industrial sector, in important ways it remains strongly rooted in its past.

Under the planned economy, China had no meaningful price or financial system. Prices of agricultural goods and other staples were set artificially low, in order to maintain a cheap supply of food and other staples for workers in urban work units. Urban wages were kept low and stable. Prices for manufactured goods were set artificially high, with the surplus reinvested in new production capacity. Production targets took the place of prices, and the price system lost all other function aside from redistributing resources. This process of allocating and reallocating resources was done by government agencies through the state's monopoly bank; individual enterprises had little discretion over investment and production decisions.

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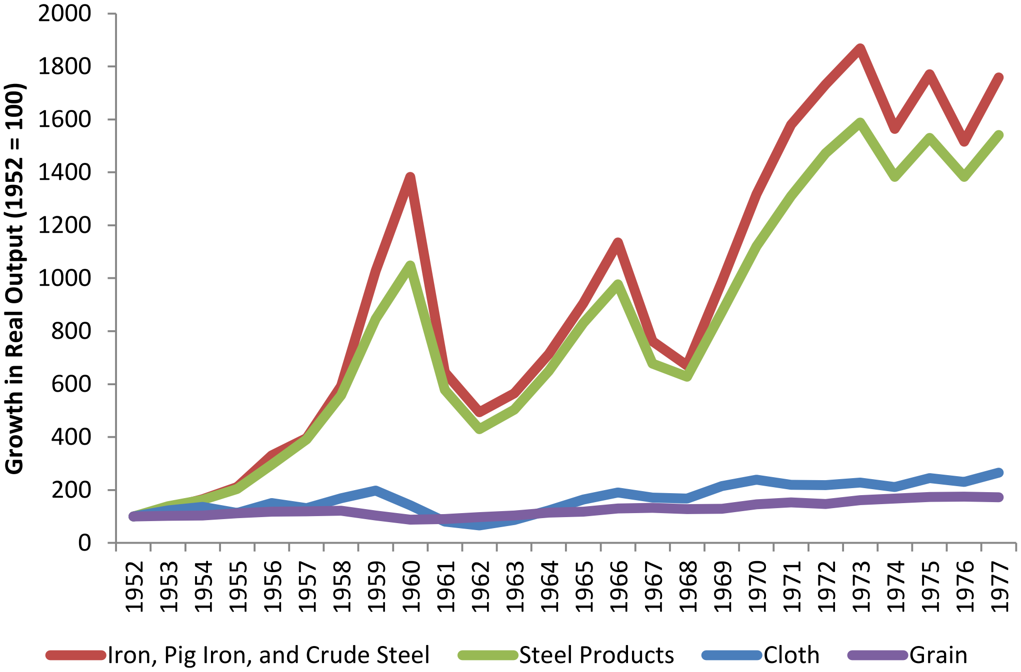
[7] The narrative in these sections draws heavily on several excellent histories of China's reforms and development, particularly Liew (1997), Wu (2005), and Naughton (2007). This section also benefitted from multiple conversations with David Roland-Holst, Jim Williams, and David Zilberman.

Figure 3. Growth in Real Output of Iron and Crude Steel, Steel Products, Cloth, and Grain, 1952-1977



Source: Data are from the China Statistical Yearbook series, accessed from China Data Online.

The singular focus of the planned economy was the rapid expansion of heavy industrial output, or what is commonly referred to as the "Big Push" strategy, and the price system served to channel most of the economy's resources into investment in heavy industry. Subject to the cycles of revolutionary politics and investment pushes,[8] this strategy successfully expanded heavy industrial output, though at the expense of the agricultural, light manufacturing, and services sectors. For instance, iron and steel output grew by nearly 20-fold between 1952 and 1977, while cloth and grain output grew by around 3- and 2-fold, respectively (Figure 3).

China hewed only selectively to the Soviet model of industrialization, pursuing an industrial system that was generally more decentralized in decision-making and relied more heavily on small enterprises. China's system of resource allocation was also much less ambitious than the Soviet system, focusing more on developing large industrial projects than on planning and

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[8] Each of the spikes in steel production in Figure 3 is associated with a policy campaign. The rapid increase in production in 1958 was part of the Great Leap Forward. The increase in 1963-64 marks the beginning of the Third Front. The rapid decline in production in 1966 reflects the beginning of the Cultural Revolution. The increase in 1970 was part of a "new leap" during the Cultural Revolution (Naughton, 2007). That growth in iron and crude steel often exceeds and precedes growth in steel products reflects the overriding emphasis on primary industrial production for its own sake.

coordinating the entire economy.[9] Isolated internationally in the 1960s, China created an enormous inland industrial supply chain (the "Third Front") in preparation for war, which had to rely primarily on domestic technology and which was disastrous economically.[10]

Technologically, these differences meant that China's capital stock was much more heterogeneous than that of the Soviet Union. Whereas the Soviet model was geared toward large, centralized factories, China pursued a "walking on two legs" policy beginning in the late 1950s that emphasized smaller-scale, locally manufactured technologies for one leg, and larger, more advanced ones for the other. The two legs policy focused on five industries in particular: cement, energy (coal mining and hydropower), iron and steel, machinery, and synthetic ammonia and chemical fertilizer. Particularly in the 1960s and 70s, central government policy promoted development of these industries in rural areas to support and complement agriculture.[11] By 1978, small firms accounted for just over a third of heavy industrial output (Hsueh and Woo, 1986).

Despite achieving lasting gains in average health and education, China's economic system under the plan proved unworkable, even during those interludes when the country was politically stable. Naughton (2007) provides two reasons for the failure of the industrial push strategy. First, agriculture was never able to generate enough food to keep pace with industrial growth. Second, and related, heavy industry, being capital rather than labor intensive, was never able to absorb surplus labor.[12]

China's initial reforms, which began on a limited scale in 1978, were in agriculture. Under the household responsibility system that was institutionalized and extended nation-wide in the early 1980s, farmers were allowed to sell any output over a set quota at market prices. This dual-track approach became the workhorse of China's reform efforts, and was later extended to the industrial sector, fiscal policy, and monetary policy. The genius of the dual-track

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[9] In general, the Chinese approach to central planning was much more pragmatic than the more comprehensive Soviet approach. Chinese planners never allocated more than 600 products, where Soviet planners were allocating 60,000 products by the 1970s (Naughton, 2007). Soviet planning also made more intensive use of mathematics and computation.

[10] When the Soviet Union withdrew its technical and financial support in 1960, China was left with major gaps in industrial production capacity, and was forced to rely on indigenous technologies and innovation to overcome these. During the Third Front, a huge number of industrial enterprises were strategically built in remote mountain locations, but because of poor planning and their remoteness were never economically viable. Naughton (1988) argues that the cost of the Third Front to the Chinese economy was higher than the cost of the Cultural Revolution.

[11] Riskin (1971) provides the canonical overview of the development of small-scale industry in China over this time period.

[12] Although intuitively a third reason would seem to be that overinvestment in heavy industry meant that the economy was producing surpluses of goods for which there was no demand, and shortages of goods for which there was, comparison with the 1980s shows that this may have not been a limiting factor for economic growth. Large inventories, reflecting an overhang in supply from overinvestment, continued into the 1980s and 1990s. From 1952 to 1977, inventory changes accounted for a simple average of 24% of gross capital formation; from 1978-1990, this average had fallen only to 20% while GDP growth had, with the exception of a downturn in 1989, been largely sustained. Data are from the China Statistical Yearbook series, accessed from China Data Online.

approach was in its facilitation of gradual transition, maintaining the stability of the planned system but providing market incentives at the margin. With rapid growth in the market track and slower growth, and even decline, in the planned track, China began to literally grow out of the plan (Naughton, 1995). By raising the average standard of living, China's reformers were able to build a large and broad constituency for reform — a reform without losers (Lau et al., 2000).

Flexibility, and government involvement, in the financial system and enterprise development were also key pillars in the success of China's reforms of the 1980s. The increase in average wages that resulted from the dual-track system amounted to a significant transfer of income from the state to households, which led to a sharp rise in household savings. Aggressive efforts were made to protect household deposits from inflation, often at the expense of banks, and high household saving rates in turn gave the financial system continued access to funds to finance high levels of investment.[13] Although SOE markets were not explicitly opened for competition, the government did not prevent township and village enterprises (TVEs) from entering traditional SOE markets and eroding their high profit margins. TVEs were typically small, rural, quasi-public firms that combined private sector managerial expertise with public sector connections.

Reforms were cemented in the 14th Congress of the Community Party in 1992, which officially recognized China as a socialist market economy. By the early 1990s, the dual-track system had all but disappeared, and the challenges of reforming China's industrial system had shifted to providing the legal and regulatory institutions needed for restructuring SOEs and creating a stable business environment. Corporate governance reforms began in the early 1990s, but accelerated in the late 1990s, when the scale of problems caused by the blend of government-backed firms and local government control of the banking sector became more apparent.

Two decades of soft budget constraints, where firms knew, or at least expected, that they would be supported regardless of performance, had wreaked havoc on China's banks. By the end of the 1990s, the scale of non-performing loans (NPLs) had grown to 40% of total lending and around one-third of GDP, threatening the solvency of China's financial system (Naughton, 2007). From 1998 to 2005, China's leaders undertook a number of urgent measures to transfer NPLs off of the banks' balance sheets and push the banks toward international standards of governance and risk management. The NPL problem was, however, never truly resolved.[14]

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[13] See Naughton (2007) for a description. Very high consumer inflation in the early 1990s, reaching 24% in 1994, eroded this protection and effectively made returns on deposit accounts negative for the next decade. Data are from the China Statistical Yearbook series.

[14] Bad loans were purchased from the banks at face value by asset management companies (AMCs), which in turn were funded primarily by 10-year bonds sold to the AMCs by the banks. These bonds came due in 2009 but were extended for another 10 years. For a detailed description of the NPL crisis and how it was handled, see Walter and Howie (2011).

A corollary of the NPL problem was the deteriorating financial shape of urban SOEs, at least part of which was caused by their inability to lay off workers until the late 1980s. In the mid-1990s, SOEs began to dramatically downsize, laying off nearly 30 million workers between 1993 and 2003 (Naughton, 2007). This massive restructuring effort was the only radical policy move during China's entire reform process, intended to strengthen performance of the state sector. It was accompanied by a significant reduction in the number of central government managed firms and the creation of an oversight body to manage them, the State-owned Assets Supervisory and Administration Commission (SASAC). This move focused the state sector on industries that either had strategic importance or high barriers to entry, including energy, metallurgy, defense, and telecommunications.

The creation of SASAC was one among several efforts to create a legal framework and independent regulation to govern the industrial marketplace, particularly in traditionally non-competitive sectors. These efforts have met with mixed success. Regulators, for instance, are often independent in name only and have limited powers over the sectors they are meant to regulate.[15] Difficulties in establishing public interest regulation are, in a sense, the cost of China's gradual approach to transition, which created a complex political economy of vested interests that stand in the way of reforms.[16]

In important ways China's industrial sector remains rooted to its past. This connection is perhaps strongest in finance. In 1994, as SOE restructuring was just beginning, policymakers exempted SOEs from paying dividends to the state, allowing enterprises to reinvest any profits, which at the time were virtually non-existent. This exemption lasted until 2007, and dividend collection from SOEs remains small though their profits have grown substantially.[17] A second policy with implications for industrial finance is the ceiling on interest rates for deposit accounts and the floor on lending rates, announced in 2002, which protects the banking system and lowers the cost of maintaining a fixed currency at the cost of an artificially low cost of capital and a huge penalty on savers.[18] Though perhaps unintentionally, both policies have contributed to the continued high share of investment and heavy industry in the Chinese economy.

Center-Local Dynamics

The relative position and strength of the central state is an enduring theme across China's history, tracing back to the founding of a unified state under the Qin dynasty in the 3rd century

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[15] For a discussion of the challenges faced by efforts to create a regulatory state in China, see Pearson (2005) and Pearson (2007).

[16] For discussion and an example, see Naughton (2008) and Naughton (2011).

[17] In late 2010, the government announced plans to increase the dividend payment from firms in non-competitive industries to 15% of after-tax profits, and from firms in competitive industries to 10% of after-tax profits.

[18] Lardy (2008) argues that the main beneficiary of this policy is the government, which has a lower cost of sterilization. Although firms have lower borrowing costs, they also receive lower interest on deposits. The net benefits to companies are, on average, small but would likely be skewed toward the state sector.

BCE.[19] Oscillations between centralized and decentralized decision-making were a salient feature of China's planned economy. The reform period, which inherited these oscillations, has seen a gradual, non-monotonic trend toward greater local autonomy, but without clearly and constitutionally defined powers and responsibilities for local government. The center-local dynamic in China is characterized by ambiguity, which provides flexibility but has weakened public service provision.

In the early years of central planning, China's leadership quickly realized the shortcomings with the Soviet model of administrative centralization, in particular its lack of an adequate incentive structure. In 1958, China began the first of what would be several attempts at decentralizing economic decision-making, granting significant autonomy to local governments over production targets, planning, project design and budgeting, and bank credit allocation. All of these decentralization campaigns ended in economic and social disorder and eventually recentralization. The fundamental problem, as Wu (2005) describes, was that China's leaders were of the implacable belief that resources should be allocated administratively, and so confused administrative decentralization with the need for economic decentralization.

The 1978 reforms again granted more autonomy to local governments, which provided incentives for investment but at the price of local protectionism and a chronic sense of looming instability. Local governments were often partners in the development of TVEs, which played a pivotal role in fostering competition in industries traditionally dominated by SOEs. At the same time, local governments protected their own enterprises, which hindered the creation of national markets. Local governments also engaged in "competitive money creation" (Liew, 1997), where they used local banks to fuel local investment booms, which kindled inflation. Maintaining the tenuous balance between rapid growth and stability required the continued presence of a strong central government.

Strong central government was also essential for ensuring more gradual transition. Liew (1997) and Lau et al. (2000) argue that the most important reason for the success of the dual-track system in China was rigorous enforcement of production quotas. In the absence of a strong central government, as was the case in the former Soviet countries, the dual-track system becomes untenable because resources are largely diverted out of the state track and into the higher reward market track. China's central government was able to enforce discipline largely because of the Communist Party's hierarchical control over personnel decisions in local governments and state enterprises.

In the early 1990s the central government began to strengthen its legal and regulatory authority vis-à-vis local governments. However, with the planned economy all but eroded and tax administration decentralized to local governments, the central government was without a stable revenue base with which to fund an expansion of its functions and bureaucracy. Fiscal

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[19] For a description of the cycles of creation and collapse of central state authority in China, and their importance in defining China's early political culture, see Fukuyama (2011).

reforms in 1994 remedied this problem, by creating a single value added tax and centralizing tax administration, with a portion of tax revenues returned to local governments. In practice, however, local governments were left with significant unfunded public service obligations. Many turned to extra-budgetary revenue sources, such as fees on land development. Over time this made revenue generation a focus of local government, obscuring their service obligations and blurring the line between government and business.[20]

The trend toward increasing decentralization in China's reform period, combined with the gradual erosion of the authority of the Communist Party, has produced a de facto federalism (Zheng, 2006). The lack of a more formal delineation of powers has provided administrative flexibility, but with conflicts in incentives and constituencies between each level of government, the result has been an excessive reliance on negotiation to ensure local compliance with central directives. The lack of stronger accountability mechanisms and a fiscal system that matches services and resources has weakened China's ability to govern (Wong, 2009).

Urbanization, Demographic Change, Income Growth

China was historically a rural, agrarian country. When the Communist Party came to power in 1949, an estimated 90% of the total population, at the time 540 million persons, was living in rural areas.[21] Urbanization has dramatically reduced the share of China's rural population, even as its absolute size has increased. By 2010, almost exactly half of the 1,341 million person population was officially categorized as 'rural.'[22] Continued urbanization, demographic change, and rising incomes will present the most substantial and far-reaching challenges for policymaking in China.

By diverting resources out of agriculture, China's command economy implicitly encouraged labor migration into industry, where the marginal product of labor was higher. During the rapid industrialization of the early Great Leap Forward (1958), migration to the cities was quite high, but the combination of more people to feed and less people and resources in agriculture led to famine of epic proportions. As the scale of the famine became apparent, China's leaders closed off the cities, imposing restrictions on mobility through a strict registration system. The result was a dualistic urban-rural society, where urban workers, who received basic staples from their work units, were privileged at the expense of rural peasants, whose wages and standard of living were artificially suppressed.

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[20] For a review of the challenges administrative and fiscal reforms have created for public service delivery, see World Bank (2005) and Saich (2008). In an influential article, Wang (2006) argues that local governments have become "quasi-corporate" (准企业). Wong (2009) argues that fiscal reforms had a radical impact on the practice of government in China, and, because they were not accompanied by a reshaping of government, effectively led to a privatization of public services.

[21] Data are from the China Statistical Yearbook series, accessed from China Data Online.

[22] Some of the decrease in rural population is the result of changing classifications. Chan and Hu (2003) estimate that reclassification accounted for 22% of urban population growth over the 1990s, whereas 60% of the increase in urban population was through rural-urban migration.

Economic reforms saw the resumption of rural-urban migration, as export businesses began to tap into the abundant surplus of rural labor. However, a cautious approach to rural land markets and continuation of the registration system tempered the pace of urban migration. Official statistics understate the scale of China's urban population; the size of its "floating population" of temporary migrants is difficult to determine.[23] Officially, however, and unlike many other parts of the world, urbanization in China has been relatively gradual. Still, and even though the rate of China's urban population growth has slowed since the 1990s, the sheer size of China's population means that its urban population has been growing by more than 100 million persons per decade since the 1980s (Table 1). If urban population growth is at least 2.9% yr^{-1} between 2010 and 2019, China's urban population will expand by more than 200 million persons over the next decade.[24]

Table 1. Urban Population Growth Rates and Absolute Growth in China, 1970-2009

Decade	**Growth Rate (% yr^{-1})**	**Absolute Growth (million persons)**
1970-1979	2.8	41
1980-1989	4.9	104
1990-1999	4.2	136
2000-2009	3.9	186
2010-2019	> 2.9	> 200

Source: Data are from the China Statistical Yearbook series, accessed from China Data Online

Economic reforms dramatically increased household incomes and consumption, with more than five-fold growth in real household consumption between 1978 and 2010. Urban consumption has been much higher than rural consumption since the 1950s, but the gap between the two has widened over time (Figure 4). The gap fell in the late 1970s with reforms in agriculture, but grew dramatically in the 1980s and more steadily in the 1990s. A leveling off of the urban-rural consumption ratio in the late 2000s was driven by high rates of urban, relative to rural, inflation.[25] Given China's huge rural population, the large differential between urban and rural consumption is an important contributor to the low share of household consumption in GDP.

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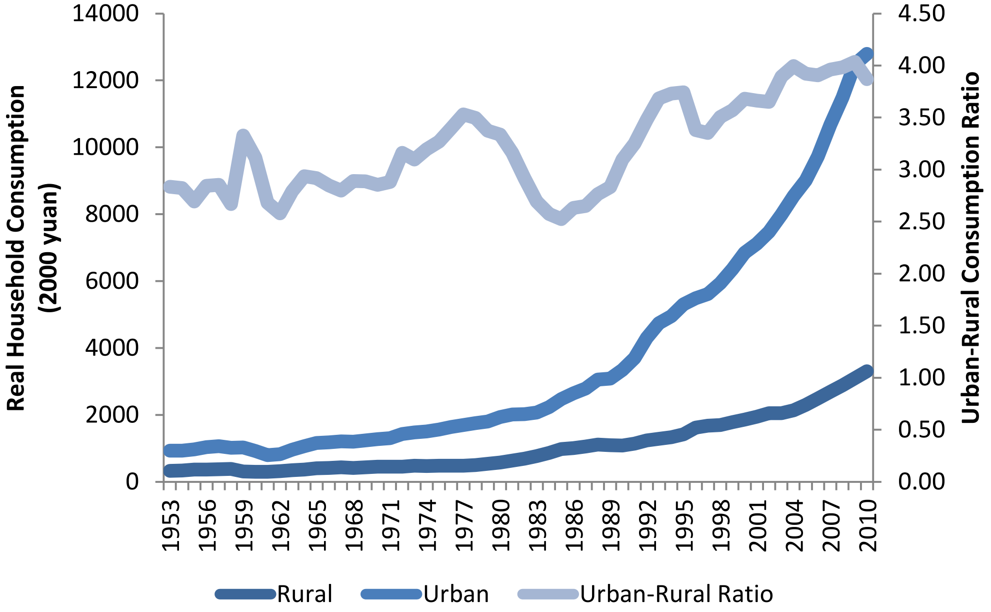
[23] See Zai and Ma (2004) for a discussion of the methodological challenges in estimating the size of the temporary migrant population. They estimate that, in 2000, China's floating population was 79 million persons.

[24] The annual rate of population growth is $r = e^{\frac{ln(P_T)-ln(P_t)}{T-t}} - 1$, where P_T is the population in year T, P_t is the base year population, T is the final year, and t is the base year. In this case P_t is 669.78 million, P_T is 669.78 million + 200 million = 869.78 million, and T-t = 2019 – 2010 = 9.

[25] Nominal growth in urban consumption was actually higher than rural consumption over this time period.

Figure 4. Real Urban and Rural Consumption, and Urban-Rural Consumption Ratio, China, 1953-2009



Notes and Source: Price indices for the pre-1980 period should be viewed with caution. Consumption and price index data are from the China Statistical Yearbook series, accessed from China Data Online.

A more important contributor to the low share of household income in GDP, and to the decline in that share in the 2000s, is the investment orientation of the domestic economy, as described above. Aziz and Li (2007) find that the disproportionately small share of households in the Chinese economy has more to do with the share of household income in national income than household savings, although the two are related. High and rising household savings is tied to, inter alia, inflation expectations, low rate of return on savings, the lack of a social safety net, and levels of public spending on health and education that are well below world averages (Figure 5).[26]

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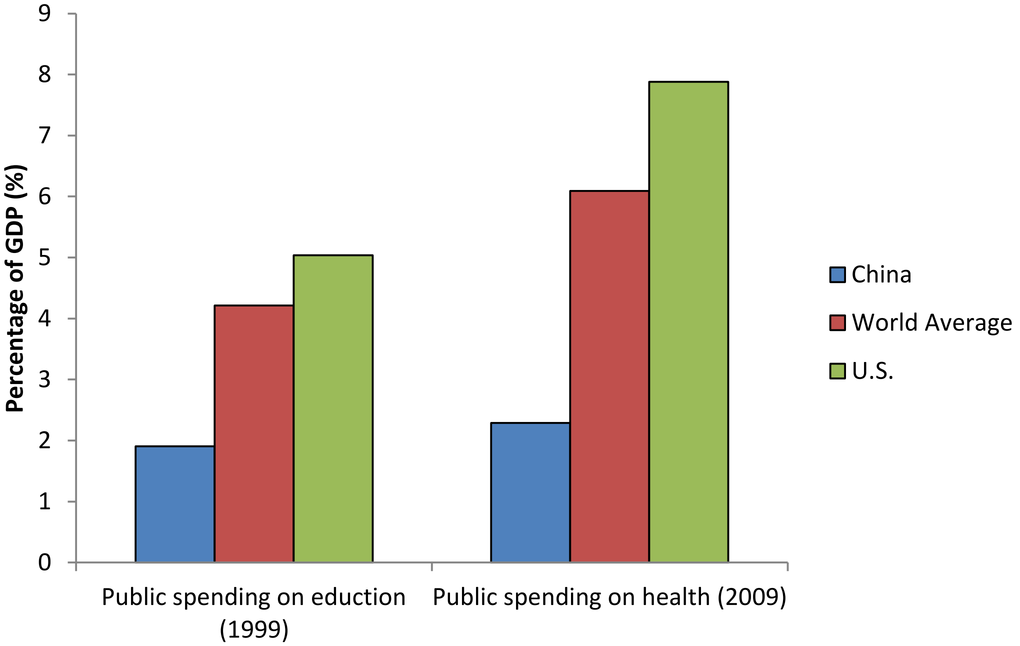
[26] The declining share of household income in national income has been mirrored by an increasing investment-GDP ratio, which has historically been associated with inflationary cycles. The ceiling on bank base deposit rates is effectively a wealth transfer from households to firms, but also means that households need to save more to meet savings goals. One source of funding for basic entitlement programs in China would be SOE retained earnings. Household savings rates in China fell from the early 1990s to 2002 but then rose dramatically from 2002 (25% of disposable income) to 2008 (39% of disposable income). Data are from the flow of funds tables in the China Statistical Yearbook series. The high and rising household savings rate in China has also been attributed to a decline in the dependency ratio and household incomes rising faster than consumption. For more on household savings in China see Wiemer (2008) and Chamon et al. (2010).

Figure 5. Public Spending on Education and Health, China, World Average, and U.S.



Notes and Source: 1999 was the last year that data on education spending were available for China, world average, and the U.S. Since 1999, China has significantly ramped up education spending in rural areas, though, given that GDP growth was so rapid over the last decade, it is not clear whether this spending is large enough to bring China closer to world average levels. Data are from the World Bank Development Indicators & Global Development Finance World databank, http://databank.worldbank.org (Accessed 8 November 2011)

A rapidly aging population may be China's most serious longer-term policy challenge. Two major population booms, one during the Qing dynasty (1644-1911) and one during the 1950s and 60s, dramatically expanded the size of China's population. In response, China began to institute population control policies in the 1970s, and the one-child policy from 1978 to the present. While population control policies have succeeded in reducing the trajectory of China's population growth, they have calibrated the course for a rapidly aging society. With current trends, by 2050 the U.S. Census projects that the share of China's working age population will fall from its current level of 66% to 55%, a level lower than that of contemporary Japan.[27] China's aging problem is ultimately a financial one, and the need to "get rich" to support an older population means that, as a society, China has a high opportunity cost of capital.

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[27] In 2011, Japan's working age population was 58% of its total population. Working age population is defined as the portion of the population from age 20 to 65. "Current levels" for China are 2011. Data are projections from U.S. Census Bureau, "International Data Base," http://www.census.gov/population/international/data/idb/informationGateway.php (Accessed 16 October 2011).

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Chapter 2

Growth and Structural Change in China's Energy Economy[1]

The Chinese economy's energy needs have increased dramatically since the turn of the millennium. A combination of sustained high rates of economic growth and structural shifts in energy use in the lead up to and following China's accession to the World Trade Organization (WTO) in December 2001 is responsible for this rapid growth in energy demand. From 2002-2006 China's primary energy demand growth (27.7 EJ, 13% annual average growth) exceeded its energy demand growth over the previous two decades (26.8 EJ, 4% annual growth from 1980-2002) (NBS, 2007). After declining steadily from 1980-2002, the Chinese economy's energy intensity began to increase after 2002 (Figure 6). The externalities associated with changing energy demand patterns in China are considerable. From 1980-2002 China accounted for 30 percent of the net growth in global energy-related CO_2 emissions; from 2002-2005 this share rose to 53 percent (EIA, 2008).

Changes in the Chinese economy's energy use after 2002 have been paralleled by two major changes in economic structure. First, investment increased dramatically after 2001 and overtook household consumption as the largest component of China's GDP in 2004. By 2006, investment had reached 43 percent of real GDP (1990 yuan) (NBS, 2007). Second, trade (both imports and exports) grew substantially, from 43 percent of GDP in 2002 to 64 percent of GDP in 2006 (NBS, 2007). Export growth was particularly robust, with the real value of exports rising to near parity with domestic household consumption in 2006 (Figure 7). In short, a significant portion of China's post-2001 GDP growth has been driven by investment and export growth. Since 2001 investment and exports have grown faster than aggregate GDP (Figure 8), while household and government consumption have grown at rates near or slower than overall GDP growth (Figure 9). As we demonstrate below, these compositional changes in the Chinese economy are important determinants of energy use and its associated externalities.

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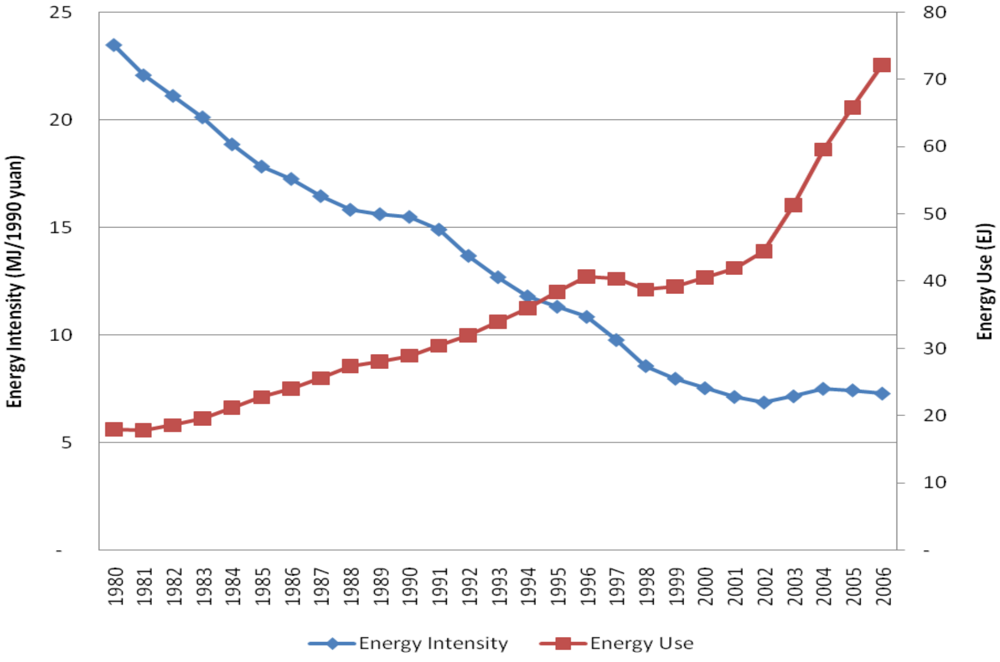
[1] This chapter was originally published as Kahrl, F., Roland-Holst, D., 2008. Growth and Structural Change in China's Energy Economy. Energy 34, 894-903.

Figure 6. Energy Intensity and Energy Use in China, 1980-2006



Sources: Energy and GDP data are from NBS (2007); GDP data are in 1990 yuan, adjusted using the IMF's deflator for China.

Growth and structural change in China have different implications and pose different challenges for policymakers, both in China and abroad. The interplay between growth and intensity is particularly important in the context of international climate negotiations. Rapidly growing countries like China have high uncertainty in economic and attendant energy demand growth. These countries are less likely to commit to binding, absolute reduction targets that do not account for growth uncertainty. Chinese government proposals to reduce CO_2 emissions, to the extent that they have mentioned targets, have indeed focused on CO_2 intensity targets rather than absolute reduction targets.[2] Quite apart from international climate negotiations, in response to the unexpected surge in energy demand during its 10th Five-Year Plan (2001-2005) the Chinese central government set a binding goal of reducing the energy intensity of the country's GDP by 20 percent during its 11th Five-Year Plan (2006-2010), and has made determined efforts to adjust the structure of the country's economy away from energy-intensive production (IEA, 2007). However, without a clearer understanding of the drivers of rising energy use and intensity in China, it remains unclear what kinds of policies will be most effective for reducing the energy-related impacts of sustained growth in the Chinese economy.

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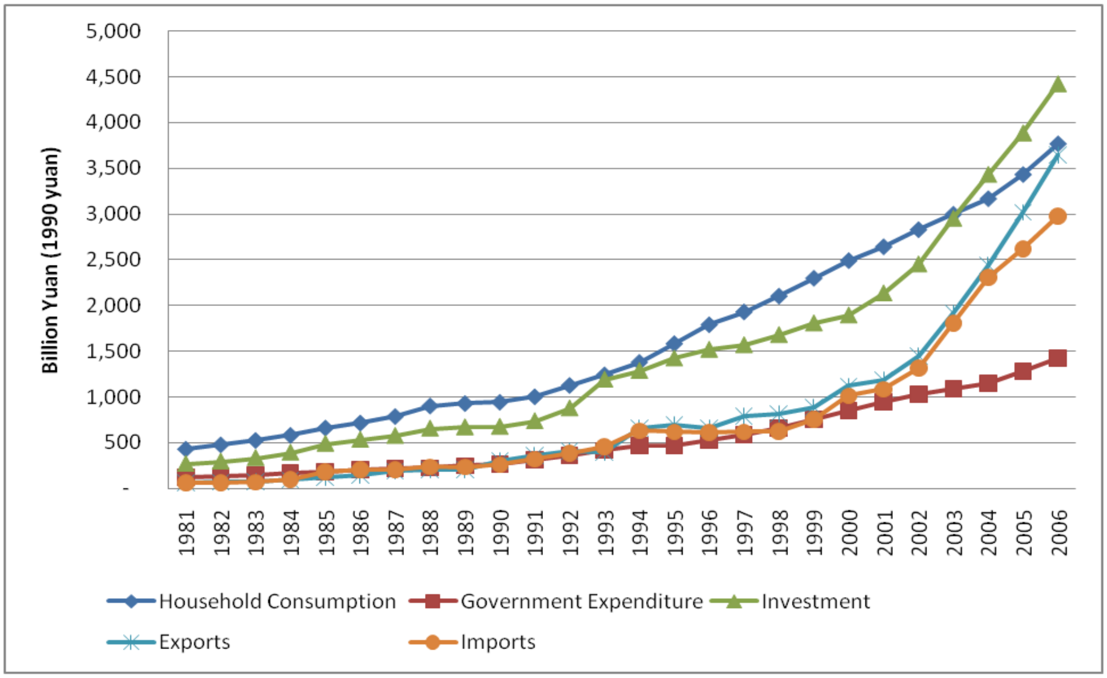
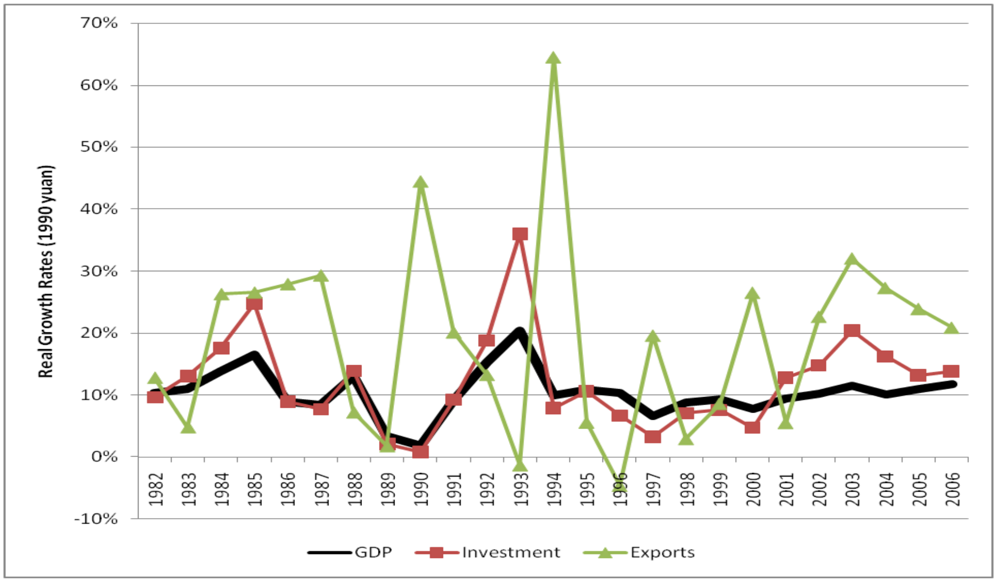
[2] The draft of China's *First National Climate Change Assessment* reportedly includes a goal of reducing the carbon intensity of the Chinese economy by 40% by 2020 and 80% by 2050 (Herzog, 2007). The final draft of *China's National Climate Change Programme* (NDRC, 2007) contains no mention of any targets.

Figure 7. Household Consumption, Government Expenditure, Investment, Exports, and Imports, China, 1981-2006



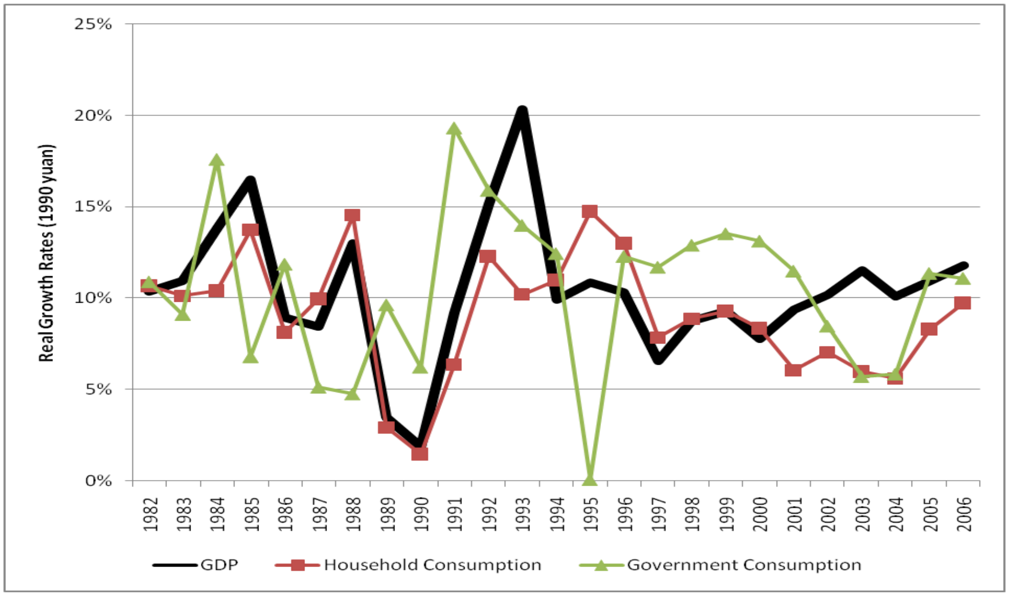
Sources: Data are based on revised NBS GDP estimates, drawn from China Data Online website, chinadataonline.org. All figures are in 1990 yuan, adjusted using the IMF's deflator for China.

Figure 8. Real GDP, Investment, and Export Growth Rates, 1981-2006



Sources: Data are based on revised NBS GDP estimates, drawn from China Data Online website, chinadataonline.org. All figures are in 1990 yuan, adjusted using the IMF's deflator for China.

Figure 9. Real GDP, Household Consumption, and Government Consumption Growth Rates, 1981-2006



Sources: Data are based on revised NBS GDP estimates, drawn from China Data Online website, chinadataonline.org. All figures are in 1990 yuan, adjusted using the IMF's deflator for China.

Explanations for the post-2002 shift in the Chinese economy's energy intensity have thus far focused on supply-side forces, including a marked increase in the share of heavy industry in China's economic output since 2002 (Lin et al., 2006; Rosen and Houser, 2007). While not disputing heavy industry's role among supply-side forces, attention to demand-side drivers of energy consumption throughout the Chinese economy is equally important for designing forward-looking, macroeconomic policies that reduce the energy intensity of China's economic growth. This paper examines the domestic energy consumption embodied in China's final demand — the sum of all energy used domestically to create the goods and services used by domestic households, government, businesses (through investment), and foreigners (through exports).

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

Data Sources and Adjustments

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

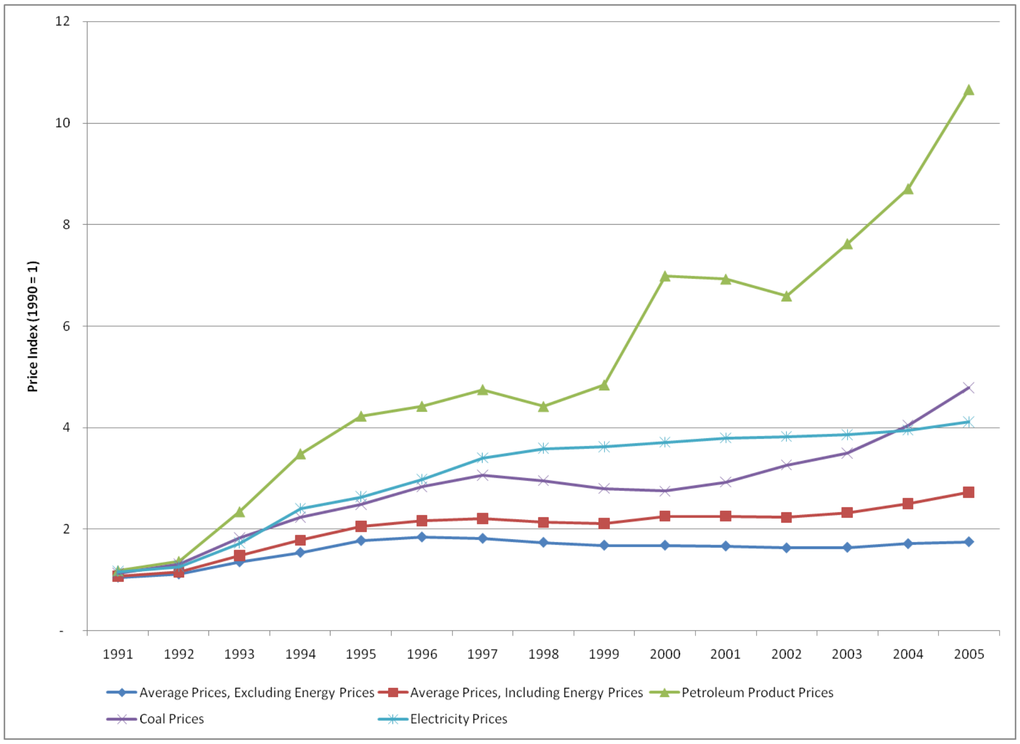
Two major recent data revisions by the NBS — corrections to GDP and energy use estimates — have implications for both I/O and energy input tables. In addition, the NBS I/O tables are in current prices and the intermediate use portions of the tables do not account for the fact that, over the past decade,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

In 2006 the NBS undertook a significant revision to national GDP estimates to correct a long-standing bias against the small business and the services sector in economic data collection (Naughton, 2007). Both the 2002 and 2004 tables account for this revision; the discrepancy between 2002 and 2004 I/O tables and 2006 statistical yearbook data for 2002 and 2004 consumption and investment is infinitesimal. Discrepancies between the 1997 I/O table and 2006 NBS data for 1997 GDP are substantial. The I/O table underestimates GDP by roughly 12 percent, household consumption by 6 percent, government consumption by 22 percent, and investment by 11 percent relative to 2006 estimates (NBS, 2007). Correcting this GDP underestimate in the 1997 table requires scaling both the final expenditure and value added portions of the table to reflect NBS revisions. While scaling final expenditure is relatively straightforward using an assumption of homothetic preferences, because revised statistics for value added at a sectoral level are not available, scaling value added for each sector by an averaged GDP correction coefficient likely introduces a non-trivial source of error into the I/O coefficients matrix. Additionally, revising the 1997 I/O table to account for NBS GDP revisions does not significantly affect our results. For these reasons we use the original 1997 table throughout this analysis.

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

China's energy prices have risen considerably over the past decade, while wholesale price rises for other industrial goods have reportedly been more stable (Figure 10). Because we use energy intensity measures to convert between monetary transactions in the I/O table and physical energy use, accounting for higher relative energy prices is important for ensuring consistency across different years. This is particularly true because, over the past decade, China's energy prices have often not moved in tandem. During the period from 1997-2002, for instance, coal and oil prices were almost perfectly out of step. To account for changing relative energy prices in the intermediate economy, we use a relative energy price index based on NBS data on inter-annual changes in ex-factory prices for coal, oil, and electricity (NBS, various years), normalizing these prices to both a base year (1990) and the general price index. Changing relative prices for energy sectors disrupts the symmetry of the I/O tables, which requires rebalancing them (see below). Correcting for disproportionate changes in relative energy prices does not ultimately have a significant effect on either the shares or intensities of embodied energy in final demand, and the results we report below are based on uncorrected prices.

Figure 10. Ex-Factory Coal, Oil, Electricity, and Average Prices in China, 1991-2005 (1990 = 1)



Sources: Based on NBS (various years).

We close our discussion of data sources with a few thoughts on the accuracy of NBS data. China's economic and energy statistics have come under greater scrutiny in recent years, often in tandem (Rawski, 2001; Sinton, 2001; Naughton, 2007). The afore-mentioned NBS data revisions indeed reflect the difficulties of maintaining data accuracy in a rapidly changing, increasingly decentralized economy where information remains highly politicized. That said, there are indications that NBS economic and energy data is not without grounding in reality. For instance, NBS data on exports comport with data from other countries; if GDP estimates were grossly underestimated, exports would now comprise an even larger share of China's GDP than they do currently (Naughton, 2007). The dramatic shock to China's energy and commodity markets after 2002 (Fang, 2006) also suggests that the country's resource use has indeed greatly accelerated over the past five years, a fact that accords with official economic and energy data. Finally, as Naughton (2007) notes the NBS is the only source of comprehensive data on the Chinese economy. As this data plays a role in Chinese policymaking, analyses based on NBS data are important for improving its accuracy and for providing common ground for policy research. By maintaining a critical eye and comparing a range of data sources, in this article we attempt to do both.

Methods

In tandem, China's I/O and energy input tables provide insight into the flows of energy throughout its economy, as these extend over long supply chains from extraction and processing to intermediate use and eventually into final goods and services. Combining the two tables integrates the economic structure of I/O tables with the energy consumption patterns characteristic of different sectors. To integrate the tables, we use a sectoral intensity technique common in energy and environmental I/O analysis (UNSD, 1999; Casler and Wilbur, 1984; Hendrickson et al., 1998).

Input-Output Tables

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

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

$$T^* = R'TC \tag{1}$$

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

Input-Output Multipliers

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

$$\begin{bmatrix} T & Y \\ V & 0 \end{bmatrix} \tag{2}$$

where T is an n x n matrix of inter-industry transactions for n industries, V is a k x n matrix of k value added accounts, and Y is an n x m matrix of m final demand sources. Y includes the four principle components of final demand: household consumption, government expenditure, investment, and net exports.

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

$$\sum_j x_{ij} + Y_i = X_i \tag{3}$$

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

$$x_{ij} = a_{ij}\hat{X}_j = AX \tag{4}$$

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

Substituting equation 3, equation 2 can be rewritten as

$$AX + Y = X \tag{5}$$

X has the solution

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

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

Energy Multipliers

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

$$\alpha = \hat{X}^{-1}E \tag{7}$$

where $\hat{X}\mathrm{X}^{-1}$ is the diagonalized matrix of sector outputs.

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

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

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

$$EE_{ik} = \varepsilon_j Y_{ik} \tag{9}$$

where EE_{ik} is the energy embodied in final demand activity k's final demand for sector i, ε_j is the embodied energy intensity for sector i, and Y_{ik} is activity k's demand for sector i. In this analysis, k = 4 and includes household consumption (C), government spending (G), gross capital formation (I), and exports (EX).

It is important to emphasize that α is a vector of primary, and not secondary, energy intensities. Primary energy inputs here include coal, crude oil, and natural gas. Hydropower, nuclear, and wind energy are included as inputs into the 'Production and Supply of Electricity and Heat' sector, based on data from EBCEPY (various years). Note that this method differs from but is ultimately consistent with an approach where all energy inputs are allocated to the extractive sectors and all other sectors have an energy intensity of zero. To harmonize energy inputs across sectors and we convert the physical units listed in the energy input tables to energy units using heating values recommended by the Intergovernmental Panel on Climate Change (IPCC, 2006).

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

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

$$E = \hat{X}^{-1} E M_L Y \tag{10}$$

Imports

Imports are often, but not always, contained in both the intermediate use and final demand portions of I/O tables. For the NBS tables, we confirm that imports are included in the intermediate use and final demand portion of the table by examining the oil and gas extraction

(O&GE) sector. The 2002 I/O table records total intermediate and final use of O&GE products (import inclusive) at 421.8 billion yuan, or US$34.8 billion. In 2002, China imported 69.4 million tons of crude oil at a total value of US$12.8 billion, or roughly US$25 per barrel. Assuming, in line with consumption data, that the bulk of these US$34.8 billion in expenditures are for crude oil, and that US$25/barrel is an upper limit on domestic prices, total crude oil consumption in the Chinese economy would be on the order of 1.6 billion barrels, which matches statistical yearbook data (NBS, various years).

Because our focus is on domestic primary energy consumption, for most of this analysis we use a domestic I/O table, which has the imports removed. Ideally, expunging imports from intermediate and final use statistics could be accomplished through the use of industry surveys that provide detailed information on imports by sector. In most cases, however, this information is not available and assumptions are required about the import content of intermediate and final goods. The most commonly used import content assumption is that imports are homogeneous components of both intermediate and final goods, excluding exports (UNSD, 1999), and using an import ratio to systematically remove them.

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

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

Actual removal of imports is done through

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

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

After making corrections to prices and imports, column and row sums in our 39-sector I/O tables are no longer equivalent. To restore I/O table symmetry, the tables must be rebalanced so that column and row sums are once again equal. We use a cross-entropy method (Robinson et al., 1998) to rebalance the tables and arrive at a consistent set of accounts.

Results: Growth and Structural Change

Aggregate Trends

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

Table 2. Annualized Growth in Final Demand, Embodied Energy, and Embodied Energy Intensity (%)

		HH	GOV	INV	EX	TOT
1997-2004	Final Demand	8%	14%	13%	17%	12%
	Embodied Energy	4%	6%	6%	9%	6%
	Energy Intensity	-3%	-8%	-6%	-7%	-6%
2002-2004	Final Demand	5%	6%	17%	27%	14%
	Embodied Energy	12%	13%	17%	28%	18%
	Energy Intensity	7%	7%	0.1%	1%	4%
1997-2002	Final Demand	9%	18%	12%	13%	12%
	Embodied Energy	1%	3%	2%	2%	2%
	Energy Intensity	-7%	-13%	-9%	-10%	-10%

Notes: HH is households; GOV is government; INV is investment; EX is exports; TOT is total. "Total" here refers to an economy-wide average.

First, the energy intensity of all final demands decreased significantly between 1997 and 2004, as each final demand source grew faster than its embodied energy consumption (Table 2). This decline was driven to a large extent by slow, two percent annual average energy demand growth between 1997 and 2002, a trend which changed abruptly after 2002 (NBS, 2007). The energy intensity of exports and government expenditure recorded the most rapid declines, while the energy intensity of household consumption decreased more slowly than other final demands. It is important to note in Table 2 that the annualized change in intensity is not equal to the difference between the annualized growth in embodied energy and final demand, though the two values are in fact close. Intuitively, if final demand grows faster than energy use then energy intensity falls, and vice versa.

Second, declines in intensity over 1997-2004 mask a minimum in 2002, and between 2002-2004 the energy intensity of all final demands increased, driven by higher embodied energy use (Table 2). This increase in embodied energy use is consistent with and ultimately identical to the 16 percent growth in total energy use between 2002-2004 reported in statistical yearbooks (NBS, 2007); the discrepancy between this 16 percent and the 18 percent reported in Table 2 is the result of NBS energy data corrections, which we discuss in Data Sources and Adjustments, above. Increases in energy intensity were driven predominantly by household and government consumption. Due to compositional shifts that we describe below, the energy intensity of investment and exports remained relatively constant over this time period, despite a four percent economy-wide increase in energy intensity.

Table 3. Shares of Total Embodied Energy, 1997-2004

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

Notes: Shares may not add to one due to rounding. Export shares reported here are higher than the shares we report elsewhere (Kahrl and Roland-Holst, 2008), both because the denominator here does not include primary energy consumption by households and because the methods we use in the two papers are different. It is important to note that these shares are necessarily estimates, and that a more accurate accounting would require a more accurate allocation and removal of imports through the use of sectoral import surveys.

Third, differing rates of expenditure and embodied energy growth led to a shift in the shares of embodied energy from 1997-2002 to 2002-2004 (Table 3). Shares of embodied energy did not change significantly between 1997 and 2002. After 2002, household and government expenditure's share of embodied energy declined roughly 9 percent on an annualized basis, whereas the share of exports grew by roughly 9 percent on an annualized basis. Despite 17 percent annual average growth from 2002-2004, investment's share of embodied energy remained roughly constant between 2002 and 2004.

In each of the three periods in question — 1997-2002, 2002-2004, and 1997-2004 —the economy-wide mean ("Total" in Table 2) provides a useful nucleus for thinking about relative shifts in the embodied energy shares and intensity of household and government consumption, investment, and exports. Despite its rising energy intensity, consumption declined as a share of total energy demand in the Chinese economy from 2002-2004 because growth in consumption (5 percent annual) was so much lower than economy-wide final demand growth (14 percent annual). Investment's share of energy demand remained constant, as the energy embodied in investment grew (17 percent annual) slower than total energy demand growth (18 percent) and investment grew (17 percent annual) faster than total final demand (14 percent annual). Exports' share of domestic energy consumption rose significantly from 2002-2004, as exports and export-induced energy demand (27 and 28 percent annual, respectively) grew faster than respective economy-wide averages.

Table 4. Embodied Energy Intensities, 1997-2004 (MJ/1990 yuan)

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

Energy intensity can be similarly analyzed. The energy intensity of consumption rose from 2002-2004 as the energy embodied in consumption grew faster than consumption growth. Investment and export energy intensity remained relatively constant because embodied energy and expenditure grew at roughly the same rate (Table 4). Intensity across final demands fell from 1997-2004 as GDP grew faster than energy consumption. The decline in China's energy intensity from 1997-2002 has recently been the subject of intensive study, focusing primarily on whether real or structural factors are behind reductions in intensity (Zhang, 2003; Fisher-Vanden et al., 2004; Wang et al., 2004; Fan et al., 2007; Hang and Tu, 2007; Liao et al., 2007; Ma and Stern, 2008; Han et al., 2007). An emerging consensus is that efficiency gains, including rising relative energy prices and technological change, drove energy intensity declines in China over this period. China's post-2002 experience highlights the importance of final demand-specific factors as drivers of changes in energy intensity.

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

Compositional Shifts within Final Demands

We focus our discussion here on compositional shifts within investment and consumption, which together form the key fulcrum of current macroeconomic imbalances within the Chinese economy (Hu, 2007). Exports are the fastest growing source of both final demand and embodied energy in China, and a shift to higher value added products should reduce their energy intensity. However, China's export regime and its broader economic and resource implications warrant greater coverage than we can provide here, and we provide more detailed discussion of the composition and embodied energy implications of exports elsewhere (Kahrl and Roland-Holst, 2008).

Investment is the largest and most energy-intensive part of China's GDP. Gross capital formation[3] in China, both in terms of value and in embodied energy, has historically been dominated by the construction sector. In the NBS I/O tables we examine, the construction sector accounted for a range of 52-71 percent of investment spending and 58-74 percent of the

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

total energy embodied in investment (2004-1997 and 2004-2002 I/O tables, respectively) over the period 1997-2004; construction sector investment accounted for 18-23 percent of China's total domestic energy use over this time period.[4] As the Chinese economy has become increasingly manufacturing intensive, the construction sector's share of investment spending and investment embodied energy have fallen, at a gradual two percent and one percent annual average, respectively, from 1997-2002. Between 2002 and 2004, these two shares plummeted, with each falling by an annual average of roughly 10 percent. As Table 5 illustrates, this precipitous decline is largely the result of higher growth in investment in non-construction and non-equipment sectors, which collectively were approximately 30-40 percent less energy intensive than combined investment in the construction and equipment sectors over the 1997-2004 period. This shift in the destination of investment, though not verifiable from statistical yearbook data and perhaps not sustained after 2004, illustrates the potential for compositional shifts within aggregate investment to reduce the Chinese economy's longer-term energy needs.

Table 5. Percentage of Investment Spending, Embodied Energy, and Embodied Energy Intensity, Construction, Equipment, and Other Sectors, 1997-2004

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

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

There is broad consensus, both within China and abroad, that the current share of investment in Chinese GDP is too high, and that the Chinese economy needs "rebalancing." The reasons for sustained, high levels of investment in China are complex and disputed, but are linked in part to the country's currency regime and lack of greater control over monetary policy; the absence of a system to reallocate state-owned enterprise profits; and high levels of household precautionary savings (Anderson, 2007; Aziz, 2007; Lardy, 2007; Kuijs, 2006; Wu, 2005). Strategies for reducing investment share of GDP range from active efforts to encourage investment-consumption shifts (e.g., Lardy, 2007), to more passive efforts based on the assumption that current levels of investment are anomalous and self-correcting in the form of marginally slower GDP growth (e.g., Anderson, 2007). In either case, a lower investment share of GDP could flatten China's energy consumption trajectory, but changes in the composition of final demand sectors that shift as a result are important for determining how much trend

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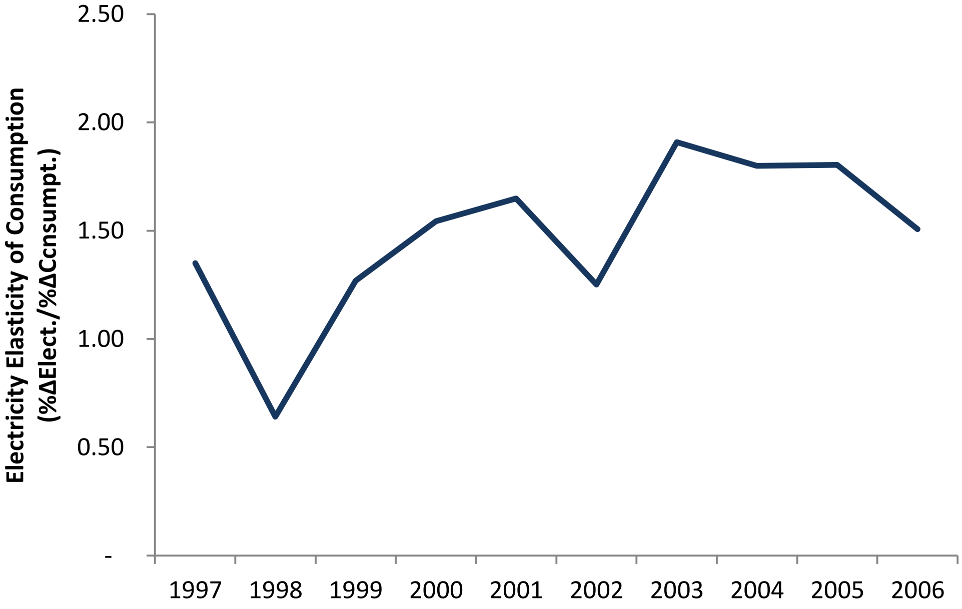
[4] Total domestic energy use here includes primary energy consumption by households.

growth might be reduced. For instance, because the average embodied energy intensities of investment (5.79 MJ/yuan) and household consumption (5.38 MJ/yuan) were close in 2004, an equivalent shift from investment to household consumption would have a relatively small effect on economy-wide energy use or energy intensity. Alternatively a shift from construction sector investment (6.51 MJ/yuan) to household expenditure on services (2.84 MJ/yuan) would have a much larger effect.

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

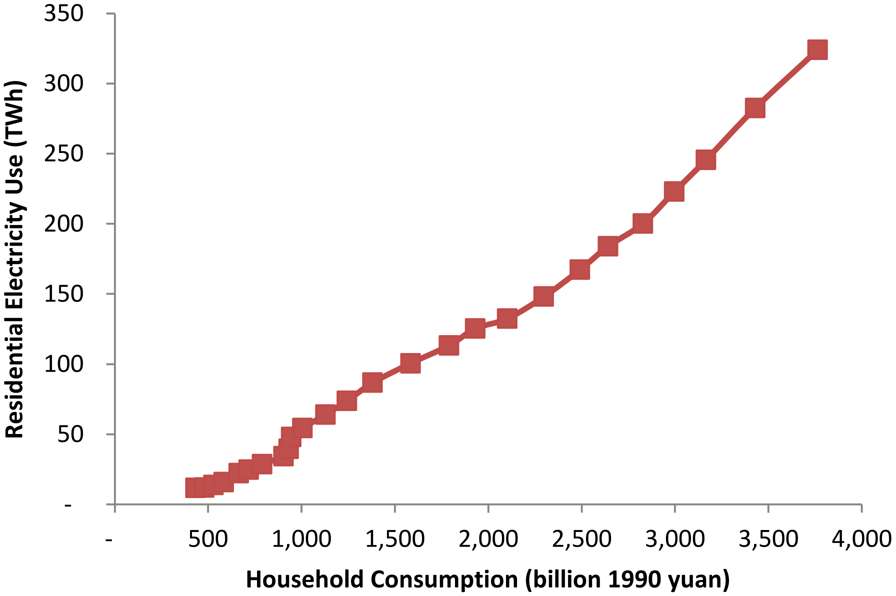
Figure 11. Electricity Elasticity of Household Consumption, China, 1997-2006



Sources: Electricity consumption data are from EBCEPY (various years); household consumption data are from NBS (2007).

NBS statistical yearbook data suggest that the higher expenditure share of electricity use was driven more by a fall in total household consumption growth rates than by a spike in residential electricity demand. Physical residential electricity consumption (i.e., in energy units) in 2003 and 2004 hewed within 1.3 percentage points of annual average growth in residential electricity consumption over 1997-2004 (10 percent) (EBCEPY, various years), while growth in household consumption (in monetary units) declined to its lowest rate over the 1997-2004 period (7.3 annual average) in 2003 and 2004 (6.0 percent and 5.8 percent, respectively) (NBS, 2007). As a result, the electricity elasticity of household consumption, or the percentage change in electricity consumption divided by the percentage change in household consumption, rose to a local peak between 2003 and 2005 (Figure 11). Residential electricity consumption actually appears to have accelerated at the end of the 1990s and a total, real household expenditure level of just over 2.5 trillion yuan (Figure 12), but the future of this trend is unclear. In the U.S., for instance, electricity consumption began to saturate as a function of private expenditure in the late 1970s. Where and when China's electricity consumption will begin to saturate is uncertain.

Figure 12. Residential Electricity Use as a Function of Household Consumption, China, 1981-2006



Notes and Sources: The markers on this curve reflect annual data point; the distance between each point reflects the magnitude of inter-annual increases. This distance rapidly increases toward the latter part of the curve, which illustrates the speed of income growth in China in recent years. Electricity consumption data are from EBCEPY (various years) and Lawrence Berkeley National Lab's China Energy Databook; household consumption data are from NBS (2007).

China's consumption dilemma is well known, but is particularly salient with regards to energy use and its attendant domestic and global impacts. On a per capita basis, residential energy consumption in China is a fraction of OECD levels. For instance, per capita annual residential electricity use in the U.S. (4,533 kWh/person-year) was more than 21 times higher than in China (216 kWh/person-year) in 2005 (EIA, 2008; EBCEPY, various years; NBS, 2007).[5] However, at 282 TWh China's total residential electricity use is higher than total electricity consumption in several major OECD and middle income countries, including Australia (220 TWh), Mexico (183 TWh), South Africa (211 TWh), and Spain (243 TWh) (EIA, 2008). Additionally, China's electricity consumption has significant room to grow, driven by declining household size, rising incomes, reduced dependence on traditional biomass in rural areas, and urbanization. Simply raising average rural per capita electricity consumption (149 kWh/person-year) to average urban levels (304 kWh/person-year) would require an additional 116 TWh (EBCEPY, various years). Although a continued shift toward services can offset some of the implications of rising household expenditure in China (Peters et al., 2007), a basic level of energy consumption is, in fact, an important development priority (Pan, 2005). Consumption, more than any other final demand source, reflects the importance of a large-scale, near-term deployment of alternative energy sources in China.

Concluding Thoughts

More so than any other large economy, China demonstrates the important linkages among economic growth, changes in economic structure, and energy consumption and intensity. Since 2002, the Chinese economy's energy needs have grown substantially (Figure 6), with a marked rise in investment- and export-driven GDP growth following the country's entry into the World Trade Organization in December 2001. Growth in energy use was paralleled by an abrupt upswing in the energy intensity of China's GDP beginning in 2002, which, although peaking in 2004 and falling slowly since, reversed a two-decade trend of steady declines in energy intensity (Figure 6). Recognizing the need to rebalance economic growth and reduce the economy's energy intensity, China's central government has made structural adjustment a key policy platform since December 2004, and reducing the energy intensity of GDP has become a national priority during the 11th Five-Year Plan (2006-2010).

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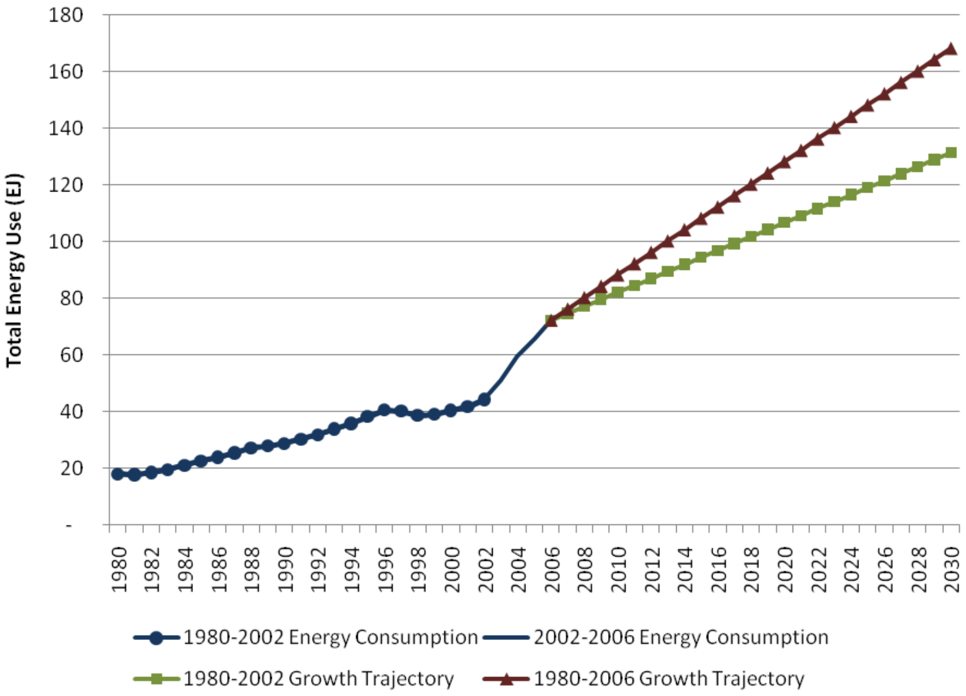
[5] U.S. population data are from the U.S. Census Bureau website.

Figure 13. Energy Consumption Pathways for the Chinese Economy, 1980-2030



Notes and Sources: "1980-2002 Growth Trajectory" is a linear extrapolation of China's 1980-2002 energy consumption; "1980-2006 Growth Trajectory" is a linear extrapolation of China's 1980-2006 energy consumption. All data are from NBS (2007).

How much macroeconomic and energy policies can influence China's long-run energy consumption path is a critical question. As Figure 13 shows, returning China to its 1980-2002 energy use trajectory would reduce the Chinese economy's energy needs by nearly one-quarter by 2030 at linearly extrapolated growth rates. To put these two trends in context, the 37 EJ difference between the two consumption pathways in Figure 13 is equivalent to 8 percent of total world primary energy consumption (488 EJ) in 2005; at a 2005 total CO_2 emission factor of 75MMTCO_2/EJ for China, 37 EJ corresponds to 2.8 GtCO_2, or 10 percent of global energy-related CO_2 emissions in 2005 (28.2 GtCO_2) (EIA, 2008). China's long-run energy consumption pathway will be shaped by the scale and structure of final demand, and understanding emerging energy-expenditure relationships will be an important part of designing policies that rationalize the country's energy needs.

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

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

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

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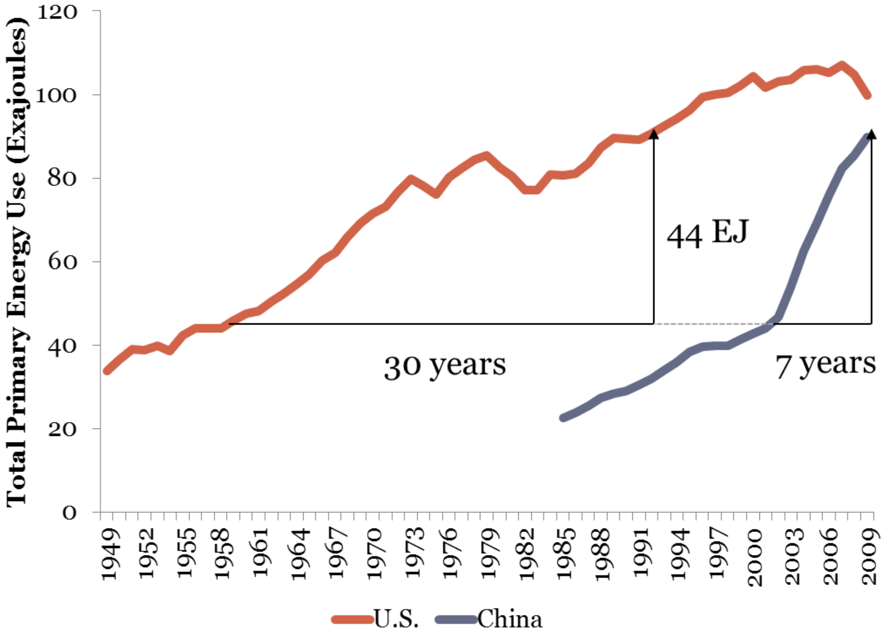
Chapter 3

Past as Prologue? Understanding Energy Use in Post-2002 China[1]

From 2002 to 2009, energy consumption in China grew by 43 exajoules (1 EJ = 10^{18} J), from 47 to 90 EJ, an increase that required nearly 30 years in the U.S. (Figure 14). Growth in energy use on this scale is without any comparable precedent, having consequences for global geopolitics, energy markets, and the global environment. It was also unanticipated. The International Energy Agency (IEA) forecast in 2002 that, by 2020, energy consumption in China would still be below U.S. 2000 levels (IEA, 2002), but China has already or soon will eclipse the U.S. as the world's largest energy consumer.[2]

Figure 14. Growth in Energy Use from 2002-2009 in China Required 30 Years in the U.S.



Sources: China data are from NBS (2010); U.S. data are from EIA (2011).

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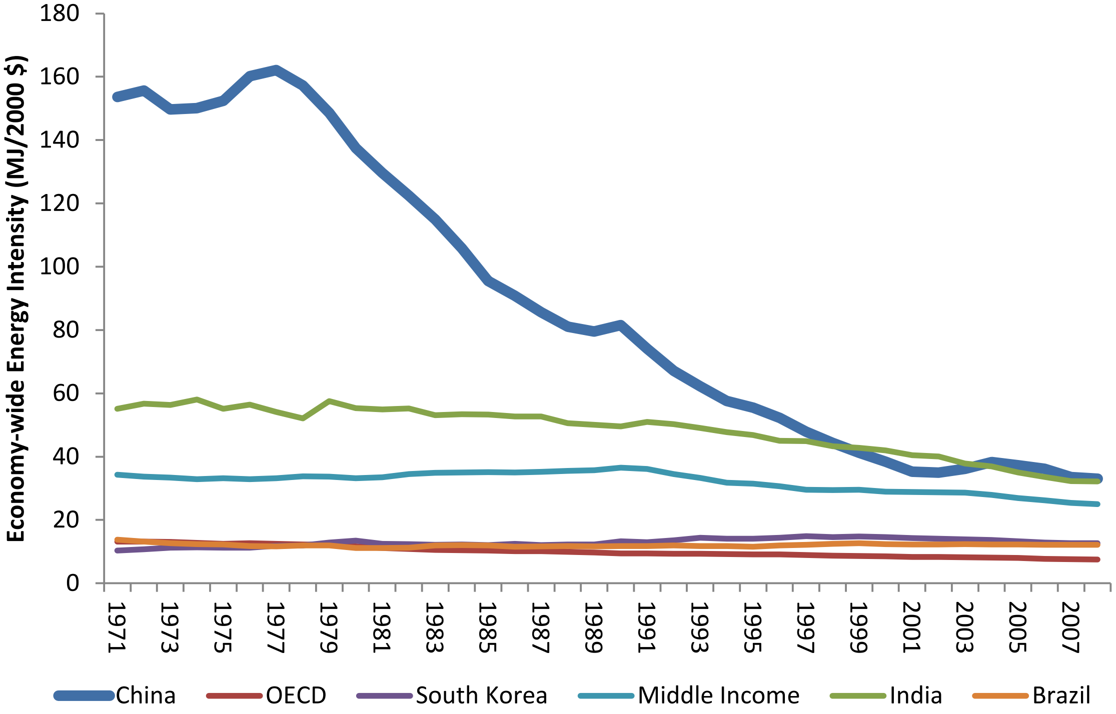
[1] This chapter is intended for publication as a multi-author article.

[2] In July 2010, the IEA announced that China had surpassed the U.S. as the world's largest energy consumer. The Chinese government, sensitive to this label, disagreed with the IEA's analysis, and in particular how the IEA had calculated primary energy use from non-combustion sources.

China's surge in energy consumption coincided with major changes in its energy intensity and economy. A momentary increase in energy intensity, from 2002 to 2004, reversed more than two decades of significant intensity declines that brought China closer to international levels (Figure 15). The year 2001 inaugurated China's membership in the World Trade Organization (WTO), spurring an intense new cycle of growth in consumption, investment, and exports, with the Chinese economy expanding at double digit annual growth rates from 2003 to 2007 (NBS, 2010).

Figure 15. China's Energy Intensity Increased between 2002 and 2004, Reversing Steep and Sustained Declines that Brought it Closer to International Levels



Notes and Source: Middle income here does not include China, which we subtract out, but does include Brazil. Data are from World Bank (2011).

In response to rising energy use and intensity, the Chinese government set a binding goal of reducing macroeconomic energy intensity by around 20% from 2005 levels by 2010. Measures to achieve this goal focused on improving the energy efficiency of industrial equipment and processes, mandatory closures of small industrial plants, and, to a lesser extent, building and appliance efficiency (Andrews-Speed, 2009; Price et al., 2010; Zhou et al., 2010; Price et al., 2011). Despite widely publicized difficulties in meeting the 2010 energy intensity target, the approach to managing energy use in China's 12th Five-Year Plan (2011-2015) appears to be a continuation of the 11th Plan, with a new target and a new suite of energy efficiency mandates, programs, and incentives. This staying of the course raises an important question: Are industrial sector energy efficiency policies, as the Chinese idiom goes, the right medicine for the symptoms (对症下药)? More to the point, perhaps, what was the ailment? What factors led to such rapid growth in energy demand?

This paper analyzes both the proximate and root causes of the rapid growth in energy consumption in China from 2002 to 2007, focusing on what this period implies for the future of energy and climate policy, in China and globally. Section 2 develops our framing questions, building on a review of available energy data and the literature on energy use in China during this period. Section 3 discusses our methods and data sources. Section 4 describes the results, followed by a final, concluding section.

Background

Given the gravity of the issues associated with rapid energy demand growth in China since 2002 — from energy security to climate change — there has been surprisingly little analytical work on what factors led to this rapid growth, how likely it is to continue, and what kinds of policy interventions could effectively address it. In this section we describe available evidence on physical energy use trends (i.e., in energy units) and energy-economy linkages in China since 2002.

Energy Use Trends

Heavy industry has driven much of the growth in China's physical energy consumption since 2002. From 2002 to 2007, the chemical, ferrous metal, non-ferrous metal, and non-metal minerals sectors[3] accounted for 17 EJ (49%) of the 34 EJ of growth in primary energy consumption.[4] The energy industry itself (coal mining, petroleum extraction and refining, coking, and electricity generation) and transportation services contributed another 7 EJ (21%) of growth, while residential use added just 3 EJ (8%). Heavy industry's share of total primary energy use increased from 42% in 2002 to 49% in 2007.

A second important change since 2002 has been the rise of coal, and the fall of oil, in China's primary energy mix. The shares of coal and oil consumption, in fact, reached historical low and high points, respectively, in 2002 (Figure 16). Coal and oil are typically more readily substitutable in the industrial sector than in the energy sector, but there is little evidence suggesting larger-scale oil-to-coal substitution in the industrial sector.[5] An alternative

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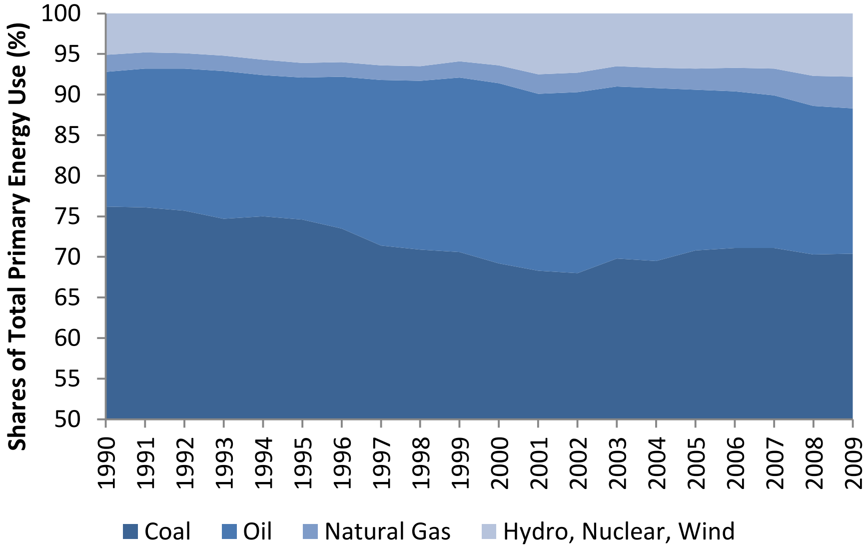
[3] By value added, the non-ferrous metals sector is mostly copper, lead, zinc, and aluminum smelting and pressing. The non-metal minerals sector is largely cement, cement products (e.g., concrete), bricks, and glass. Data are from China Data Online's Yearly Industrial Data dataset.

[4] All of the data in this and the next paragraph are from the Consumption of Energy by Sector tables in the China Statistical Yearbook series.

[5] No sectors saw declines in petroleum product use that were large relative to the 1.2 petajoule (1 PJ = 10^{15} J) equivalent decline in oil share from 2002 to 2007. Of the sectors that had large increases in coal use, none are major petroleum product consumers except for the Processing of Petroleum, Coking, Processing of Nuclear Fuel sector, and the large shift in the shares of coal and oil in this sector is likely the result of the petroleum processing

explanation is that the shift to coal was driven by higher growth in coal-dominant sectors relative to oil-dominant ones.

Figure 16. The Share of Coal in China's Primary Energy Mix Increased after 2002, while the Share of Oil Fell



Notes and Source: Vertical axis scaled from 50%. Coal averages 70% of primary energy over this period. Data are from NBS (2010).

Changes in Energy-Economy Linkages

Though their relationship is still somewhat unclear, emergent economic trends have clearly been an important driver of both the magnitude and composition of energy use in China since 2002. Previous analyses of energy-economy linkages that cover this time period implicate a broad range of policy issues, which we divide generically into supply side and demand side (production and consumption) perspectives. To elucidate the determinants of aggregate energy use, we adopt the concept of a three-fold conceptual decomposition of energy use in both our discussion and analysis below. Simply put, aggregate energy demand is determined by aggregate economic growth, economic structure (sector composition), and technology (sectoral energy efficiency). Together, these components interact to determine total energy requirements for the overall economy. All three evolve concurrently, to some extent independently, and can interact in both reinforcing and offsetting ways. In dynamic emerging economies like China they might all be significant.

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and coking sectors being aggregated into a single sector. Data are from the NBS Consumption of Energy by Sector tables.

Much of the production-side analysis has focused on the role of the industrial sector. Ma (2008) argues that, using sector price indices rather than an economy-wide deflator, the increase in total energy intensity from 2002-2004 disappears, and that changes in nominal prices made the economy look more heavy industry-oriented in value than it was in real terms. Decomposing energy use in the industrial sector over 1998-2006, Zhao et al. (2010) argue that changes in industrial structure and sub-sector enrgy intensity both reduced baseline intensity of industrial energy demand, and that virtually all of the increase in industrial energy consumption over 1998-2006 can be accounted for through aggregate increases in output. Looking at the economy as a whole, Price et al. (2011) argue that energy consumption growth over 2002-2008 was mainly the result of aggregate growth in economic output. Focusing on 2002-2004, Chai et al. (2009) make a structural argument, that higher energy use was the result of growth in residential consumption and more rapid growth in heavy industry vis-à-vis light industry. Liao et al. (2007) argue, qualitatively, that the rapid growth in energy-intensive sectors relative to energy efficiency improvements led to the 2002-2004 increase in energy intensity.

A more limited number of analyses have examined final demand (consumption, investment, net export) drivers of energy use. Chai et al. (2009) argue that the shift toward heavy industry from 2002-2004 was caused primarily by changes in the structure of final demand, but do not specify what those changes were. Karl and Chen (2010) argue that government consumption was a significant driver of energy intensity since 2002. Previous work by the present authors (Kahrl and Roland-Holst, 2009) argues that investment and exports are the largest energy demand growth drivers China, but that household consumption drove the increases in energy intensity from 2002 to 2004. Liao et al. (2007) argue that increases in energy consumption were driven by investment and urbanization, but give no evidence to support the role attributed to the latter.

Taken together, these analyses leave a number of important questions unanswered, two of which we focus on in this study. First, from the supply side perspective, what were the relative contributions of structural change and energy intensity across the economy to growth in energy consumption, what sub-sector-level changes shaped these contributions, and was either a meaningful contributor to energy demand growth? Second, from the perspective of final demand, how did changes in technology, final demand structure, and growth in final demand across households, government, investment, and net exports affect economic activity in energy-intensive sectors?

Methods and Data

Our methodology relies heavily on index decomposition analysis (IDA) and structural decomposition analysis (SDA). For IDA and SDA, the two most commonly used decomposition techniques are the Divisia index and Laspeyres index methods.[6] We use different methods to

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[6] For a review of the strengths and weaknesses of each approach in the context of energy analysis, see Ang (2004).

address the supply- and demand-side questions discussed above, describing each individually below.

Supply Side — Index Decomposition Analysis

For this first set of questions, we are interested in the decomposition of total energy use (E) into sectoral energy intensity (E_i/Y_i), sector shares of value added (Yi/Y), and total value added (Y)

$$E_t = \sum_i \frac{E_{it}}{Y_{it}} \frac{Y_{it}}{Y_t} Y_t \tag{1}$$

Using additive decomposition, the change in total energy use (ΔE_{TOT}) for Equation 1 is additively decomposable into changes in energy that result from changes in sector energy intensity (Technology, ΔE_{INT}), sector value added shares (Structure, ΔE_{STR}), and total value added (Aggregate, ΔE_{ACT})

$$\Delta E_{TOT} = \Delta E_{INT} + \Delta E_{STR} + \Delta E_{ACT} \tag{2}$$

To calculate the indicators, we use a logarithmic mean weighting scheme for the Divisia index, or the logarithmic mean divisia index (LMDI) (Ang et al., 1998).

$$\Delta E_{INT} = \sum_i \frac{E_i^T - E_i^0}{ln(E_i^T) - ln(E_i^0)} ln\left(\frac{I_i^T}{I_0^T}\right) \tag{3}$$

$$\Delta E_{STR} = \sum_i \frac{E_i^T - E_i^0}{ln(E_i^T) - ln(E_i^0)} ln\left(\frac{S_i^T}{S_0^T}\right) \tag{4}$$

$$\Delta E_{ACT} = \frac{E_i^T - E_i^0}{ln(E_i^T) - ln(E_i^0)} ln\left(\frac{Y^T}{Y^0}\right) \tag{5}$$

where

- 0 and T are the beginning and ending periods

- I_i is the energy intensity of sector i ($I_i = E_i/Y_i$),
- S_i is the share of sector i in total output ($S_i = Y_i/Y$)
- Y is total value added

Equations 3-5 require three main data sets: energy consumption, value added, and price indices. We draw our energy data from the Consumption of Total Energy and its Main Varieties by Sector (分行业能源消费总量) tables in the 2009 and 2010 China Energy Statistical Yearbooks, which includes 43 sectors and residential use.[7] Our E variable here includes only non-residential energy use, though we discuss how residential energy use would affect our findings. The values in the Consumption of Total Energy tables are estimates of total primary energy consumption by each sector, meaning that energy conversion losses are allocated across end use sectors. For examining intensity and structural effects at a sector level, this approach can lead to misleading results by allocating effects that are attributable to changes in the energy sectors across other sectors.

To correct for this problem, we reallocate electricity conversion losses back to the electricity sector by subtracting the difference between total final consumption using "coal equivalent calculation" (发电煤耗计算法) and the "calorific value calculation" (电热当量计算法) from each sector's energy consumption and adding the total to electricity sector energy consumption.[8] For the remaining energy conversion sectors (e.g., oil refining, coking) there is not enough available data to reallocate conversion losses, and we leave any remaining energy conversion losses in end use sectors.

The detailed sector aggregation for energy consumption and value added are consistent, with the exceptions of the Wholesale and Retail Trades and Hotels and Catering Services sectors, which are aggregated into one Wholesale, Retail, Restaurant sector in the energy data, and the Financial Intermediation, Real Estate, and Others sectors, which are aggregated into Other. We allocate energy use from the aggregate to individual sectors by assuming that individual sectors have the same energy intensity as the aggregate sector.

There is no ideal measure of economic activity for use in IDA. Gross output can be more straightforward to deflate than value added. However, gross output is a less meaningful measure of economic activity, and for that reason we primarily use value added here. To

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[7] The 2009 Energy Statistical Yearbook includes revisions to energy data in all years from 1996 to 2008. In some years, and in particular for the period 1999-2003, these revisions are significant.

[8] These data are in the Final Energy Consumption by Industrial Sector (Standard Quantity) (工业分行业终端能源消费量 [标准量]) tables of the Energy Statistical Yearbook series. These final consumption tables only include industrial sectors. For the primary and tertiary sectors, we use electricity consumption data from the Energy Balance of China (Standard Quantity) (中国能源平衡表 [标准量]) tables, and calculate electricity conversion losses using the average implied thermal efficiency $\left(\frac{\mathrm{ELCT}}{\mathrm{TFC_{cec}}-\mathrm{TFC_{cvc}}}\right)$ from the Final Energy Consumption tables for each year, where ELCT is total industry electricity consumption, TFC is total final consumption, and the CEC and CVC subscripts refer to coal equivalent calculation and calorific value calculation, respectively.

address some of the uncertainty with deflating value added, we examine four "cases," with 46- and 3-sector aggregations that use different price indices. We also explore where using gross output rather than value added changes the results.

Our value added and gross output data are from the China Statistical Yearbook series.[9] The NBS publishes value added data separately in the National Accounts and Industry sections of the yearbook. Value added data in the National Accounts section includes: a 4-sector (primary, secondary, construction and tertiary sectors) aggregation of GDP; a 3-sector (mining, manufacturing, utilities) aggregation of the secondary sector; and a 6-sector aggregation of the tertiary sector. The 3-sector aggregation of the secondary sector is available only for 2004 and after. Value added data in the Industry section includes a 40-sector aggregation of the secondary sector, which we further aggregate to 38 sectors.[10] These data are only for state-owned enterprises and non-state owned enterprises with revenues above five million yuan.[11] The Industry section includes gross output by sector, but NBS does not publish total gross output in the National Accounts section, aside from in the input-output tables.

The National Accounts and Industry data are not consistent, as the ratio between the two declines over time and becomes positive after 2006.[12] To make the Industry (38-sector) value added data consistent with secondary sector value added in the National Accounts data, we scale value added for each sector by the ratio between secondary sector value added in the National Accounts (SVA_t), using data in the 2010 Statistical Yearbook, and the sum of sector industrial value added (IVA_{it}) in the Industry Accounts

$$IVA_{it} = \frac{TIVA_t}{\sum_i SIVA_{it}} SIVA_{it} \tag{6}$$

where IVA_{it} is the scaled industrial value added data for sector i at time t. Ideally, the 38-sector data could be scaled to the 3-sector secondary sector aggregation in the National Accounts data, but because data for the latter are not available before 2004, this is not possible. The shares of value added in the 38-sector and 3-sector secondary sector aggregations are close but not identical, and scaling leads to an overestimate of industrial value added and an underestimate

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[9] NBS economic data have a discontinuity in 2004, as a result of an economic census of the secondary and tertiary sectors that led to significant upward revisions of 1993-2004 value added, with the largest revisions to the tertiary sector. All of the economic data we use here have been revised to account for economic census revisions.

[10] We combine the Other Mining Industries and Other Minerals and Mining sectors, and the Waste Resources and Old Material Recycling and Processing with the Craftwork and Other Manufactures sector.

[11] These data are accessed from China Data Online's Yearly Industrial Data series. China Data Online's Yearly Industry Data is a revised data series from the NBS based on the Industry accounts.

[12] This ratio declines monotonically from 1.58 in 2000 to 0.94 in 2007. We were not able to find an explanation for why the less comprehensive 38-sector data would be larger than total nominal industrial GDP in 2007. The Mining, Manufacturing, and Production of Supply of Electricity, Gas and Water sectors are 11-13%, 78-80%, and 8-9%, respectively, of total value added in both data sets. National accounts data are from the Value-added by Sector table in the 2010 Statistical Yearbook.

of mining and utilities value added. Scaling has a significant impact on the results, as we show below.

Prices are an important consideration in IDA because they affect the balance between economic structure and energy intensity. Rising prices give the perception of decreases in energy intensity and higher value added shares, whereas in real terms changes could have the opposite sign. In a sector where prices are rising faster than elsewhere in the economy, using sector prices to deflate value added tends to reduce the contribution of economic structure and increase the contribution of energy intensity to increases in energy consumption relative to more aggregate deflators. If prices are not stable across sectors, more aggregate deflators will bias the results, as argued by Ma (2008) and as we explain below.

We use three sets of deflators: a GDP deflator that we apply to both the 46 and 3-sector data; a 3-sector price index; and a 46-sector price index. The GDP deflator and 3-sector price index are calculated using the NBS GDP indices in the 2010 Statistical Yearbook. The 46-sector price index uses multiple sources. For the primary, construction, and tertiary sectors, we use the value added indices in the National Accounts section of the 2010 Statistical Yearbook. For industrial sectors, we use the 38-sector producer price index (PPI).[13] Because the PPI is for output prices rather than value added, this approach assumes that output and inputs prices are changing at the same rate. In fact, they were not, and this assumption has a significant influence on the results. However, it is consistent with the single-indicator approach to deflation used by the NBS, though, at an aggregate level, the NBS uses an index of resource costs to adjust its industrial value added deflator (Zhao, 2004; Zhang, undated).

Demand Side — Structural Decomposition Analysis

For final demand and its linkage to production, we are interested in the decomposition of gross output for sector S induced by demand for good j by final demand k in period t ($\mathrm{X}^{\mathrm{S}}_{\mathrm{jkt}}$) into the sum product of a j x j diagonal matrix of the sector S row in the multiplier matrix ($\widehat{\mathrm{M}}^{\mathrm{S}}_{\mathrm{jjt}}$); a j x k matrix of expenditure shares on sector j by final demand k (θ_{jkt}); a k x k diagonal matrix of the shares of final demand ($\widehat{\beta}_{\mathrm{kkt}}$); and a k x k diagonal matrix of total final demand ($\widehat{\mathrm{Y}}_{\mathrm{kkt}}$), where all elements on the diagonal are total final demand

$$X^S_{jkt} = \sum_l \sum_m \sum_n \widehat{M}^S_{jlt} \theta_{lmt} \widehat{\beta}_{mnt} \widehat{Y}_{nkt} \tag{7}$$

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[13] 38-sector PPI data for 2002-2007 are published in the China Statistical Yearbook series. We obtained 38-sector price indices for before 2002 from CEIC Data, which has monthly price data We convert these monthly indices to annual indices by taking the arithmetic average across 12 months, which is the approach used by the NBS (Zhao, 2004).

Summing the rows of this $\mathrm{X}^{\mathrm{S}}_{\mathrm{jkt}}$ matrix of gross output gives the total gross output of sector S induced by each final demand k at time t

$$X^S_{kt} = \sum_j X^S_{jkt} \tag{8}$$

For multiple S sectors, these $\mathrm{X}^{\mathrm{S}}_{\mathrm{kt}}$ row vectors can be summed to a total $\mathrm{X}^{\mathrm{T}}_{\mathrm{kt}}$ row vector that is the gross output for multiple sectors (1,2 … n) induced by final demand k at time t

$$X^T_{kt} = X^1_{kt} + X^2_{kt} + \cdots + X^n_{kt} \tag{9}$$

We leave imports in the multiplier matrix and final demand accounts. The NBS does not publish estimates of import use by sector, and removing imports by assuming constant import shares across all marketed output would not affect our results.

For additive decomposition, changes in total gross output for sector S induced by final demand k (ΔX^S_{TOT}) are the sum of changes in the four components in Equation 7: technology (ΔX^S_M), changes in the composition of final demand (ΔX^S_θ), changes in the shares of final demand (ΔX^S_β), and changes in aggregate final demand (ΔX^S_Y). For ease of exposition, we leave the j and k subscripts off of the ΔX terms.

$$\Delta X^S_{TOT} = \Delta X^S_M + \Delta X^S_\theta + \Delta X^S_\beta + \Delta X^S_Y \tag{10}$$

ΔX^S_θ, ΔX^S_β, and ΔX^S_Y are straightforward. Changes in technology (ΔX^S_M) arise from changes in average input shares for firms, which may reflect a variety of factors, such as changes in industry structure, production processes, and supply chains. In this analysis, if ΔX_M is positive it means that at least some firms are, on average, spending more on heavy industrial goods.

We use a Laspeyres approach to decompose Equation 10, where ΔX^S_M, ΔX^S_θ, ΔX^S_β, and ΔX^S_Y are

$$\Delta X^S_M = \sum_l \sum_m \sum_n \Delta \widehat{M}^S_{jl} \theta_{lm0} \widehat{\beta}_{mn0} \widehat{Y}_{nk0} + \varepsilon \tag{11}$$

$$\Delta X_{\theta}^{S} = \sum_{l}\sum_{m}\sum_{n} \widehat{M}_{jl0}^{S} \Delta\theta_{lm} \widehat{\beta}_{mn0} \widehat{Y}_{nk0} + \varepsilon \tag{12}$$

$$\Delta X_{\beta}^{S} = \sum_{l}\sum_{m}\sum_{n} \widehat{M}_{jl0}^{S} \theta_{lm0} \Delta\widehat{\beta}_{mn} \widehat{Y}_{nk0} + \varepsilon \tag{13}$$

$$\Delta X_{Y}^{S} = \sum_{l}\sum_{m}\sum_{n} \widehat{M}_{jl0}^{S} \theta_{lm0} \widehat{\beta}_{mn0} \Delta\widehat{Y}_{nk} + \varepsilon \tag{14}$$

where the 0 subscript indicates the base year and ε is a residual term. Each of the ΔX terms is a j x k matrix of the total gross output of sector S induced by demand for product j for final demand k. As above, these can be summed across j rows and n sectors to compute the total gross output for multiple sectors induced by each final demand k, which is how we show the results.

A shortcoming of the Laspeyres index method is that, for n factors, it generates $2^n - 1 - n$ interaction (residual) terms. Although these terms can be consistently allocated across the main n terms, resulting in perfect decomposition, there are multiple ways to allocate interaction terms, each giving different results. To address this problem, we calculate and present results using three different decompositions: 1) a base case where the residual term is not allocated, 2) an "average" case where the residual is equally allocated across individual terms, based on the method proposed by Sun (1998); and 3) an "extreme" case where none of the residual is allocated to the largest term, ΔY.[14]

Equations 11-14 require two main data sets: input-output tables and price indices. The NBS compiles survey-based I-O tables every five years (1992, 1997, 2002, 2007), with tables in intervening years that are updated based on the structure of the previous table. To capture changes in structure, it is important to use the survey-based tables. We use the 17-sector, 5-institution (rural household, urban household, government, investment, exports) tables for 2002 and 2007 reported in the 2007 and 2010 China Statistical Yearbooks, respectively. Our choice of S in Equation 7 focuses on three industrial sectors in the 17-sector I-O table: Chemical Industry, Manufacture of Nonmetallic Mineral Products, Manufacture and Processing of Metals and Metal Products. These three sectors are the largest energy consumers in the economy.

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[14] The full term is:
$\Delta X_{TOT} = \sum_l \sum_m \sum_n \Delta\widehat{M}_{jl}^{S} \theta_{lm1} \widehat{\beta}_{mn1} \Delta\widehat{Y}_{nk1} + \sum_l \sum_m \sum_n \widehat{M}_{jl0}^{S} \Delta\theta_{lm1} \widehat{\beta}_{mn1} \widehat{Y}_{nk1} + \sum_l \sum_m \sum_n \widehat{M}_{jl0}^{S} \theta_{lm0} \Delta\widehat{\beta}_{mn} \widehat{Y}_{nk1} + \sum_l \sum_m \sum_n \widehat{M}_{jl0}^{S} \theta_{lm0} \widehat{\beta}_{mn0} \Delta\widehat{Y}_{nk}$. An alternative formulation would be to allocate the residual in β in the second term to θ in the third term.

As with IDA, changes in prices can have a significant bearing on SDA results. We compare results from the original I-O tables with those from the original 2002 table and a 2007 table in constant 2002 prices. To deflate the 2007 table, we use several different price indices. We use the afore-mentioned PPI, scaled to 2002, to deflate the intermediate portion of the 2007 I-O table, deflating value added at sector PPI values for lack of a better alternative. For household consumption, we use the NBS consumer price indices (CPIs) for rural and urban households, using separate price indices for food and fuel. For government consumption we use the urban CPI. For investment, we use the NBS price indices for fixed asset investment, with separate indices for construction and equipment investment. For exports, we use the PPI. Given the rapid increases in prices in the mining, refining, and metals sectors, balancing the deflated I-O table causes major, unreasonable changes in table structure. Rather than rebalance the table, which would overstate the role of changes in technology, we let the error term absorb row-column differences and remove the error term when compiling the results.

Results

Supply Side — Index Decomposition Analysis

Figures 17-19 show ΔE_{INT}, ΔE_{STR}, and ΔE_{ACT} shares of ΔE_{TOT} using our four cases. Three clear trends can be seen in the results. First, the contribution of sector energy intensity to growth in total non-residential energy consumption rose from 2000 to 2003 or 2004, depending on cases, was momentarily positive between 2002 and 2004 or 2005, and by 2006 was clearly negative again. Second, a structural shift toward more energy-intensive sectors contributed to rising energy consumption in all four cases between 2003 and 2004, but in other years the results are highly variable. The ΔE_{STR} figure most clearly illustrates the importance of aggregation and prices in energy IDA, as these determine differences between the four cases. Third, rising aggregate growth (value added) contributed to increasingly less of the total growth in energy consumption from 2000 to 2004, but most of the growth in energy use in 2002-2003 and almost all after 2004.

Figure 17. Contribution of Energy Intensity (ΔE_{INT},) to Total Change in Energy Consumption (ΔE_{TOT}), 2001-2009

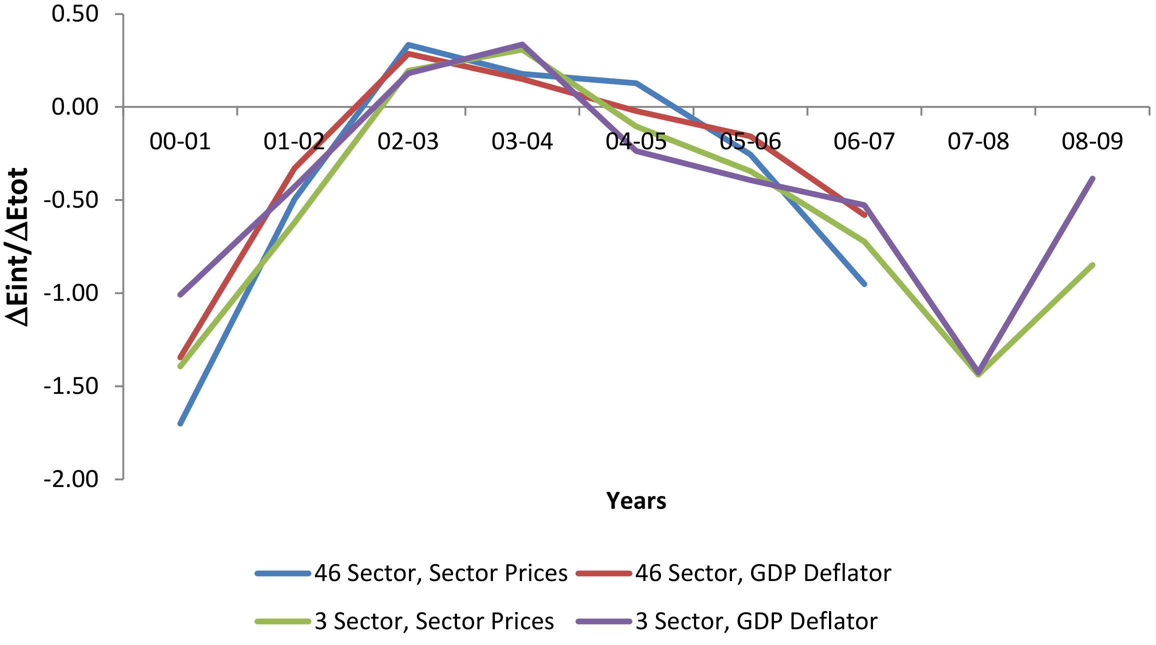


Figure 18. Contribution of Structural Change (ΔE_{STR},) to Total Change in Energy Consumption (ΔE_{TOT}), 2001-2009

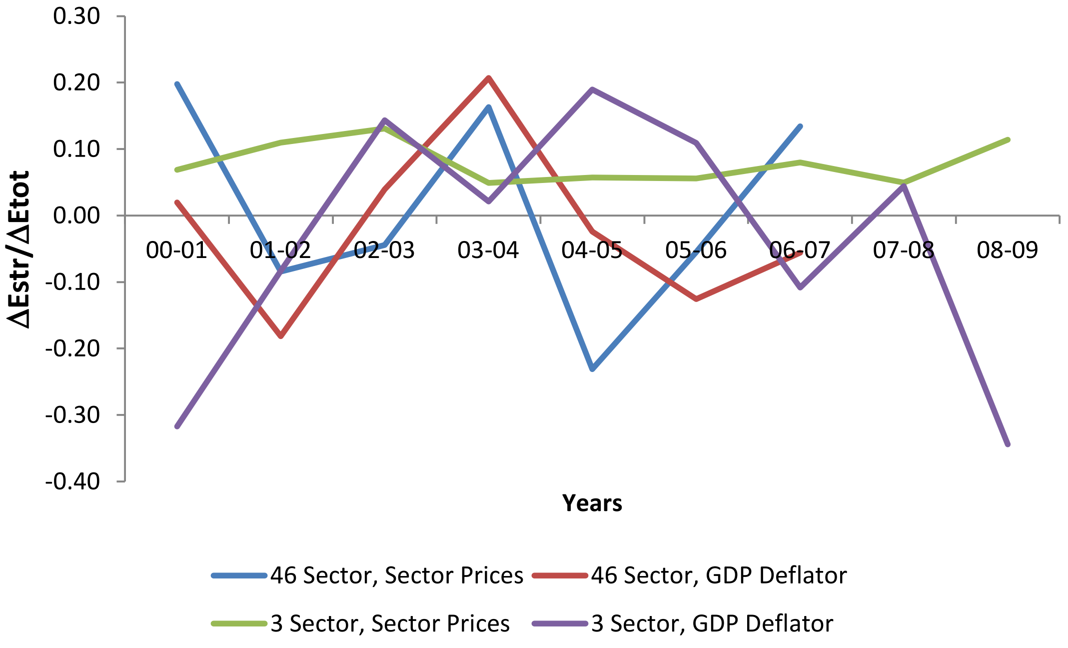
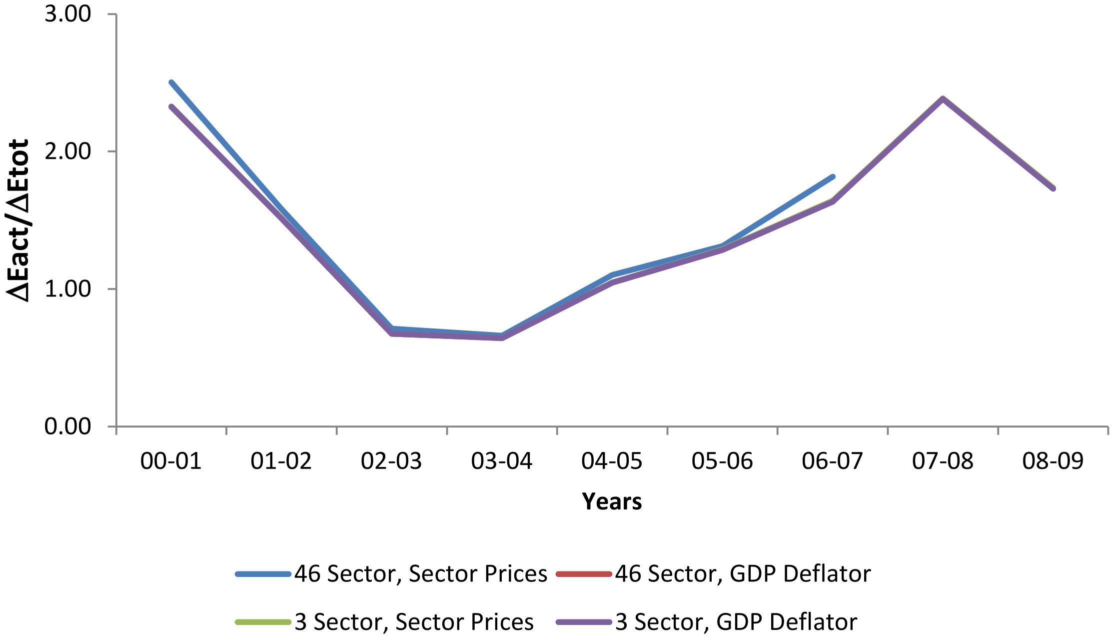


Figure 19. Contribution of Economic Activity ($\Delta E_{ACT},$) to Total Change in Energy Consumption (ΔE_{TOT}), 2001-2009



The results in Figures 17-19 are misleading, and examining sector contributions to the ΔE_{INT} and ΔE_{STR} terms sheds light on what is driving these effects. Both ΔE_{INT} and ΔE_{STR} have positive and negative totals, as the value of both ΔE_{INT} and ΔE_{STR} for each sector can either be positive or negative. For ΔE_{INT}, as Table 6 shows, eight sectors accounted for the bulk of the positive total from 2002 to 2006.

Table 6. Sector Values of ΔE_{INT}, Total Positive and Negative ΔE_{INT} Values, and Contribution of these Eight Sectors to the Total Positive ΔE_{INT} Value

Sector	**Years**						
	00-01	**01-02**	**02-03**	**03-04**	**04-05**	**05-06**	**06-07**
Coal Mining and Dressing	-343	-711	679	-449	-248	-465	-552
Petroleum and Natural Gas Extraction	381	695	267	-1242	54	191	125
Petroleum Processing, Coking and Nuclear Fuel Processing	-31	-308	1,021	2,850	595	1,383	-1,311
Raw Chemical Material & Chemical Products	-1,252	291	142	-61	636	-1,124	-2,368
Smelting and Pressing of Ferrous Metals	-1,215	-1,410	-306	106	-1,972	-2,628	-3,781
Nonmetal Mineral Products	-1,644	-1,111	670	3,038	3,961	-1,864	-320
Electricity and Heating Production and Supply	-1,501	-1,236	4,944	-1,199	2,465	1,475	-5,607
Transport, Storage, and Post	-589	0	830	532	58	87	-660

TOTAL +ΔE_{INT}	694	1,684	9,442	9,098	8,171	3,517	299
TOTAL -ΔE_{INT}	-8,646	-5,753	-1,985	-4,273	-5,468	-8,951	-19,460
Above sectors % +ΔE_{INT}	55%	58%	91%	72%	95%	89%	41%

Some combination of four potential reasons explain why a sector would have a positive ΔE_{INT} value: 1) its average sector or sub-sector technical efficiency (i.e., energy per unit physical output) declined; 2) its value added grew slowly relative to gross output; 3) value added in its energy-intensive sub-sectors grew faster than its average value added; and 4) issues with data adjustments and data.

For the two largest contributors to positive ΔE_{INT}, technical efficiency increased over the 2000 to 2007 time period. Petroleum refining, coking, and electricity conversion efficiencies were all either stable or increased, as did final energy consumption in the electricity and coking sectors.[15] Trends in technical efficiency in the chemical products, ferrous metals, non-metal mineral, and transportation sectors are more difficult to gauge without more disaggregated energy data because these sectors have heterogeneous products.

The lack of declines in technical efficiency in the electricity and petroleum refining and coking sectors, given that these sectors have large ΔE_{INT} values, suggests that prices, structure, and data issues are likely to explain a significant portion of the positive ΔE_{INT} effect. In both the electricity sector and petroleum refining and coking sectors, nominal value added shares of gross output declined from 2002 to 2006, as coal and crude oil prices rose. Rising iron ore prices reduced the value added shares in the ferrous metals sector between 2004 and 2005. These reductions in value added shares, a result of our use of output price deflators, create the illusion of rising energy intensity, when, in reality, real value added is being underestimated. For the electricity and petroleum refining and coking sectors, this price effect may explain a significant amount of their positive ΔE_{INT} values from 2002 to 2006.

Intra-sector structural change also contributed to the positive ΔE_{INT} effect. From 2003 to 2004, value added in the more energy-intensive coke sector grew more rapidly than in the petroleum refining sector.[16] In the ferrous metals sector, energy-intensive pig iron production grew faster

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[15] Petroleum refining and coking efficiencies, defined as the energy value of outputs divided by the energy value of primary inputs, were steady at 97-98% and 96-98%, respectively, over 2000 to 2007. Gross average electricity efficiency, calculated as the gross energy (kWh) output divided by total energy input, increased monotonically and substantially over this time period, from 30% in 2000 to 35% in 2007, driven largely by the rapid deployment of large (600 MW), efficient coal units. In the petroleum refining and coking sector, final energy consumption, the energy required to run equipment for energy conversion and distribution, remained steady at 0.15 tce per tce of energy produced over the first portion of the 2000s and fell to around 0.13 tce tce^{-1} by 2006. Final energy consumption in the electricity sector fell from 0.25 tce tce^{-1} to 0.15 tce tce^{-1} by 2007. All data are from the 2009 China Energy Statistical Yearbook.

[16] The relative growth in coke production was particularly rapid in 2002-2004, growing from 7% to 20% of nominal value added in the Processing of Petroleum, Coking, Processing of Nuclear Fuel sector. From 2002 to 2007, coking's

than steel and steel products from 2004 to 2005. In both of these cases, and potentially in others that are not discernable with available data, what appears as an energy intensity effect is actually a structural effect.

Some of the ΔE_{INT} effect in these sectors may be explained by inconsistencies between the 38-sector value added data and secondary sector value added in the national accounts. Scaling the latter by the former significantly increases inter-annual variability in sector energy intensity relative to what it would be if calculated with the 38-sector data (see Appendix). However, given that the 38-sector data is, in theory, less comprehensive than the national accounts value added data, it is not accurate to use total sector energy consumption with the 38-sector data. Ultimately, it is difficult to say whether the industrial value added data or the national accounts value added data are more accurate.

Positive ΔE_{INT} values for the non-metal minerals sector over 2002-2005 are likely the result of a misestimated price index for the sector over 2002 to 2005. Prices for other heavy industrial products had begun to rise rapidly by 2004, but the price index for the non-metal minerals sector does not exceed 1.0 until 2006. More generally, we believe that GDP for the late 1990s and early 2000s in China was significantly over-reported, which causes energy intensity declines over this time period to appear larger than they actually were. It is more plausible, in our view, that China's GDP growth was much lower than reported in the late 1990s (Rawski, 2001), as a result of major internal restructuring and the Asian financial crisis, in which case GDP growth rates from 2002 to 2004 would have been much higher and would have been more consistent with energy consumption growth rates (Figure 20).

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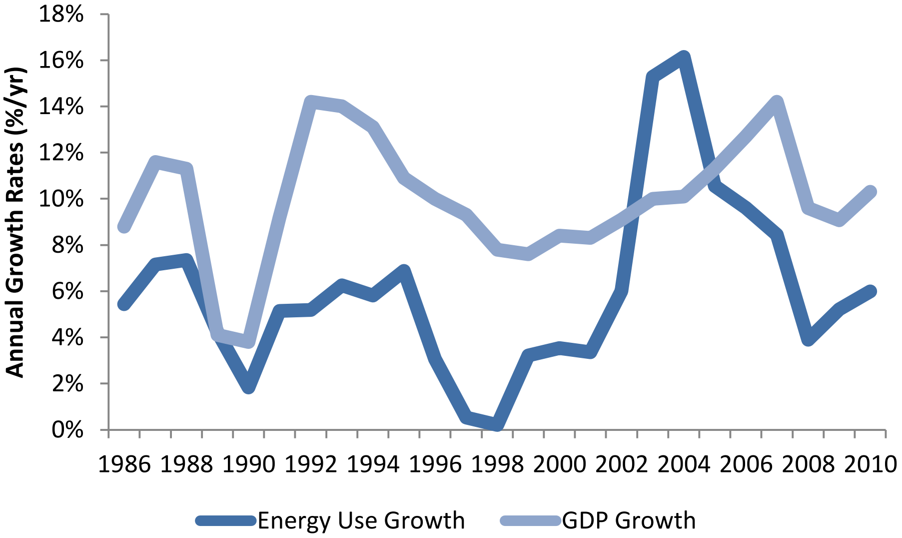
share increased from 7% to 25%. Data are from China Data Online's Yearly Industrial Data series. In 2007 coal consumption, most of which is used to make coke, accounted for 31% of energy consumption in the Processing of Petroleum, Coking, Processing of Nuclear Fuel sector, but coke production accounted for only 25% of value added in the sector in 2007. Energy data are from the 2009 Statistical Yearbook. Value added data are from China Data Online's Yearly Industrial Data series.

Figure 20. Energy Consumption Growth and GDP Growth Rates in China, 1986-2009



Source: NBS (2010).

The same eight sectors that account for most of the positive ΔE_{INT} effect contribute to the bulk of both positive and negative ΔE_{STR} effects (Table 7). The negative ΔE_{STR} values for the electricity and petroleum processing and coking sectors are the flip side of apparent increases in energy intensity, caused by an underestimation of value added. The large ΔE_{STR} values for the non-metal mineral sector are also tied to the high positive ΔE_{INT} value for this sector and what we argue is most likely an underestimated price index.

Table 7. Sector Values of ΔE_{STR}, Total Positive and Negative ΔE_{STR} Values, and Contribution of these Eight Sectors to the Total Positive ΔE_{STR} Value

Sector	**Years**						
	00-01	**01-02**	**02-03**	**03-04**	**04-05**	**05-06**	**06-07**
Coal Mining and Dressing	21	-39	-43	845	-93	-119	167
Petroleum and Natural Gas Extraction	-478	-509	-612	-104	-330	-469	-438
Petroleum Processing, Coking and Nuclear Fuel Processing	-126	20	-647	-709	-2,097	-2,193	420
Raw Chemical Material & Chemical Products	415	16	660	623	-944	297	1,316
Smelting and Pressing of Ferrous Metals	-307	-205	639	37	337	1,146	1,182
Nonmetal Mineral Products	821	267	3,022	2,224	-251	1,655	-1,253
Electricity and Heating Production and Supply	581	-284	-3,948	1,173	-2,353	-1,806	1,273
Transport, Storage, and Post	-15	-245	-507	523	-111	-492	-710

TOTAL +ΔE_{INT}	2,684	1,151	5,542	6,165	1,750	4,852	5,953
TOTAL -ΔE_{INT}	-1,760	-1,842	-6,533	-1,721	-6,639	-6,019	-3,252
Above sectors % +ΔE_{STR}	68%	26%	78%	88%	19%	64%	73%

The large dip in the ΔE_{ACT} share curve is essentially what the net positive ΔE_{INT} and ΔE_{STR} terms are taking away from ΔE_{ACT}. Although it is not possible to accurately estimate by how much, better accounting for changing prices would likely reduce this dip substantially, leaving the majority of growth in energy consumption explained by ΔE_{ACT}. Residential final energy consumption grew faster than value added from 2002 to 2003, and thus contributed to the increase in total energy intensity during this period. This contribution was small, however, as the residential share of total energy consumption was only 8% in 2002 and 2003.[17]

The most obvious sign of structural change in China's energy economy is from energy data. From 2002 to 2007, the share of ferrous metals in total energy consumption increased from 13% to 18% and the share of non-ferrous metals increased from 3% to 4%, accommodated by a decline in the energy shares of the electricity, petroleum and natural gas extraction, and chemical fibers sectors. This increase in the share of metals energy consumption, which amounts to 13% of the growth in China's total energy consumption from 2002 to 2007, occurred primarily over 2004-2005, matching China's emergence as a net metals exporter, as we describe below. Using the LMDI approach to decomposition, most but not all of this 13% would be a structural effect (i.e., some would also be an activity effect).

Aside from this relatively small structural effect, the energy data imply that the largest driver of high growth in energy consumption in China after 2002 was economic growth, and in particular growth in output of heavy industrial sectors. The question, then, is why heavy industry in China grew so rapidly over this time period.

Demand Side — Structural Decomposition Analysis

Figures 21-22 show, for each final demand, the contributions of changes in technology, final demand composition, final demand shares, and total final demand to growth in gross output for the chemicals, non-metal minerals, and metals sectors. Figures 21-22 are for the average case (i.e., equal allocation of residual) decomposition.

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[17] Residential energy consumption grew by 16% from 2002 to 2003, while GDP grew by 13%. Change in economy-wide energy intensity can be approximated as $dEI = \frac{dP}{E} + \frac{dR}{E} - \frac{dVA}{VA}$, where EI is energy intensity, P is production-based energy consumption, E is total energy consumption (E = P + R), R is residential energy consumption, and VA is value added. Because R/E is small, unless dP/E is close to zero the effect of dR/E will be small.

Figure 21. Technology (ΔX_M), Demand Composition (ΔX_θ), Demand Shares (ΔX_β), and Total Demand (ΔX_Y) Contributions to the Change in Gross Output (ΔX_{TOT}) for the Chemicals, Non-metal Minerals, and Metals Sectors in Each Final Demand Category, Nominal I-O Tables

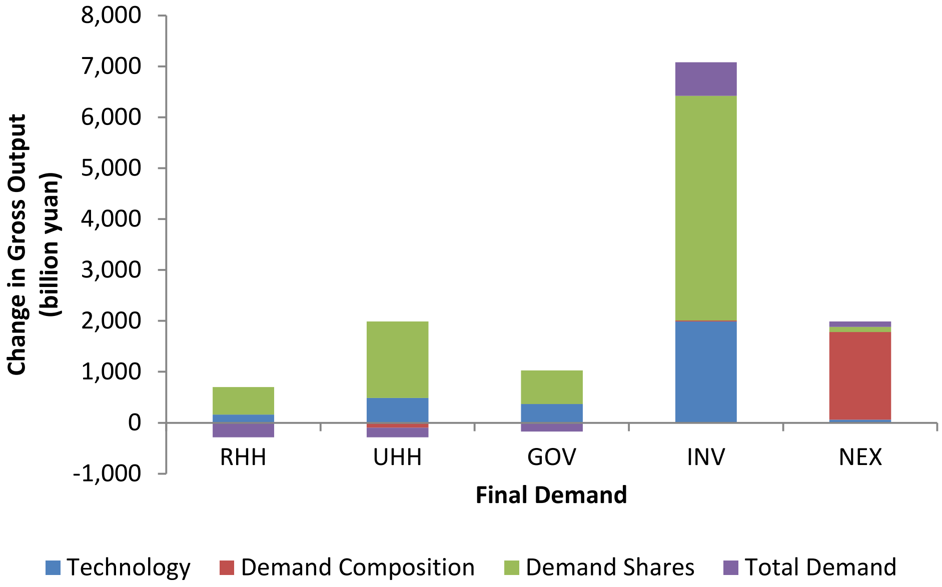
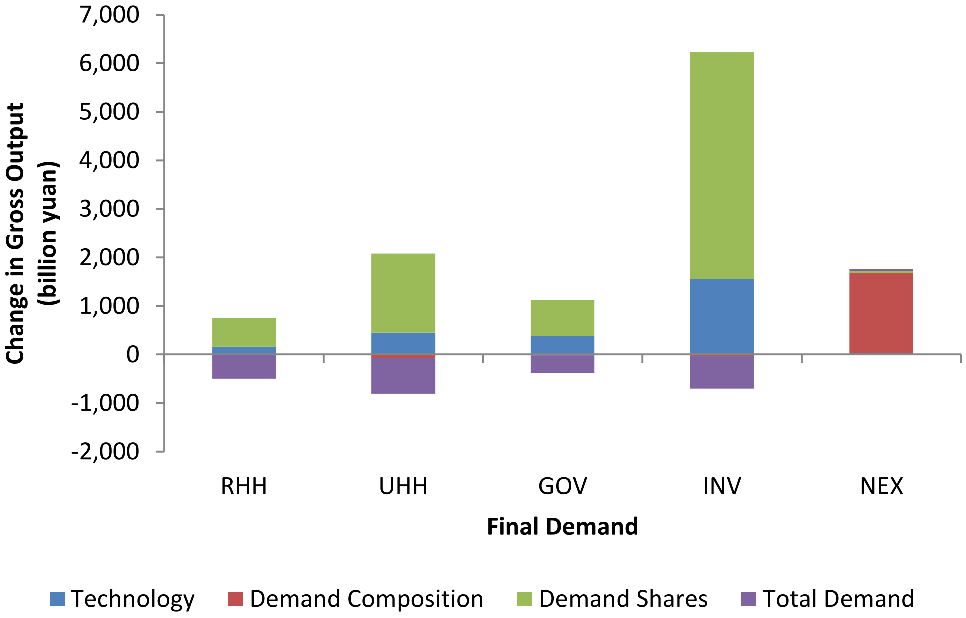


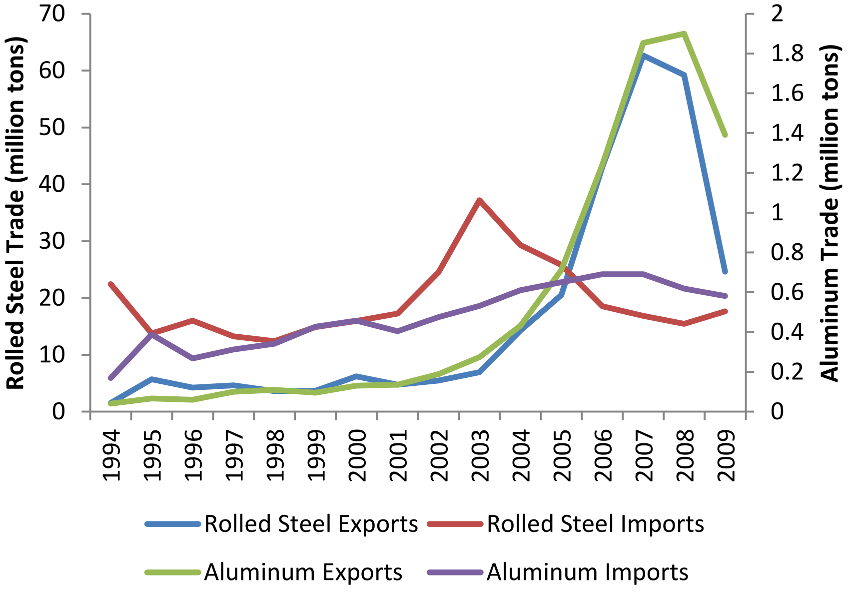
Figure 22. Technology (ΔX_M), Demand Composition (ΔX_θ), Demand Shares (ΔX_β), and Total Demand (ΔX_Y) Contributions to the Change in Gross Output (ΔX_{TOT}) for the Chemicals, Non-metal Minerals, and Metals Sectors in Each Final Demand Category, Constant Price I-O Tables



Note: RHH is rural household consumption, UHH is urban household consumption, GOV is government consumption, INV is gross investment, and NEX is net exports.

Shares of ΔX_M, ΔX_θ, ΔX_β, and ΔX_Y differ among the three cases, but generally tell a similar story. Some amount (4-31%) of the growth in heavy industrial output was caused by the shifting composition of net exports, as China became a significant metals, and particularly steel, net exporter in 2006 (Figure 23). Final demand shares played a smaller role ((-39)-1%), and are negative in the constant price tables because the fixed asset price index rose faster than the consumer price index from 2002 to 2007.

Figure 23. China's Imports and Exports (Tons) of Rolled Steel and Aluminum, 1994-2009



Sources and Notes: Data are from the China Statistical Yearbook series. By value, steel (steel products and crude steel, not shown here) and aluminum increased from 63% of metals exports in 2002, to 81% in 2008, with steel accounting for the lion's share.

Technology (ΔX_M) was a surprisingly large driver of growth in heavy industrial output, even in the constant price tables, which account for changing commodity prices. The origins of this positive ΔX_M effect can be found by examining changes in the matrix of intermediate expenditure shares (the A matrix). In the constant price tables, most of the increased spending on chemicals, non-metal minerals, and metals are on non-metal minerals and, to a lesser extent, chemicals.[18] In both cases, at least part, and potentially most, of the higher expenditure shares is likely due to data anomalies in the tables.[19] What portion of ΔX_M remains is primarily a

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[18] Subtracting the row of the 2002 A matrix from the 2007 A matrix and summing across the row gives the total increase in expenditure shares on a sector. In the constant price tables, for the chemicals and non-metal minerals sectors this sum was 0.14 and 0.26, respectively.

[19] Increased spending on non-metal minerals is primarily in the non-metal minerals (40%) and construction (53%) sectors. For the construction sector, most of the rise in the share of expenditures on non-metal minerals comes from an effective zeroing out of expenditure shares on agriculture and real estate, which we argue is more likely to

transfer from value added to gross output, which should be a worrying sign for China's economic policymakers.

When prices and data anomalies are accounted for, the primary two drivers of the results in Figures 21 and 22 are GDP growth and, to a lesser extent, China's emergence as a net metals exporter. Most of the GDP growth-induced increase in heavy industrial output was driven by investment. The household sector, and particularly rural households, who still make up more than half of China's population (NBS, 2010), played a comparatively negligible role.

Within investment, the equipment and construction sectors dominate the results, accounting for 56% of total growth in gross output in the chemicals, non-metal minerals, and metals sectors from 2002 to 2007 (Table 8). Adding metals net exports, which accounted for 7% of the growth in nominal terms, means that construction investment, equipment investment, and metals net exports together accounted for 63% of the growth in heavy industrial output from 2002 to 2007. The prevalence of the construction and equipment sectors suggests the multiplier forces at work in the Chinese economy over this time period. Construction induced demand for resources and equipment, which needed more resources and equipment to produce, and so on.

Table 8. Changes in Nominal Gross Output in the Chemical (CHEM), Non-metal Mineral (NMMN), and Metals (MTLS) Sectors Induced by Equipment and Construction Investment Demand

	Change in Gross Output (billion yuan)			
Investment Sector	**CHEM**	**NMMN**	**MTLS**	**Total Row**
Equipment	721	116	1,636	**2,473**
Construction	838	1,273	1,823	**3,934**
Total Column	**1,559**	**1,389**	**3,459**	**6,407**
Total Change in Gross Output	4,043	1,700	5,744	11,486
EQPT & CONS % Change in Gross Output	39%	82%	60%	56%

Conclusions and Discussion

Based on the above results, we offer a new interpretation of the explosive growth in energy consumption in China that occurred after 2002. Changes in sector energy intensity and structural change played relatively minor roles in this growth. A significant portion of the

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be a result of changes in methods than a change in real expenditure shares. For the non-metal minerals sector, most of the increasing in expenditure shares for non-metal minerals is accommodated by declining shares in value added, and in particular labor compensation. It is unclear whether this shift, from value added to own consumption, is an accounting issue or a real change in production. The chemicals sector resembles the non-metal minerals sector, where most of the increase in expenditure shares was on the chemicals sector and the "other services" sector and was accommodated by a decline in value added.

energy intensity and structural effects in our index decomposition analysis results are driven by price and data anomalies. The main structural effect is associated with China's emergence as a net metals exporter, which likely accounted for around 10% of total energy consumption growth from 2002 to 2007.

The dominant driver of energy consumption over 2002 to 2007 in China, and particularly after 2004, was growth in aggregate economic output. The energy-intensive sectors that were China's largest energy consumers in 2002 —the ferrous metal, basic chemical, non-metal mineral, electricity, and transport sectors — accounted for more than half of the growth in energy consumption from 2002 to 2007. Indeed, what is most striking about the Chinese energy-economy over 2002-2007, a time of extensive integration into the global economy, is the persistence of heavy industrial sector growth and the lack of a more significant (negative) contribution for structural change. Put differently, what drove energy use in China after 2002 was not fundamental changes to but rather the amplification of its established, energy-intensive growth model.

WTO entry in late 2001 sent the Chinese economy into overdrive, exacerbating structural imbalances that were already present. National income grew much faster than consumption, leading to a dramatic increase in aggregate savings rates, from 40% of GDP (nominal) in 2002 to more than 50% by 2007 (NBS, 2005; NBS, 2009).[20] As the rise in savings outpaced investment growth, China's trade surplus reached the hundred billion dollar mark by 2005 and has remained above that mark since (NBS, 2010). Between 2003 and 2007, investment and net exports accounted for more than 60% of real GDP growth (NBS, 2010).

In the corporate sector, banks, government, and households had relatively small claims on firms' gross operating surplus and so rising profits were retained, providing more volatile fuel for accelerating private investment than commercial credit.[21] Corporate savings grew nearly 5-fold to 6.9 trillion yuan between 2002 and 2008 (NBS, 2005; NBS, 2010). With few alternative investment options, these savings were largely reinvested. Interest rates, which might have served to rationalize investment decisions, were held at low levels beginning in 2002, which

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[20] Some caution is called for in the 2002 savings numbers, as revised historical flow of funds and GDP by expenditure data were not released after the 2004 economic census. Given that the largest revision to GDP data was in the tertiary sector, the largest omission on the expenditure side was likely consumption, in which case the savings-GDP ratio should have been even lower in 2002.

[21] The majority of investment in China is reportedly from self-raised funds; the share of self-raised funds in total investment increased from 51% to 61% from 2002-2007 (NBS, 2010), suggesting the huge role of retained earnings in financing investment. Bank loans and foreign direct investment accounted for around 17-25% of total investment funds after 2002 (NBS, 2010), though, as Barnett and Brooks (2006) note the "Other" category in NBS statistics (16-18% of investment) includes mortgage lending, which they estimate increased the share of bank lending from 20% to 27% in 2003. Reliance on self-raised funds is even higher than the economy-wide average in the manufacturing sector, where it accounted for 82% of investment in 2009 (NBS, 2010). Before 2007, non-listed state-owned or state-dominated firms, or parent companies of listed firms, had no obligation to pay dividends, either to the government or directly to households. As Anderson (2009) notes, there may not be a meaningful distinction between public and private firms in this context.

kept the cost of borrowing artificially low.[22] As a result of essentially free and low cost access to capital, industrial investment grew strongly; manufacturing's share in total investment grew from 26% in 2003 to 32% in 2007 (NBS, 2010). The result was a boom in industrial production capacity that exceeded the domestic economy's absorptive capacity, and a subsequent increase in exports of competitively priced industrial goods. This narrative, of a corporate sector awash in inexpensive credit, explains why China suddenly became a net exporter of metals, a sector in which China's main comparative advantage is cheap capital.

Household and government savings grew even faster than corporate savings after 2002, reaching a combined 10 trillion yuan in 2008 (NBS, 2010). Some portion of household savings was lent by banks to cover the difference between corporate investment and corporate savings. A significant amount of household savings, however, found its way into real estate investment, which nearly tripled in real terms between 2002 and 2007 (NBS, 2003; NBS, 2008). Rising household and government savings were also invested in transportation and urban infrastructure, with real investment in both growing nearly threefold between 2002 and 2007 (NBS, 2003; NBS, 2008). Rising construction investment required even more investment to keep pace with demand for construction materials and the equipment to produce them. From the early 2000s until the global financial crisis, China became the ultimate Keynesian economy.

Our structural decomposition results tie sustained levels of heavy industrial output on the production side of the Chinese economy with the export-investment model of growth on the final demand side. The two largest contributors to increases in heavy industrial output between 2002 and 2007 were growth in construction and equipment investment and exports of equipment and heavy industrial goods. The most important structural change was China's emergence as a net metals exporter, which was in many ways a consequence of financial distortions. These results indicate that, on the final demand side as well, most of the increase in energy use over 2002-2007 was the result of a continuation of, rather than a departure from, China's economic growth model.

Returning to the question posed at the beginning of this paper, were the energy efficiency policies of the 11th Five-Year Plan (2006-2010), largely focused on industrial end users, the right medicine for the ailment? Although these policies were important in their own right, they were not designed to, nor did they, address the root cause of the rapid growth in energy consumption in China after 2002. That root cause, we argue in this paper, was China's overall growth model. Although there is still scope for reducing energy intensity in heavy industrial sectors through more advanced equipment and processes, reducing the share of those sectors in GDP through rebalancing the economy is a more direct means of addressing China's future energy challenges.

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[22] Low interest rates were maintained through a binding ceiling on deposit accounts set by the State Council through the People's Bank of China. See Lardy (2008) for a discussion.

The high energy and materials intensity of China's current growth phase is typically explained as a consequence of "high urbanization and industrialization," but this rationale is at best partial and at worst misleading. Even with a continued slowdown in the rate of urban population growth, China's cities will likely add another 200 million people over the next decade.[23] However, as far as we know, there is no empirical connection between levels of investment and urbanization in China over the past decade. For instance, there does not appear to be significant linkage between urbanization and real estate development (Barnett and Brooks, 2006). High levels of growth in industrial output are driven by the level and destination of investment, which is determined to a significant degree by monetary and fiscal policy. There is, in other words, nothing sacred or inexorable about China's current growth model.

From an energy and materials perspective, economic rebalancing is not simply a matter of shifting final demand shares. Without changes in the rest of the economic structure, as reflected in the multiplier matrix, there are limits to reductions in heavy industrial output, and, by extension, energy inputs, that result from reducing investment and net export shares of GDP. For instance, eliminating the trade surplus and reducing the share of investment in GDP to 33% in the 2007 I-O table (i.e., assuming no changes in GDP and no adjustment) would reduce gross output of the metals sector by a modest 14%.[24] Rebalancing also requires more fundamental changes in income allocation. Value added in China is particularly low in China's construction and equipment sectors, for instance, at just 23% and 19% of gross output, respectively, in 2007 vis-à-vis 49% and 43% in the U.S.[25]

The need to transform its growth model is a central part of China's 12th Five-Year Plan, but it was also a largely unmet aspiration of the 11th Five-Year Plan. Solutions to many of the individual problems (e.g., high precautionary savings, no dividend obligations for state-owned firms) that make up China's larger structural imbalance problem have been in place since the mid-2000s, but meaningful implementation has been slow. As Naughton (2011) argues, China's economic policymaking is caught between the legacy of vested interest created by its industrial policies and the increasingly apparent need for difficult, more comprehensive economic reforms that would require substantial trade-offs and redistribution. For instance, easing controls on bank deposit and lending rates would likely improve returns, reduce total investment, and lead to a significant wealth transfer from enterprises to households (Feyzioğlu et al., 2009). However, given decades of "status quo reform," there may be strong institutional impediments to the monetary reforms needed to allow greater flexibility in interest rates.

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[23] Even if the growth rate of urban population fell from its 2000-2009 average of 3.9%/yr to 2.9%/yr, China's urban population would still grow by 200 million people from 2010 to 2019. Data are from NBS (2010).

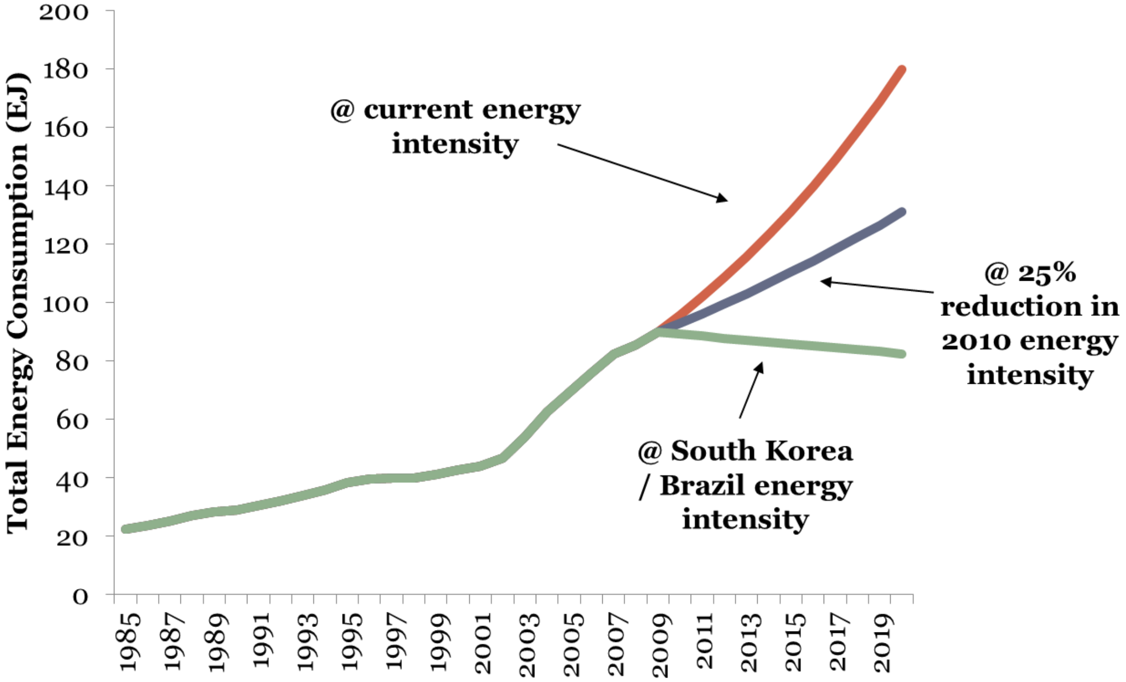
[24] Change in gross output for a given sector (ΔX_S) here is $\Delta X_S = \frac{\sum_k M_S \theta_k Y_k^1}{\sum_k M_S \theta_k Y_k^0}$, where M_S is the multiplier row for sector S, θ_k is a vector of final demand shares for final demand k, and Y_k^1 and Y_k^0 are final demands for sector k in the adjusted (1) and base (0) cases. For individual final demands, M_S and θ_k values cancel, and $\Delta X_S = \frac{Y_k^1}{Y_k^0}$.

[25] Data for China here are from the 2007 I-O table. Data for the U.S. are from the U.S. Bureau of Economic Analysis' GDP-by-industry & Input-Output tables, online at: http://bea.gov/iTable/index_industry.cfm.

Similarly, increasing dividend payments by state-owned enterprises would likely reduce investment levels by transferring income to households, but would require strengthening regulatory institutions to overcome powerful corporate interests (Naughton, 2008), as well as financial sector reforms to ensure that firms have adequate access to formal commercial credit markets. Rebalancing would also likely mean slower GDP growth, as demand composition rotates from external to domestic, and from investment to consumption spending. Both export revenue and high household saving have been potent catalysts for high investment rates.

These reforms grow more urgent as the Chinese economy grows in size. Quite apart from resource and environment sustainability issues, China is outgrowing the external markets that propelled it to develop supply capacity so rapidly. Investment rates must respond to this before excess capacity sends the economy into a downward spiral of oversupply and a hard landing. On the resource side, the impacts of energy use, whether political, market, or environmental, are felt in absolute rather than relative terms. The energy implications of the Chinese government's "choice" — growth models are not chosen but rather are the outcome of political processes — between harder and softer growth models are illustrated in Figure 24. At current energy intensity and 6-7% annual GDP growth, rising energy demand would require huge investments in energy efficiency to reduce baseline energy demand growth and allow China to meet its energy and climate goals. A softer growth model, somewhere between the China's current energy intensity and Brazil and South Korea's energy intensity and at 6-7% annual GDP growth, would substantially reduce the Chinese economy's energy requirements and the level of effort needed to energy and climate goals over the next decade.

Figure 24. Energy Trajectories for China and at Current (2010) Energy Intensity, at a 25% reduction in Energy Intensity over 2010 Levels by 2020, and Reaching South Korea's and Brazil's Energy Intensity by 2020



Notes and Sources: All three trajectories assume 7% (2011-2015) and 6% (2016-2020) annual GDP growth rates. Based on NBS estimates of 2010 total energy consumption (95 EJ) and GDP (26.8 trillion yuan, 2000 yuan), China's 2010 energy intensity was 3.6 MJ/yuan. A 25% reduction in 2010 energy intensity by 2020 is equivalent to 3.5%/yr annual energy demand growth. We calculate South Korea and Brazil's energy intensity in MJ per 2000 yuan by using the ratio of 2008 energy intensities (MJ/2000 $) between China and South Korea and Brazil from the World Bank's World Development Indicators database. This ratio works out to 1:0.33-0.38. South Korea and Brazil had similar energy intensities in 2005, at 12.7 and 12.2 MJ/$, respectively, and we use South Korea's energy intensity in the above figure.

Appendix: Additional Tables

Table 9. Sector Values of ΔE_{INT} Calculated using Total Energy and 38-Sector Industrial Value Added Data

Sector	Years						
	00-01	01-02	02-03	03-04	04-05	05-06	06-07
Petroleum Processing, Coking and Nuclear Fuel Processing	-183	-782	295	1,539	-98	661	-2,018
Raw Chemical Material & Chemical Products	-1,514	-537	-1,175	-2,224	-473	-2,368	-3,620
Smelting and Pressing of	-1,488	-2,178	-479	927	-3,101	-3,826	-4,913

Ferrous Metals							
Nonmetal Mineral Products	-2,028	-2,290	-2,187	-3,212	2,077	-4,173	-2,698
Electricity and Heating Production and Supply	-2,470	-4,237	1,121	-9,105	-952	-449	-8,376

Table 10. Sector Values of ΔE_{INT} Calculated using Total Energy and 38-Sector Industrial Gross Output Data

Sector	**Years**						
	00-01	**01-02**	**02-03**	**03-04**	**04-05**	**05-06**	**06-07**
Petroleum Processing, Coking and Nuclear Fuel Processing	321	-203	175	764	-1,654	-204	-515
Raw Chemical Material & Chemical Products	-1,172	-355	-729	-1,651	-996	-2,688	-2,850
Smelting and Pressing of Ferrous Metals	-1,643	-2,230	-98	848	-3,242	-3,434	-4,929
Nonmetal Mineral Products	-2,409	-1,733	-1,840	-3,797	1,381	-3,303	-3,938
Electricity and Heating Production and Supply	-358	-3,536	-22	-36,831	-1,549	-631	-5,240

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Chapter 4

Challenges to China’s Transition to a Low Carbon Electricity System[1]

China’s electricity system is among the most important energy systems in the world. It powers the growth of the world’s second largest economy and the emergence of a middle class society in China. Predominantly coal based, the Chinese electricity system is also the world’s single largest source of CO_2 emissions (IEA, 2009). The transition to a low carbon electricity system in China is critical to global efforts to reduce the risks of climate change.

Recognizing the electricity sector’s importance in reducing China’s greenhouse gas emissions, the Chinese government has drafted ambitious targets for renewable generation capacity by 2020. These targets, which would make China the world’s largest market for wind and solar, demonstrate that political will exists at the highest levels of the Chinese government for deploying renewable energy and decarbonizing the power system. However, China’s renewable energy targets are best thought of as industrial policy. They are not grounded in the realities of China’s electricity system, and leave unanswered crucial questions of implementation and cost.

Integration of renewable generation, and decarbonization more broadly, poses considerable and unique challenges for China’s electricity sector. Still governed largely by planned economy institutions, China’s current electricity system lacks the flexibility in demand, generation, transmission, and pricing necessary to integrate renewables and reduce CO_2 emissions on a large scale at an acceptable level of cost and reliability. At the same time, shifting patterns of demand, growing environmental awareness, and rising costs are forcing change on the Chinese electricity sector. Dealing with these pressures will require changes in how the sector is managed, but there is no guarantee that these changes will make the electricity system more flexible, or that they will support efforts to decarbonize the system.

Increasing flexibility in China’s electricity system will require balancing supply- and demand-side investments, increasing the share of dispatchable generation, and cost-effectively expanding the transmission network. Adding this flexibility will depend on developing more cost-reflective wholesale and retail pricing, including mechanisms to integrate demand-side efficiency into pricing and investment. China’s electricity sector has never been governed under the traditional regulated cost-of-service model, which provides the basis for cost-reflective electricity pricing in

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[1] This chapter was originally published as Kahrl, F., Williams, J., Ding, J., Hu, J., 2011. Challenges to China’s Transition to a Low Carbon Electricity System. Energy Policy 39, 4032–4041.

many other countries. Rather than creating complex, competitive market structures, China will need innovation in basic regulatory and planning institutions and processes to better manage and allocate costs in its electricity sector.

Major institutional reforms in China's electricity sector began more than a decade ago, but have made only limited progress in changing the fundamentals of how the system is operated. Many of the obstacles to electricity reform in China lie outside the electricity sector and will require longer-term solutions involving political and legal reforms. However, we argue that in the near term, incremental, bottom-up improvements in planning and ratemaking could promote the transition to a more flexible, cost-reflective electricity system, giving the Chinese government's decarbonization and renewable energy policies a better chance of succeeding in practice. The appropriate transfer of OECD electricity sector experience and skills could assist this transition.

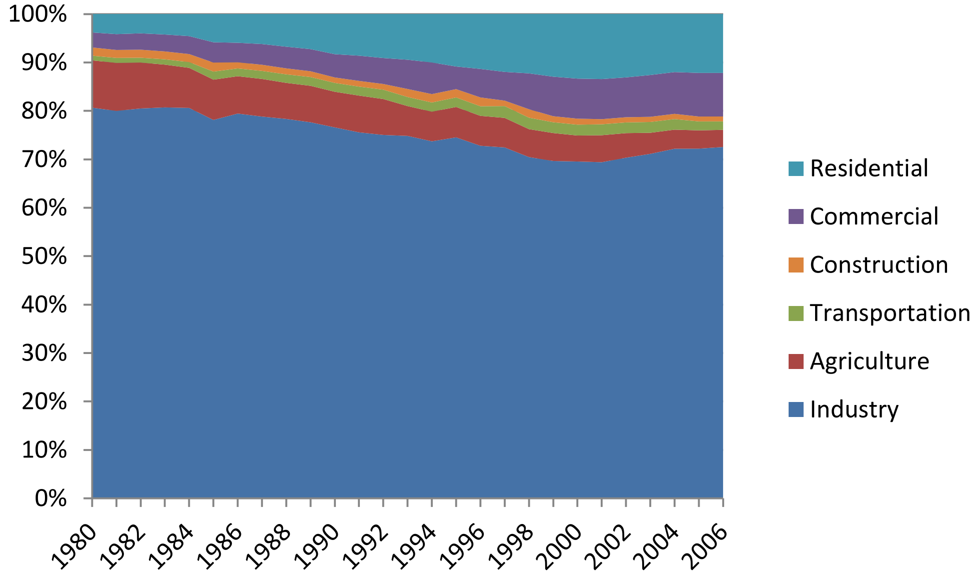
An Overview of China's Current Electricity System

China's transition toward a low carbon electricity system will be shaped and constrained by the engineering and economics of the current system, both of which are surprisingly inflexible. This section describes the demand, generation, operations, and pricing characteristics of China's current electricity system, and why the system evolved as it did. We then discuss the challenges that the current system poses for integrating renewable energy on a larger scale.

Demand

Although the first power plants in China were designed, as in many other countries during the late 19th century, to provide street lighting, since then the expansion of the Chinese power system has been driven mainly by industrial growth. In 1980, during the early years of economic reform, industry accounted for roughly 80% of China's electricity consumption (CEG, 2008). Residential and commercial demand grew rapidly over the 1990s and 2000s; by 2007 residential and commercial electricity consumption (626 TWh [NBS, 2009]) was larger than total consumption in 1990 (580 TWh [CEG, 2008]). However, industry has continued to constitute more than 70% of China's net electricity demand (Figure 25). Heavy industry dominates industrial load, accounting for 83% of industrial electricity consumption in 2009 (CEC, 2010a).

Figure 25. Shares of Electricity Consumption by Sector, China, 1980-2006



Source: Data are from CEG (2008).

The high share of industrial load has driven the evolution of the Chinese power system, allowing China to maintain a high system load factor (i.e., a relatively flat load shape) compared to countries with relatively more residential and commercial electricity consumption. As a result of its high load factor, China's electricity system has historically needed less load-following and peaking generation.

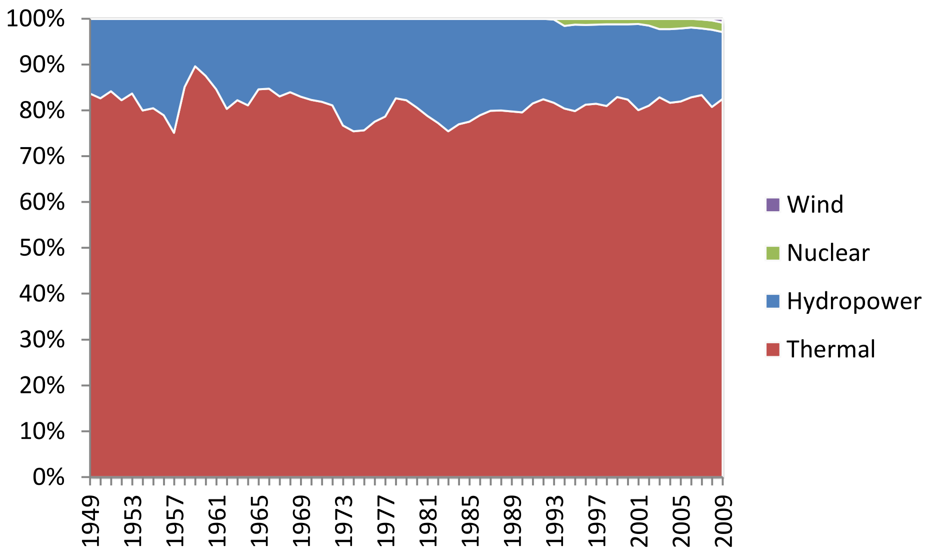
Growth is a second defining characteristic of electricity demand in China. From 1980 to 2009, annual electricity demand in China grew more than 12 fold, from 295 TWh to 3,660 TWh (CEC, 2010b). Demand growth of this magnitude and speed has contributed to severe capacity shortages, impacting system reliability and requiring regulatory agencies to sacrifice other goals for sector reform to simply ensuring there was sufficient supply to meet demand. Significant electricity reforms, for instance, began in 2002 but were put on hold because of shortages that plagued the electricity sector from 2002 to 2007 (Williams and Kahrl, 2009).

Generation

The Chinese electricity system's high load factor facilitated its heavy reliance on coal-fired generation, which, in most countries, is used as a baseload resource. Though hydropower, nuclear, and wind generation in China grew more than 7 fold, from 92 TWh to 669 TWh, from 1985 to 2009 (CEG, 2008; CEC, 2010b), coal still accounted for 78% of China's generation mix in

2009 (CEC, 2010c). The share of thermal generation, of which coal forms the vast majority, has in fact gradually risen since the mid-1980s (Figure 26).[2]

Figure 26. China's Generation Mix, 1949-2009



Sources: 1949-2006 data are from CEG (2008); 2007-2008 data are from EBEPY (2009); 2009 data are from SERC (2010).

Although China's generation mix has been relatively stable over the past two decades, the composition of coal-fired power plants has undergone a significant shift toward larger, more efficient units. The share of units 300 MW and above rose from only 23% of total thermal generating capacity in 1993 (CEG, 2008) to 69% by the end of 2009 (CEC, 2010a). In addition, China's central government agencies have led an effort to shut down small (≤ 50 MW) and old (> 20 years, ≤ 200 MW) units, retiring down 60.6 GW of these units between 2006 and 2009. As a result of this push toward higher generation efficiency, the average thermal efficiency of coal-fired power plants in China has been able to sustain a linearly increasing trend since the 1960s, and now reportedly surpasses the average efficiency of U.S. coal plants by a significant margin.[3]

Operations

China's physical grid is divided into four regional synchronous grids, with the Northeast-North-Central (东北-华北-华中), East (华东), and Northwest (西北) regions operated by the State

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[2] For instance, coal accounted for 95% of thermal generation in 2009 (CEC, 2010c)

[3] In 2009 the reported average "gross heat rate" (发电煤耗) for thermal power plants in China, at 320 kgce MWh^{-1} (8,890 Btu kWh^{-1}) (CEC, 2010c), was 12% lower than the reported average operating heat rate of coal-fired units in the U.S. (10,114 Btu kWh^{-1}) in 2009 (EIA, 2010b). Potential inclusion of combined heat and power units in China's statistics, and other differences in how energy data are collected and calculated, may contribute to this difference.

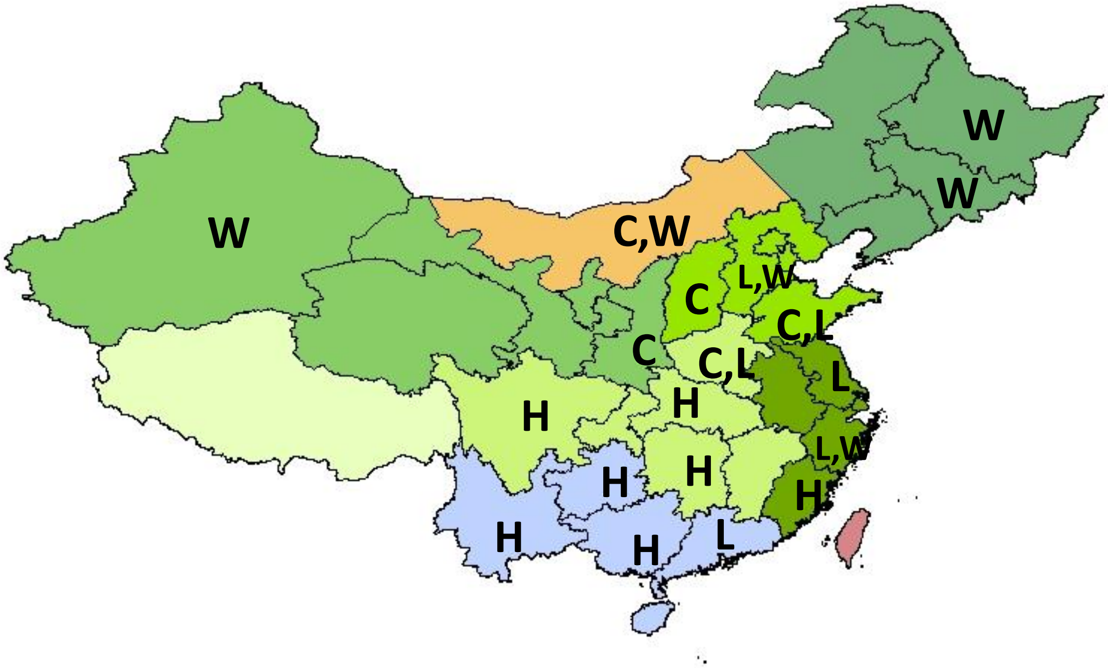
Grid Corporation, and the South (南方) operated by the China Southern Power Grid Corporation (Figure 27). Although basic DC interconnection among regional grids was achieved in 2005 (Zhou et al., 2009), power flow among regions and even between provinces within regions remains limited.

China has large spatial disparities between energy resources and load centers, and between regions with coal, hydropower, and wind resources (Figure 28). Coal reserves are concentrated in the north, load centers along the eastern seaboard, wind resources in the Northeast and North grids, and hydropower in the Central and South grids. The lack of greater interconnection among regional and sub-regional grids imposes constraints on optimal use and delivery of energy resources, limiting the availability of dispatchable hydropower resources to provide peaking and ancillary services and straining the transportation system because of the need to ship coal by rail and road.

Figure 27. Regional Grids in China

Note: The Western Inner Mongolia Power Grid is operated independently from the State Grid Corporation, but lies within the Northeast-North-Central region.

Figure 28. Distribution of Provinces that Account for More than 5% of Domestic Coal Production (C), Hydropower Generation (H), Wind Generation (W), and Electricity Consumption (L) in China



Source: Data are from EBEPY (2009).

Dispatch in the Chinese power sector has, since the early 1980s, operated under an "equal shares" formula (平均调度), whereby generators of a given type are guaranteed a roughly equal number of operating hours to ensure adequate revenues to recover their fixed costs. Economically and environmentally, this practice is inefficient, as generating units with high heat rates (i.e., low efficiency) may receive the same number of operating hours as those with low heat rates. Additionally, equal shares dispatch has contributed to inefficient generation investment by encouraging overbuilding (Liu and Chen, 2010). Average capacity factors for coal-fired generators were only 55% in 2009 (CEC, 2010b). Five provinces began to experiment with an energy efficient dispatch (节能调度) system in 2007, but this pilot system has met with technical and economic obstacles and has yet to be replicated in other provinces (Gao and Li, 2010).

As a coal- and hydropower-dominated system, many of the generation services provided by natural gas units in other countries are instead provided by coal or hydropower units in China. In regions that do not have significant hydropower resources, coal units are used for load-following and peaking generation, requiring significant cycling of coal units and reducing the efficiency of these units.[4] Coal is also often used to provide the ancillary services required to maintain grid reliability, including spinning and non-spinning reserves.

Pricing

Despite incremental changes to wholesale generation and retail rates, China continues to lack a formal, transparent mechanism for linking costs and retail prices in its electricity sector. Wholesale generation rates (上网电价) in China have historically been loosely based on average costs.[5] Since 2004, rates for thermal generators have been set using benchmark pricing (标杆电价), in which generators in the same technology class are given the same tariff, based on an estimate of annual output and fixed and variable costs for that class. As coal prices rose in the 2000s, China's central government developed a "co-movement" (煤电联动) mechanism that allows for some pass through of fuel cost increases.[6] Wholesale rates for renewable generators are set using regional benchmark prices, while rates for hydropower and nuclear generators are set on a facility-by-facility basis. Provision of ancillary services has historically been limited in scale and scope, mandatory and uncompensated, and concentrated in a few power plants, but plans to compensate generators for services are currently in the early stages of implementation.[7] Because of the dominance of coal in China's electricity system, this predominantly benchmark-based approach to wholesale pricing means that generation supply curves in China tend to be relatively flat.

The revenues grid companies receive for T&D services are currently based on the residual between retail sales and generation costs. This residual is inherited from historical prices and is not based on a bottom-up accounting of T&D costs. Beginning in 2005, the State Electricity Regulatory Commission (SERC) developed accounting standards and reporting requirements for

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[4] Average load factors for coal-fired units are commonly thought to be 70-80% in China (Luo and Zhang, 2010), but coal-fired units run at load factors as low as 50%. For a mid-size (350 MW) unit, Luo and Zhang (2010) estimate that running at 50-80% load factor increases heat rates by 2-11%. For a larger (600 MW) unit, Lv et al. (2010) estimate that running at a 50-80% load factor increases heat rates by 2-7%. The relationship between load factor and heat rates is non-linear; at 70-80% load factors the efficiency penalty is relatively modest.

[5] The "investment recovery price" (还本付息电价), adopted in 1985, allowed investors to recoup capital investments through individually negotiated wholesale rates. In 2001, this approach gave way to an "operational life price" (经营期电价), which, inter alia, amortized investment costs over the expected technical rather than financial lifespan of the facility. This plant-specific approach to pricing was changed in 2004, with the adoption of a "benchmark price" (标杆电价), which sets uniform prices for generators on the basis of industry-wide technologies and performance.

[6] More specifically, the co-movement mechanism allows for 70% of coal price increases to be passed through to retail rates if coal prices increase by more than 5%. Retail prices were raised five times between 2005 and 2009 Prices were raised once in 2005, once in 2006, and twice in 2008 (Luo and Zhang, 2010). An additional price increase occurred in 2009. Price adjustments were initially based on co-movement rules but were ultimately negotiated between government agencies and generators and grid companies. This negotiation has reportedly included threats by power companies to withhold generation if demands for price increases were not met (Qiu, 2007).

[7] For more on rules and compensation standards for ancillary services, see Implementation Plans for Ancillary Services,《并网发电厂辅助服务管理实施细则》, which have been developed individually by region.

grid companies,[8] but the level of detail and transparency in the disclosures required by SERC is not sufficient to assess whether costs are reasonable (Cai, 2010). Moving toward cost-based T&D pricing is a continuing priority for regulators (SERC, 2010).

Retail electricity prices in China have historically been designed to reflect government policy and social priorities, instead of the cost of service (Zhang and Heller, 2004; IEA, 2006). Commercial customers and, to a lesser extent, other industrial customers pay high electricity rates that subsidize agricultural users, fertilizer producers, large industrial customers, and residential customers. There have been some adjustments to the retail pricing system to deal with emerging challenges. Since the 1990s, many provinces have begun to use retail pricing to manage peak demand, with both interruptible and time-of-use (TOU) pricing for industrial, commercial, and, in a limited number of provinces, residential customers. To encourage conservation, China's central government is currently drafting rules to create inclining block rates for residential customers. Neither TOU prices nor inclining block rates are ultimately cost-based. The lack of a cost basis can lead to perverse incentives, such as encouraging grid companies to sell more power in peak periods under TOU rates (Hu et al., 2005).

Renewables Integration in the Current Power System

Given relatively high costs for solar and biomass power, wind is and will likely continue to be the principal non-hydro renewable resource in China. China has abundant wind resources, with total onshore wind resources estimated at 250 GW and offshore wind resources estimated at 750 GW (Martinot, 2010). Wind capacity has grown more than 50-fold over the 2000s, from 0.3 GW in 2000 (CEG, 2008) to 17.6 GW, with an additional 7.2 GW under construction, at the end of 2009 (CEC, 2010c). Wind integration has created a number of widely publicized challenges for grid companies in China (Cyranoski, 2009; Liao et al., 2010). Wind curtailment and lack of basic interconnection continue to keep wind capacity factors low, at 23.7% in 2009 (CEC, 2010c).

High integration costs pose a challenge for scaling up wind generation in China. The relatively small amount of dispatchable generation and the lack of interconnection in China's electricity system, both examples of the system's general lack of flexibility, contribute to high wind integration costs. The recent experience of the Western Inner Mongolia Power Grid (WIMPG), widely reported in the Chinese media, provides an example of how inflexibility contributes to higher costs.[9]

At a technical potential of 150 GW (Liu and Kokko, 2010), Inner Mongolia has the largest onshore wind resource in China and has significantly expanded its wind generation capacity

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[8] See Methods for Calculating Transmission and Distribution Costs 《输配电成本核算办法》.

[9] See, for instance, "An Embarrassment to Inner Mongolia's Wind Development: Hold Up in Grid Construction Leads to Waste" [内蒙古风电发展遇尴尬 电网建设滞后致产能浪费], 12 June, 2010, China Economic Herald; "Western Inner Mongolia Power Grid's Wind Sample: Success from and Constrained by its Unique System" [蒙西风电样本: 受益并受制于独特体制], 22 June 2010, Economic Observer; "Three Gorges of Wind Faces Difficulty in Exporting Electricity" [风电三峡"的输电困局], China Economic Times, 8 October 2010.

over the last ten years. By December of 2009, WIMPG had 4.0 GW of wind capacity out of 33.3 GW of total generating capacity (Zhang, 2009a). With a peak demand of 15.7 GW in 2009 (Zhang, 2009a), Inner Mongolia already had significant surplus generating capacity before its wind build-out began.

The WIMPG currently exports around one quarter of its electricity. However, its two 500 kV AC lines limit export expansion, thus forcing the WIMPG dispatch center to curtail wind. Wind curtailment is a particularly serious problem during winter nights, when generation from the WIMPG's 12 GW of coal-powered combined heat and power (CHP) plants, used to provide heating, cannot be reduced. When CHP plants are not in use, the provincial dispatch center has accommodated wind generators by ramping down coal units. None of these costs — transmission congestion, wind curtailment, or coal-plant cycling — is captured in the current pricing system (Huang, 2009), which limits the ability of the grid and generation companies involved to play a more active role in addressing integration challenges.[10]

The generation, transmission, and pricing flexibility that could reduce wind integration costs in WIMPG could also improve the economic efficiency of China's electricity system. A more comprehensive planning, regulatory, and pricing framework for new generation could lead to a more efficient generation mix, facilitating, for instance, the use of natural gas units for load-following and peaking generation and a more rational plan for closing of small coal-fired units that accounts for the role they play in system balancing.[11] Integrating intermittent renewables into the grid, and particularly into regional grids, will require a more economically rational dispatch system. New transmission to support renewable generation could also be used to optimize hydropower and thermal generation in different regions.

Drivers of Change in the Chinese Power System

The current Chinese power system is under stress from a number of different directions. In some ways, these pressures are much like those faced by policymakers in OECD countries during the 1970s: high forecasted demand growth, an energy crisis and rising fuel prices, a flattening out of technology cost declines, and growing environmental awareness (Hirsh, 1999).

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[10] Jurisdictional and incentive issues are a major contributing factor to this impasse. The Inner Mongolia Power Company (IMPC), which operates the WIMPG, has few options for raising investment in new transmission. For a variety of reasons IMPC was allowed to remain independent from the national-level State Grid Company (SGCC) after unbundling reforms after 2002, and SGCC has reportedly been reluctant to invest in transmission between its region and WIMPG. NDRC's National Energy Administration is responsible for transmission planning, but is concerned that the neighboring service area, the North China Power Grid, does not need the electricity. SERC, despite being the national regulator, does not have the authority or the standing to play a mediating role.

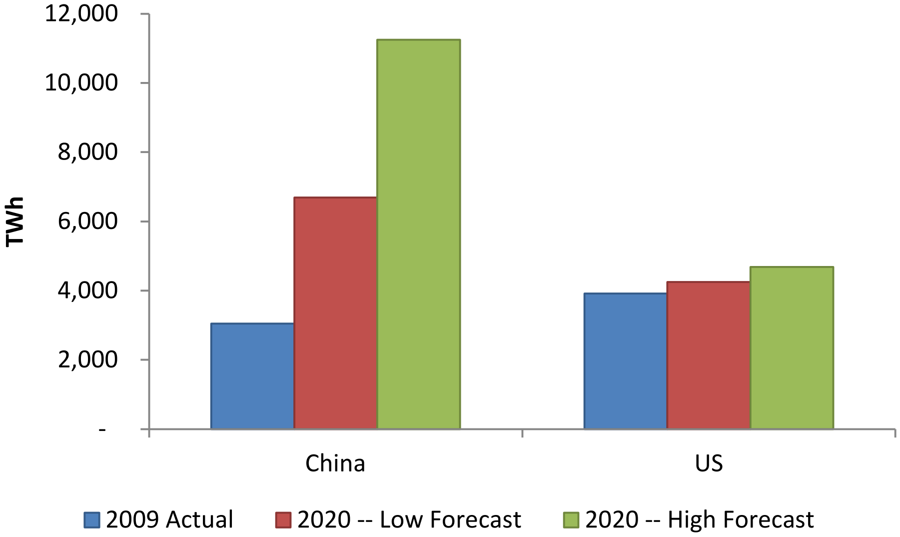
[11] China, in fact, did have a 24 GW of natural gas generating capacity by the end of 2009 (CEC, 2010b). However, according to CEC data (CEC, 2010c), these plants generated only 5,217 GWh in 2009, giving natural gas an average capacity factor of just over 2% and suggesting that many plants are not in use. Since the energy requirements for peaking and load following plants, which run a relatively small number of hours in the year, are relatively low, substantially increasing the use of natural gas for this purpose is not subject to the resource constraints that make natural gas an unlikely substitute for coal in baseload applications.

In other ways, drivers of change in the Chinese power sector are unique, stemming from the sheer magnitude of China's economic growth, its transition from an industrial to a consumer-based economy, and the electricity sector's strong reliance on coal. After examining demand, environment, and costs as drivers of change, we discuss how these drivers create both the need, and the enabling environment, for incorporating energy efficiency as a cornerstone of a more flexible and cost-reflective electricity system.

Demand Growth and Structural Change

Electricity demand in China will continue to grow, but the magnitude and speed of this growth is very uncertain. Forecasts for electricity demand in 2020, for instance, range from 6,692 TWh (IEA, 2009) to 11,245 TWh (Zhang, 2009b).[12] Against 2009 consumption of 3,659 TWh (SERC, 2010), the former forecast would represent a near-doubling of demand (+3,013 TWh) while the latter would represent more than a tripling of demand (+7,586 TWh). Although rates of demand growth will inevitably slow, the decade from 2010 to 2020 will likely be, in absolute terms, the largest portion of China's power sector build out. To put these forecasts in context, electricity demand in the U.S. is forecast to grow 329-767 TWh between 2009 and 2020, an 8-20% increase over 2009 levels (Figure 29).

Figure 29. 2009 Actual and High/Low Forecasted 2020 Electricity Demand, China and U.S.



Sources: For China, "2009 Actual" data are from SERC (2010); "2020 – Low Forecast" is from IEA (2009); "2020 – High Forecast" is from Zhang (2009b). For the U.S., all data are from EIA (2010a).

In addition to the speed and magnitude of demand growth, the structural composition of demand growth will also put pressure on the Chinese electricity sector. Shares of residential

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[12] Zhang (2009b) forecasts a range of 7,284 to 11,245 TWh.

and commercial electricity consumption will likely increase over the next two decades, tending to reduce system load factors and average capacity factors for generators. Large declines in system load factors will require major changes in China's generation mix, and greater use of natural gas generation in particular.

As China's economy shifts away from heavy industry and toward high value-added industry (e.g., information technology), demand for reliability will increase. Although China's grid companies have made significant strides in improving reliability, at a system average interruption duration index (SAIDI) level of 9.1 hours per customer in 2009 (SERC, 2010) the number of outage hours would need to be reduced by more than half to reach current U.S. average SAIDI levels (4.1 hours) (Eto et al., 2008).

Growing Environmental Awareness and Environmental Policy

Greater recognition of the extent of environmental damage, combined with growing environmental activism, has led to important progress in addressing China's environmental challenges over the past decade (Economy, 2010). In the power sector, this includes advances in controlling particulate matter (PM) and sulfur dioxide (SO_2) emissions, and forthcoming efforts to regulate nitrous oxide (NO_x) emissions. These improvements, however, have been made through mandating the use of pollution control technologies, and not through reductions in coal-fired generation.

During the 11th Five-Year Plan (2006-2010), China's central government put in place the legal and planning framework to address the economy's high reliance on fossil fuels, and coal in particular. These measures include: a Renewable Energy Law, passed in 2005 and amended 2009; a renewable portfolio standard (RPS) for electricity generators;[13] aggressive economy-wide targets for renewable energy and nuclear power; and an ambitious target for reducing economy-wide carbon dioxide (CO_2) emissions intensity.

The alternative energy target aims to achieve 15% of the country's final energy consumption from renewables and nuclear power by 2020.[14] The CO_2 target seeks to reduce the CO_2 intensity of GDP by 40-45% by 2020. Although neither of these targets has specific requirements for the electricity sector, the electricity sector is both China's largest source of CO_2 emissions (IEA, 2009) and the only sector that can integrate large amounts of non-fossil energy over the next decade. Electricity policy will be critical in determining whether these targets can be met.

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[13] China's RPS target requires that investors with 5 GW or more of generating capacity must have at least 8% of their capacity and 3% of their generation from non-hydro renewables by 2020 (NDRC, 2007a).

[14] In its original form, this target was for 15% of total primary energy consumption to come from renewables by 2020. In 2009, the denominator in the target was changed to final energy consumption and the target was broadened to include nuclear power (Martinot, 2010).

Meeting the 15% alternative energy goal will require a massive effort to develop alternative energy sources. Using the IEA's (2009) 72.4 EJ forecast of final energy consumption for China in 2020,[15] a 15% alternative energy target would require 10.9 EJ of alternative energy in 2020. Meeting proposed 2020 targets for hydropower, wind, biomass, solar, and nuclear capacity (Table 11) would provide an estimated 8.0 EJ (2,213 TWh) of electricity, accounting for 73% of the target. From another perspective, though, even with 362 GW of new alternative generation capacity, China would still need 2.9 EJ of alternative energy to meet the 15% target, and it is unclear what other sectors might be able to provide non-fossil fuel energy on a large scale. Energy demand growth is an essential determinant of the amount of energy resources required to meet the target. If final energy consumption in 2020 were 53.1 EJ rather than 72.4 EJ, the alternative energy build out shown in Table 11 would be sufficient to meet a 15% target.[16]

Table 11. Estimated Alternative Energy Generation based on 2020 Capacity Targets

	2020 Target (GW)	Implied New Capacity, 2010-2020 (GW)	Average capacity factor	Generation (TWh)
Hydropower	300	104	0.38	986
Wind	150	132	0.25	329
Nuclear	86	77	0.89	668
Biomass	30	29	0.71	186
Solar	20	20	0.25	44
Total	**586**	**362**		**2,213**

Sources and Notes: Renewable targets are from Martinot and Li (2010). Nuclear targets are from Chai and Zhang (2010). These targets are still under discussion; official targets are much lower (NDRC, 2007a). Capacity data for 2009 are from CEC (2010c). Hydropower capacity factor is a 1980-2006 historical average, from CEG (2008); nuclear and biomass capacity factors are 2009 average levels, from CEC (2010c); wind and solar capacity factors are estimates.

Energy demand growth poses a similar challenge for China's 40-45% CO_2 intensity goal. Assuming that non-coal thermal generating capacity and generation reach 60 GW and 124 TWh,[17] respectively, in 2020, in tandem with the alternative energy build out in Table 11 China would generate a total of 2,337 TWh of electricity from non-coal sources. Vis-à-vis the lower and higher electricity demand forecasts for 2020 described above (6,692 TWh and 11,245 TWh, respectively), the share of coal generation would shift from 78% in 2009, to 65% in the lower

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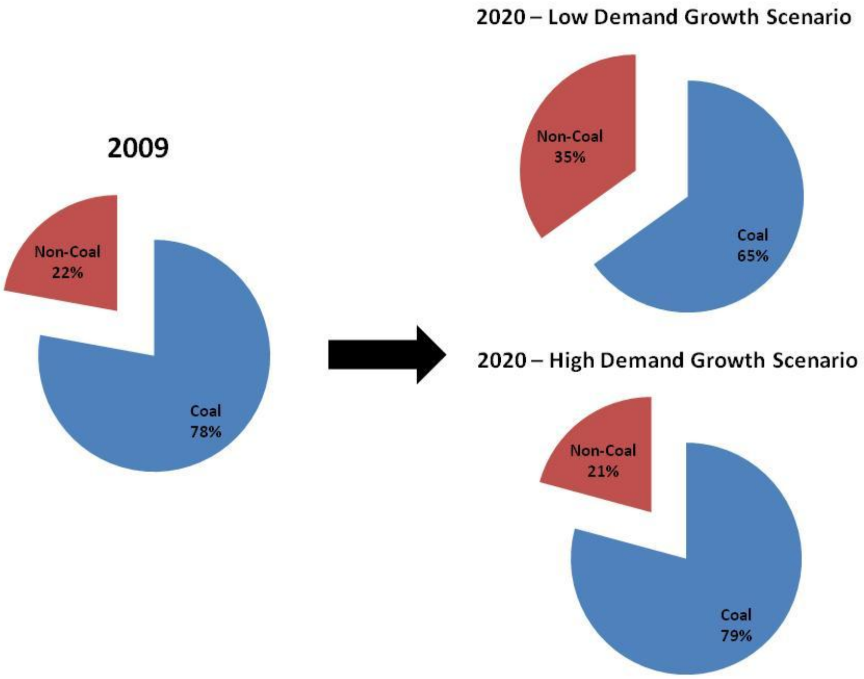
[15] We subtract "biomass and waste" from the IEA's final consumption forecast to make this estimate more comparable with Chinese energy statistics.

[16] Final energy consumption of 53.1 EJ would imply energy demand growth of 8.6 EJ between 2007 and 2020, or 1.3% yr^{-1}.

[17] Non-coal thermal here would most likely be a build out of natural gas capacity. China had 8.2 GW of heavy oil capacity, 24.0 GW of natural gas, and 1.3 GW of waste incineration capacity in 2009 (CEC, 2010c). We assume that this non-coal thermal has a 23.68% capacity factor, the level of oil-fired generation in China in 2009 (CEC, 2010c) and on par with capacity factors for natural gas in the U.S. (EIA, 2010b).

demand case and 79% in the high demand case in 2020 (Figure 30). In the latter instance, in other words, the share of coal would actually increase, and the electricity sector's contribution to the CO_2 intensity goal could well be negative.

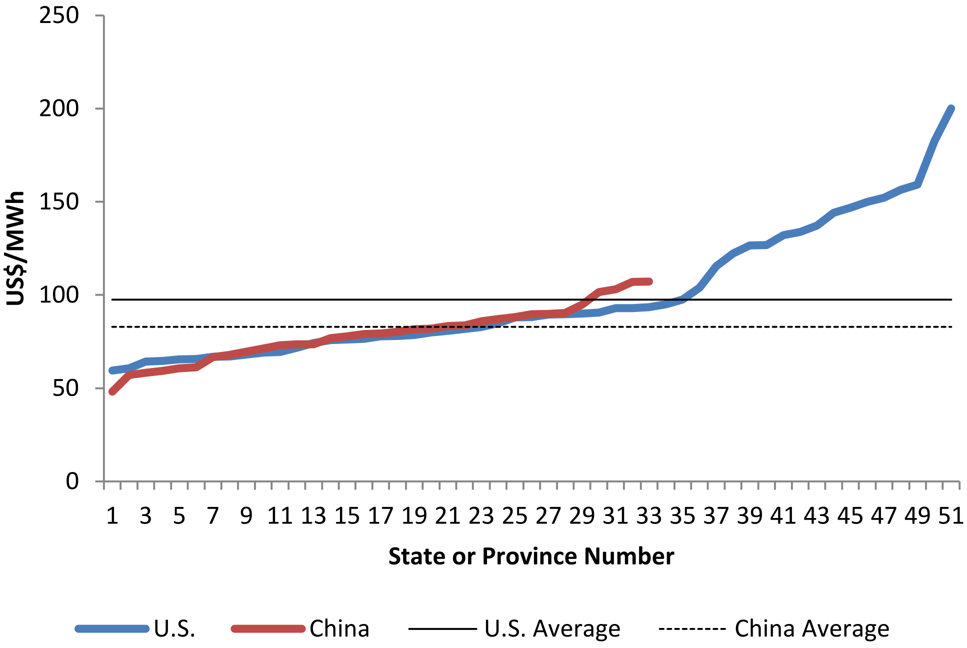
Figure 30. Shares of Coal and Non-Coal Generation, 2009 and Low and High Demand Growth Scenarios for 2020



Rising Costs

Rising generation, transmission, and distribution costs are threatening to raise the average cost of electricity provision in China, which will put greater pressure on retail prices. Retail electricity prices in China are already relatively high. Average retail rates in most Chinese provinces are on par with many lower cost (US$0.06-0.10 kWh^{-1}) states in the U.S., as shown in Figure 31. As a share of income, electricity expenditures in China are much higher than in the U.S. (Jiang, 2007).

Figure 31. Average 2009 Retail Electricity Prices in China and the U.S., Ranked by Province/State in Ascending Order



Sources and Notes: China data are from SERC (2010); U.S. data are from EIA (2010b). Data from SERC do not include adders (政府性资金及附加费); we include these adders using 27.19, 27.30, and 26.88 yuan MWh^{-1} values for the State Grid, Southern Grid, and Western Inner Mongolia grids, respectively, and a 27.20 yuan MWh^{-1} average value for the entire country (SERC, 2010).

The cost of coal-fired generation in China will face upward pressure over the next decade. Sustained high growth in demand for coal, transportation bottlenecks, and coal resource scarcity will lead to growing reliance on imports (Lin and Liu, 2010; Shealy and Dorian, 2010). Coal mining in China is still extremely dangerous and inadequately regulated (Tu, 2007), and the implementation of safety and environmental standards for coal mining could increase coal costs. After falling by more than 20% from 2001-2008,[18] declines in the investment cost for new coal power plant projects have begun to flatten out (SERC, 2010), suggesting that reductions in capital costs may not be able to offset future increases in operating costs. Increasing peakiness of demand due to structural shifts in the economy will require coal units to run at lower load factors, which will increase average heat rates and raise fuel costs. Stricter pollution standards, and in particular proposed NO_x control requirements, will also increase the cost of coal-fired generation.

Ambitious targets for alternative energy will put upward pressure on wholesale generation costs, to the extent that the marginal system cost of adding these technologies is higher than

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[18] Liu and Chen (2010) argue that the decrease in capital costs was the direct result of benchmark pricing for new generation, which gave generators an incentive to reduce construction costs.

baseline system costs. Despite substantial reductions over the last decade, at current feed-in tariffs onshore wind (510-610 yuan MWh^{-1}), biomass (750 yuan MWh^{-1}), and solar (1,090-1,160 yuan MWh^{-1}) costs are still much higher than the average wholesale cost of generation (271-416 yuan MWh^{-1}) in China,[19] and these differences are even larger when the integration costs of intermittent renewables are accounted for. The impact of adding a large amount of nuclear capacity on system costs will depend on how nuclear plants are financed and insured, and how adding an inflexible baseload resource to an already inflexible system will affect load and capacity factors for coal units.

The extent to which grid investment will influence retail prices in China is difficult to assess because of the lack of a clear relationship between T&D costs and retail prices. Grid investment more than doubled over the last five years, rising from 153 billion yuan in 2005 to 385 billion yuan in 2009 (SERC, 2007; SERC 2010). Despite higher levels of grid investment and an increase in grid company costs, average T&D prices actually declined from 2006 to 2009, from 153 yuan MWh^{-1} to 125 yuan MWh^{-1} (SERC, 2007; SERC 2010), as sales rose faster than T&D costs (SERC, 2009). High levels of investment in the transmission and distribution systems are likely to continue. Major investments in transmission will be necessary for greater regional interconnection and to connect wind and solar resources with load centers (see Operations, above). Investment in China's distribution system has historically lagged behind transmission investment. Most of China's line losses and power outages occur in its distribution system (Zhong et al., 2007), and achieving higher system reliability, smart grid implementation, and electric vehicle integration will require major new investments in distribution.

Energy Efficiency as a Strategy for Managing Growth, Peak, and Rising Costs

Much as they did in OECD countries in the 1970s, these drivers of change in China's power system create the need, and the opportunity, for using demand-side measures as a complement to supply-side policies. The prospect of continued demand growth and changes in the composition of demand signal the need for investments in end-use efficiency and demand response. Rising costs and growing environmental awareness provide an enabling environment for significantly scaling up energy efficiency investments.

Rising system costs increase the cost-effectiveness of energy efficiency. At the lower end, rising costs of coal-fired generation increase the scope and scale of energy efficiency investments that qualify as cost-effective. In addition, if renewable and CO_2 targets are binding, the long run marginal cost of generation against which the cost-effectiveness of energy efficiency projects should be evaluated will be a weighted average of renewable energy and coal, which significantly increases the scope and scale of cost-effective energy efficiency (Mahone et al., 2009). Energy efficiency investments can be extremely cost-effective if, for example, they reduce the need to build more expensive renewable generation technologies, such as solar PV.

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[19] For reference, at an exchange rate of 6.6 yuan per dollar these feed-in tariffs are \$77-92 MWh^{-1} for wind, \$114 MWh^{-1} for biomass, and \$165-176 MWh^{-1} for solar. Wholesale generation prices are from SERC (2010). Feed-in tariffs for wind are from NRDC (2009) and for biomass and solar are from Martinot (2010).

Rising peak demand and growth in wind capacity, and particularly the combination of the two, will also increase the cost-effectiveness of demand response and load control. There is some evidence to suggest that the equivalent firm capacity of wind might be relatively low in China (Chi, 2010), implying that in meeting resource adequacy requirements China's grid companies would need to build a significant amount of backup generation capacity that goes unused most of the time. This additional capacity, which will most likely be coal, will further reduce capacity factors and increase costs in the system.

Ensuring that cost-effective energy efficiency resources in China are developed on the scale required to make meaningful reductions in electricity demand growth — on the order of tens of TWh in annual savings based on current forecasts[20] — will require integrating energy efficiency investment decisions into the electricity sector's resource planning process to allow more direct comparisons between supply- and demand-side investment options. Although energy efficiency has been a national policy priority since 2005 (Andrews-Speed, 2009; Zhou et al., 2010), China still does not have a formal, transparent mechanism for raising and rationalizing larger-scale investment in energy efficiency. The central government is currently the largest source of investment for energy efficiency projects, which is likely not sustainable given the levels of investment required to make energy efficiency a more significant part of electricity supply. For instance, investing 1-3%[21] of grid company revenues in energy efficiency, at 2009 revenue levels of 1.6 trillion yuan (SERC, 2010), would require 16-47 billion yuan yr^{-1} (US$2-7 billion yr^{-1}). If grid company revenues grow by 7% yr^{-1} from 2009-2020, by 2020 required levels of investment would reach 33-100 billion yuan yr^{-1} (US$5-15 billion yr^{-1}). Recent policy efforts, including a mandate on grid companies to meet 0.3% of annual sales (kWh) and peak load (kW) from energy efficiency, aim to integrate energy efficiency into the resource planning process.[22]

Developing Institutions to Address New Challenges

Whether in terms of lack of flexibility or emerging pressures, the institutions governing China's electricity sector are not well matched to the challenges that the sector faces. Addressing these challenges will require changes in how the electricity system is planned, operated, and regulated. In this section we describe the need for, and obstacles and pathways to, institutional development in China's electricity sector.

Institutional Change in China's Electricity Sector

During the last three decades, the Chinese electricity sector has evolved from a state-owned, vertically integrated utility to a diverse collection of generation, grid, and distribution companies that increasingly operate under incentive-based principles. Government and

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[20] For instance, using the IEA's (2009) forecast for total electricity demand would amount to demand growth of roughly 330 TWh yr^{-1} between 2009-2020. 10-99 TWh yr^{-1} in savings would be 3-30% of this forecast.

[21] These levels are comparable to those found in the U.S. (Lin, 2007).

[22] This national demand-side management policy, 《电力需求侧管理办法》, though it sets a low target, is an important first step. Details for how this policy is to be implemented have yet to be worked out.

business functions are legally separate, and the sector has had a national, independent regulator, the State Electricity Regulatory Commission (SERC), since 2005.[23]

However, reforms in China's electricity sector have been gradual, piecemeal, and often reactive. During the reform process policymakers never transitioned the sector toward a traditional, regulated cost-of-service model. As a result, the Chinese electricity sector's current institutions and modus operandi continue to have deep roots in the planned economy. For instance, electricity sector planning, project approval, and ratemaking is still primarily done by the National Development and Reform Commission (NDRC), China's chief planning agency, and not by SERC.

Drawing on an extensive literature,[24] Table 12 summarizes the history of China's electricity sector and its reform process.

Table 12. A Brief History of the Chinese Electricity Sector, 1949-present

Period	**Guiding Policies**	**Description**
1949-1985	Centrally planned and administered system 政企合一	Vertical integrated SOE; government agencies plan, finance, manage, and operate the system; oscillations between centralized and decentralized management
1985-1997	Decentralization to provinces; opening of investment 以省为实体，集资办电	Opening up of the sector to provincial government, private, and foreign investment; guaranteed investment return on generation investment
1997-2002	Separation of government and business 政企分开	Corporatization of the sector through the creation of the State Power Corporation (SPC); Ministry of Electric Power dissolved, functions transferred to the State Economic and Trade Commission (SETC) and the State Development and Planning Commission (SDPC), later merged into the NDRC
2002-present	Unbundling of generators and grid companies	Dismantling of the SPC into 5 national generating companies, 2 national grid companies; creation of SERC

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[23] SERC was created by the State Council in 2002 and began operations in 2003. However, it was not until 2005 that the State Council's Law on Electricity Regulation《电力监管条例》more formally empowered SERC to regulate the electricity sector.

[24] See, for example, Johnson, 1992; World Bank, 1994; Li and Dorian, 1995; Yang and Yu, 1996; Shao et al., 1997; Andrews-Speed et al., 1999; Blackman and Wu, 1999; Andrews-Speed and Dow, 2000; Berrah et al., 2001; DRC, 2002; Xu, 2002; Yeh and Lewis, 2004; Zhang and Heller, 2004; Xu and Chen, 2006; IEA, 2006; Ma and He, 2008; Pittman and Zhang, 2008; Williams and Kahrl, 2009.

	厂网分开	

The rapid construction of China's electricity system, on such a massive scale, owes its success to China's unique combination of decentralized investment and operations decision-making and centralized planning and ratemaking. Decentralized investment and operations decision-making provided the necessary incentives for raising capital outside of the state sector. Central government control over planning and pricing allowed the setting of ambitious technology and performance targets and the rapid mobilization and allocation of investment funds.

Although this system of governance has been effective in mobilizing capital, expanding supply, and supporting new technologies, it lacks formal mechanisms for managing and allocating costs. As noted above, China's current electricity system is already relatively expensive and faces the prospect of sustained cost increases, posing a dilemma for policymakers. On the one hand, there are limits to how high average retail rates can rise before they lead to inflation and public discontent. On the other hand, without adequate price incentives investment will fall below levels required to meet demand growth and environmental goals. At some level, balancing these two imperatives will require institutionalizing planning and ratemaking processes that allow regulatory agencies to maximize benefits, minimize costs, and more systematically, transparently allocate those benefits and costs.

Obstacles and Pathways to Institutional Change

Reforms to institutionalize these processes face two primary obstacles. First, China lacks the federalist and independent legal institutions to govern the interactions between different levels of government, between regulators and regulated entities, and between public and private sector actors. Second, China does not have an explicit role for ratepayer advocacy and intervention in ratemaking, which limits regulatory agencies' incentives to find least cost solutions for system investment and operations.

The first obstacle originates in incompatible incentives, of which the most obvious example is the discord between China's central and provincial governments. Beginning with the central government's decentralization of decision-making authority to the provincial level in the 1980s, provincial-level control over electricity systems in China has steadily grown. Provincial-level companies owned 45% of generation assets in 2006 (Ma and He, 2008) and provincial grid companies control day-to-day grid operations and short-term planning. China's centralized regulatory structure does not reflect the current electricity sector's decentralized character, in that planning for larger-scale projects and ratemaking is still ultimately controlled by central government agencies. This disjuncture has led to the emergence of parallel policy agendas, and difficulties in reconciling these agendas is a major barrier to more efficient electricity planning, dispatch, and pricing.[25]

The second obstacle stems from the splitting of ratemaking authority and the protection of ratepayer interests between government agencies. Wholesale and retail electricity prices are set by the NDRC's Price Department, which is primarily tasked with managing inflation. The NDRC, as an economic planning agency, is responsible for ensuring levels of investment in electricity supply that are sufficient to maintain high levels of economic growth. Among government agencies, only SERC has a mandate to protect ratepayer interests, but, as described above, it does not have the authority or capacity to be an effective ratepayer advocate. Even if it were more proactive in regulating industry costs, SERC still lacks the authority to set wholesale and retail prices based on those costs.

Establishing a well-functioning legal framework for electricity sector jurisdiction and decision-making is a top-down process that will likely require decades. However, bottom-up solutions, such as developing the regulatory and analytical tools that support a more cost-reflective electricity system, can improve sector management in the near term and can lay the groundwork for longer-term institutional changes. Because China never developed or adopted the regulatory and analytical tools that emerged around the cost-of-service model of utility regulation in OECD countries, introducing and localizing these tools in China could help to fill an important institutional gap.

Toward a Low Carbon Electricity System in China

Renewable energy can be a significant part of China's electricity generation mix, and can play an important role in China's transition to a lower carbon electricity system. However, as in other countries, reconciling the intermittency associated with renewable resources with the need to balance electricity supply and demand on the grid at all times will create nearer-term engineering and economic challenges. In China, these challenges will be formidable and unique, because its electricity system currently lacks the flexibility in demand, generation, transmission, and pricing to integrate renewable generation at a reasonable cost and without impacts on

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[25] There are numerous examples of jurisdictional conflict between China's central government and provincial governments in electricity sector decision-making, but the two most important conflicts are in ratemaking and planning. For ratemaking, a recent example is the central government's differential pricing (差别电价) policy, which has been strongly contested by governments in provinces that have a strong reliance on heavy industry. See NDRC (2007b) and NDRC (2010) for examples of the central government's approach to local government resistance to this policy. For planning, an ongoing example is the central government's continued control over approval for larger power plant projects, which, given provincial governments' incentives to promote local economic growth, has historically incentivized provincial governments to build smaller units that have short lead times and have often not gone through a more formal project approval process. In 2003, for instance, only around 50% of power plant projects reportedly gained formal central government approval (Wang, 2006). These split incentives between center and province have created an obstacle to central government environmental policy, such as the closing down of small-scale units.

system reliability. The absence of cost-reflective pricing is an important contributor to this inflexibility.

The lack of flexibility and cost-reflectiveness stem from China’s incomplete transition from a planned to a cost-of-service-based electricity system. The obstacles that have slowed this transition, as well as strategies to overcome them, are institutional rather than technological. As this paper describes, some of these obstacles, such as the lack of constitutional federalism, are outside of the scope of the electricity sector and will require longer-term solutions. Others, and in particular the lack of analytical tools and regulatory processes that facilitate more transparent planning and ratemaking, are more amenable to nearer-term improvements.

Current discourse on technology transfer from OECD countries has focused on “hard” technologies: Carbon capture and storage (CCS), renewable energy technologies, advanced nuclear. We argue that this emphasis is misplaced. In the near term, Chinese government agencies will need to focus on developing the institutional capacity in electricity planning, analysis, and regulation that, for historical reasons, they never fully and adequately developed. OECD countries have a wealth of experience in these areas that could provide a useful reference for China as it develops its own regulatory infrastructure. This “soft” technology engagement — methods for analysis, planning, information disclosure, regulation, and public engagement — could play an important role in facilitating a more flexible, cost-reflective electricity system that will enable a lower carbon electricity sector in China.

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Chapter 5

The Political Economy of Electricity Dispatch Reform in China[1]

Unlike in most of the world's power systems, grid operators in China do not use marginal cost dispatch. Instead, in China operators have historically allocated operating hours equally across coal-fired generators. To reduce the energy inefficiency of this approach, government agencies recently began to pilot an "energy efficient" dispatch system, in which day-ahead unit commitment is done on the basis of heat rates and emission rates. Using a case study from Guangxi Zhuang Autonomous Region, this paper assesses the benefits and costs of China's proposed energy efficient dispatch system, examines whether energy efficient dispatch leads to the kinds of changes in incentives needed for least cost dispatch and efficient capacity investment.

The paper is organized as follows. Section 1 provides a historical overview of electricity dispatch in China, focusing on why the government adopted dispatch rules that are inefficient from a power system perspective. Readers who are already familiar with the history of the Chinese power sector may choose to skip this section. Section 2 describes the power sector in Guangxi, which provides the paper's empirical foundation. Section 3 examines how the equal shares dispatch system has been implemented, and assesses the benefits and costs of implementing energy efficient dispatch, in Guangxi. Section 4 examines energy efficient dispatch in the broader context of changes in incentives needed for least cost dispatch and efficient capacity investment in China. Section 5 offers concluding thoughts.

Historical Overview of Dispatch in the Chinese Power System

History offers essential context for understanding the questions posed in this paper. This section provides a brief overview of how the Chinese power sector's dispatch institutions evolved in the context of its changing industrial structure, ownership arrangements, and wholesale generation pricing (Table 13).

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[1] This chapter is intended for publication as a multi-author article.

Table 13. Historical Synopsis of Industrial Structure, Ownership, Dispatch, and Wholesale Generation Pricing in the Chinese Power Sector

	1980-1984	**1985-2001**	**2002-present**
Industrial Structure	Vertical integration	Vertical integration	Unbundled generation and transmission & distribution (2002)
Ownership	Predominantly central government owned	Central and provincial government ownership, increasing domestic and private investment in generation	Central and provincial government ownership, declining share of private investment
Dispatch	Economic dispatch based on total embedded cost	Equal shares dispatch	Equal shares dispatch; pilot projects for energy efficient dispatch (2007)
Wholesale Generation Pricing	Internal transfer prices	Investment recovery based on financial life (1985) Investment recovery based on operational life (2001)	Benchmark price (2004) Fuel price-wholesale price co-movement (2004)

As China's economic reforms gathered steam in the early 1980s, surging electricity demand combined with limited state capital led to inadequate generating capacity and power shortages. To encourage investment in power generation, in 1985 central planners took two primary actions: 1) opening up investment to local governments, the domestic private sector, and foreign investors, and 2) restructuring wholesale generation rates to improve terms for investors. Wholesale generation rates were calculated based on a levelized cost of electricity (LCOE) formula with a fixed number of annual operating hours (Equation 1), with specific costs and technical parameters negotiated between government planners and individual power plants on a case-by-case basis. The amortization period (t) used in calculating the LCOE was based on the financial lifetime of the unit, which meant that generators were paid using an LCOE with this t value during the unit's financial lifetime, and then using an LCOE with a t value of zero after the unit had fully depreciated.

$$LCOE = \frac{CC \cdot \frac{r}{1-(1+r)^{-t}} + FOM}{AOH} + FC + VOM \qquad (1)$$

- LCOE is the levelized cost of electricity
- CC is an overnight capital cost (yuan/kW)
- r is a blend of the interest rate and the rate of return
- t is the amortization period
- FOM is fixed operations and maintenance costs
- AOH is annual operating hours
- FC is fuel costs
- VOM is variable operations and maintenance costs

This approach to wholesale pricing required that generators produced enough electricity to achieve their negotiated rate of return. To ensure reasonable returns, annual operating hours for generators were set administratively by provincial Economic Commissions (ECs) or Economic and Trade Commissions (ETCs)[2] and approved nationally by the State Planning Commission (SPC), and later by the National Development and Reform Commission (NDRC). To ensure fairness, operating hours were expected to be allocated equally across generators.[3] This institution, which we refer to as 'equal shares dispatch' here (known as 'average dispatch' [平均调度], or more formally as the 'generation quota system' [发电配额制度], in Chinese), is in marked contrast to the merit order (marginal cost) approach adopted in most other countries.

Despite a more open investment environment, China's electricity sector remained firmly under government ownership, albeit with a growing investment role for provincial governments. Additionally, despite greater decentralization of power system operations to provincial governments, central government agencies retained key decision-making powers. Most germane here, the central government maintained control of project approval for generation projects larger than 50 MW, which effectively split capacity planning between central and provincial government agencies and encouraged the building of small, less efficient coal-fired power plants that could bypass the formal approval process. The central government also retained control over wholesale and retail pricing, which were both set by the SPC's, and now the NDRC's, Price Department, through separate processes.

Slowing electricity demand growth during the Asian financial crisis in the late 1990s strained this model of investment, wholesale generation pricing, and dispatch. Overcapacity in generation led to reports of local protectionism, where provincial grid companies would prioritize provincially-owned units in the dispatch stack (Zhang and Heller, 2004). In some cases, local governments reneged on or renegotiated power purchase agreements with national and

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[2] ECs and ETCs are the provincial equivalents of the National Development and Reform Commission. In some provinces this agency is called the EC, while in others it is called the ETC.

[3] The potential for corruption in this equal shares system is evidenced by, for instance, the State Grid Corporation of China's "Five Things Not Permitted" for Dispatch Agency Staff 《国家电网公司电力调度机构工作人员“五不准”规定》, which include not taking gifts, cash, stock, meals, or trips from organizations with an interest in dispatch outcomes.

private foreign-owned generators (Woo, 2005). Power sector reforms, begun in 1999, were intended to address these inefficiencies by breaking the power of local monopolies. Following the OECD model of electricity sector deregulation, reforms in China unbundled generation from transmission and distribution and created an independent regulator for the sector, the State Electricity Regulatory Commission (SERC), in 2003.

Although reforms were intended to lead to a more competitive wholesale pricing and dispatch system, neither pricing nor dispatch was fundamentally changed through the reform process. The three major changes in pricing in the 2000s resulted from independent, largely reactive policies. First, responding to what it perceived to be high retail prices, in 2001 the NDRC changed the formula for calculating wholesale generation tariffs, amortizing capital costs across a generating unit's technical rather than its financial lifetime (i.e., a longer value of t in Equation 1). Second, a surge in coal prices following coal price liberalization forced the creation of a limited fuel price adjustment mechanism (known as "co-movement" [联动)) in 2004 to allow generators to pass through higher coal costs in their rates. Third, to standardize rates and encourage deployment of advanced coal technologies the NDRC adopted a benchmark approach to generation pricing in 2004, whereby all coal-fired units within a province receive roughly the same wholesale rate, based on the total embedded cost for a new advanced coal unit in that province.

Although wholesale prices were periodically adjusted over the 1990s and 2000s, dispatch remained largely unchanged from the mid-1980s to the late 2000s. In 2007, the State Council approved Measures for Energy Efficient Dispatch 《节能发电调度办法(试行)》, with the expressed goals of increasing power generation efficiency, conserving natural resources, reducing pollution, reducing reliance on coal, maintaining system reliability, and promoting sustainable growth in the industrial sector. Subject to the important caveat that it not adversely impact system safety or reliability, Detailed Measures for Implementing Energy Efficient Dispatch 《节能发电调度办法实施细则(试行) 》stipulates the following order for unit commitment:

1) Non-dispatchable renewables and hydropower
2) Dispatchable hydropower and renewables
3) Nuclear
4) Cogeneration units, where electricity is the byproduct
5) Demonstration projects and units under national dispatch control
6) Cogeneration units, where heat is the byproduct
7) Coal gangue, washed coal, and other "integrated resource use" (综合资源利用) units authorized by environmental protection agencies at a provincial level or higher, and approved by the NDRC and local ECs and ETCs
8) Natural gas and gasified coal

9) Coal, including coal cogeneration units that are generating only electricity and integrated resource use units that are using conventional coal
10) Oil

Units in each thermal generation category are to be prioritized in order of increasing heat rates. Where heat rates for thermal generators are identical, prioritization is to be done on the basis of emission rates. Heat rates are to be initially determined based on manufacturer's specifications, but will ultimately be measured with real-time monitoring devices. Based on the rules described above, local ECs and ETCs must create a "priority order table" (排序表) before November 20 of each year, which is to be updated quarterly based on changes in generator parameters and the addition of new units.

Using load forecasts, and considering unit availability and system reliability constraints, dispatch agencies[4] set day-ahead unit commitment plans. Once units have been committed, agencies then allocate forecasted load across generators in a day-ahead generation supply curve. Although dispatchers are required to prioritize generators according to heat rates in unit commitment plans, the energy efficient dispatch policy is, importantly, not a mandate for optimizing dispatch to minimize average thermal heat rates or cost.[5]

Five provinces[6] began a pilot with energy efficient dispatch in 2007. Although the central government had originally planned to extend to the pilot to all provinces by the end of 2008, the energy efficient dispatch system has proved difficult to implement and uptake has been slow (Gao and Li, 2010). In late December 2010, the China Southern Power Grid began implementation of an energy efficient dispatch policy that will cover all five provinces within its jurisdiction, with each province required to design and implement its own approach.

Description of the Power Sector in Guangxi Zhuang Autonomous Region

We use Guangxi Zhuang Autonomous Region, a provincial-level administrative region in Southern China, as a case study to provide an empirical basis for our analysis. This section describes the supply- and demand-side characteristics of Guangxi's power system. Unless otherwise indicated, all of the data used in this paper are based on monthly reports issued by the Guangxi Power Grid Corporation (GPGC, 广西电网公司).[7]

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[4] "Dispatch agencies" (调度机构), also referred to as "dispatch centers" (调度中心), are organizations under the authority of national, regional, provincial, or lower level grid companies (电网公司). For our purposes, there is not a meaningful distinction between dispatch agencies and grid companies, and we use both names interchangeably in this paper.

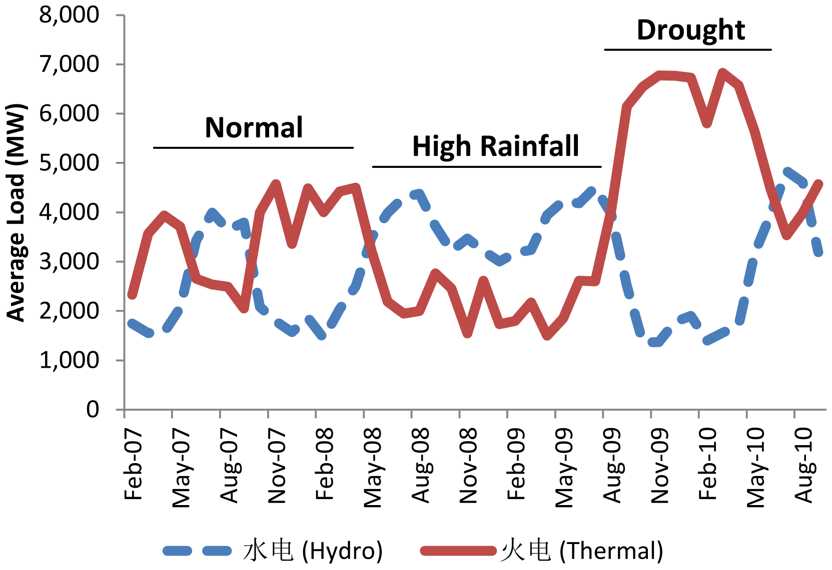
[5] The Detailed Measures, for instance, only requires that dispatch agencies "reasonably" allocate load across generators, but does not specify standards for reasonableness.

[6] These five provinces included Guangdong, Guizhou, Henan, Jiangsu, and Sichuan.

[7] These reports are publicly available online at http://www.gx.csg.cn.

Guangxi is part of the China Southern Power Grid, a synchronous regional grid that also includes Guangdong Province, Guizhou Miao Autonomous Region, Hainan Province, and Yunnan Province. Guangdong is China's largest provincial economy and electricity consuming province, playing an important role in the Southern Grid as a source of investment and an electricity importer.

Figure 32. Hydropower and Thermal Load Cycles in Guangxi, 2007-2010



Located in water-abundant southern China, hydropower accounted for 56% of Guangxi's total installed capacity and 52% of its total generation in 2009.[8] The high hydropower season typically begins around May and lasts until around November. During this period, hydropower becomes a baseload resource and coal units are ramped to follow load. During the dry season, this relationship is reversed as coal becomes the baseload resource and hydropower is used to follow load. This hydropower-coal cycle is shown in Figure 32.

The 2008 and 2009-2010 anomalies in the hydropower-thermal cycle in Figure 32 are weather related. Rainfall from the Asian summer monsoon was above normal in 2008 (NOAA, undated), and higher than usual precipitation meant that hydropower availability remained high even in winter months. In 2009 and 2010, by contrast, a major draught struck southwestern China, forcing the GPGC to use coal units to offset the decline in summer hydropower availability.

Using coal units to follow load requires the GPGC, like other system operators in China, to cycle these units. Coal units in Guangxi are typically not turned on to follow load, which implies that sufficient coal-fired capacity to meet the peak in thermal net load (total load minus hydropower) must be online throughout the course of a day. These coal units are then ramped down to

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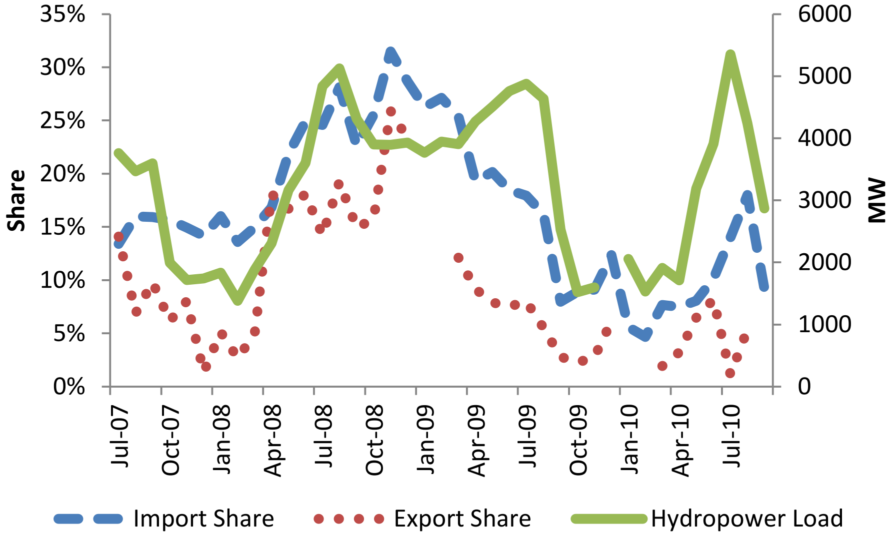
[8] These data are from the China Electricity Council.

partial load in the evening when electricity demand is low. This practice, known in China as "reducing load to meet peak" (降负荷调峰), differs from the approach used in most other countries, in which load following generation is ramped up to follow intermediate and peak demand.

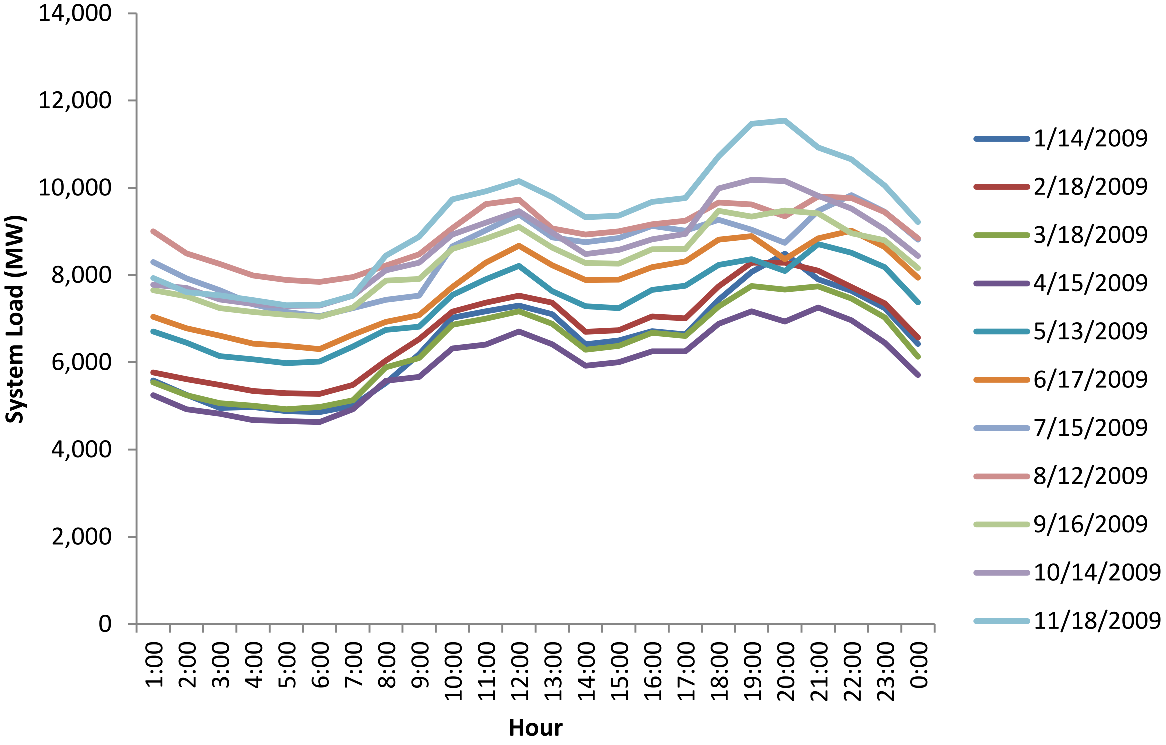
Figure 33. Exports as a Share of Gross Generation, Imports as a Share of Total Generation Supply, and Average Hydropower Load, Guangxi, 07/2007-09/2010



Guangxi is a significant electricity importer and exporter, although "imports" are primarily from hydropower facilities located within Guangxi's borders that export most of their power to Guangdong Province. Exports from units in Guangxi that are not dedicated for export are also predominantly to Guangdong. Because hydropower is the prime mover behind Guangxi's electricity trade, the share of imports and exports follows changes in hydropower load, as shown in Figure 33.

Dispatch within Guangxi is divided among regional (网调), provincial (省调), and sub-provincial (地调 / 县调) dispatch authorities. Inter-provincial trade within the Southern Grid involves a number of large, dedicated power plants that are under the dispatch control of the regional dispatch authority, the Southern Grid Company. Like other provinces, Guangxi has an extensive rural electricity grid that is, in many cases, not interconnected with the main provincial grid. Generation units serving these isolated grids — numerous but small in terms of total capacity and generation — are not under the direct dispatch control of the GPGC. The GPGC controls units under provincial dispatch authority, which account for the majority of capacity and generation in Guangxi.

Figure 34. Typical Daily Load Shapes, January-November 2009



Guangxi is an evening peaking system, as Figure 34 shows, with peak demand occurring roughly between 7 and 9 pm.[9] In general, though, load is relatively flat for the roughly ten hours between 10 am and 10 pm. In 2009, the maximum and average differences between daily peak and minimum load were 4,748 and 3,174 MW, respectively, with most of this difference driven by the disparity between day and evening loads.

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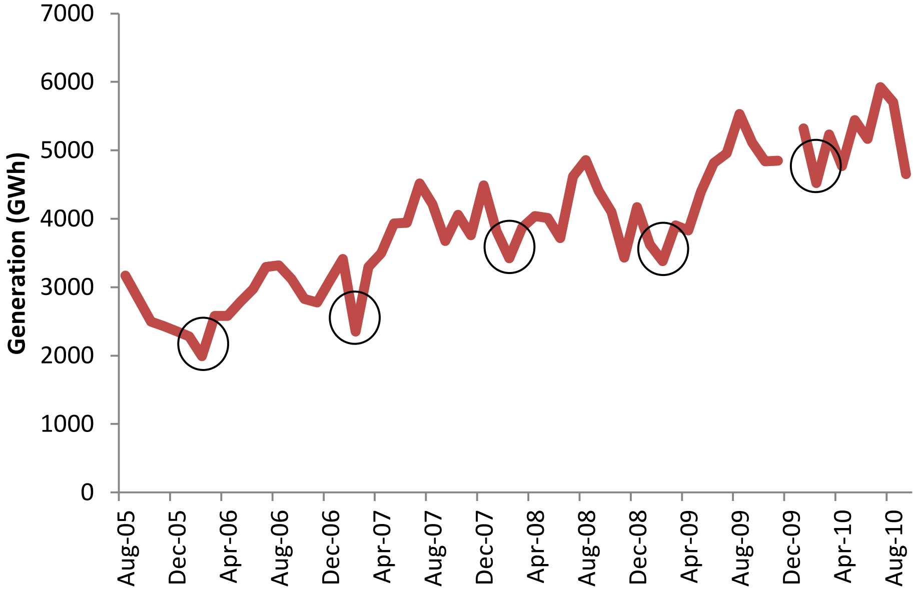
[9] The "dual hump" of Guangxi's load shape is unusual, and is consistent across all months for the years 2005 to 2010. It is unclear whether the drop-off in demand from 12 to 2 pm is the result of pricing policies that shift load or an afternoon break in manufacturing.

Figure 35. Electricity Generation in the GPGC Region, 2005-2010



Note: Data were unavailable for December 2009.

Electricity demand in Guangxi is rising rapidly, though not always monotonically (Figure 35). Although demand levels nearly doubled between 2005 and 2010, the 2008 global recession had a marked influence on electricity demand, reducing it by nearly one quarter. The effects of economic stimulus are equally clear, though electricity demand appears to have leveled off after late 2009. The momentary dips in February 2005, January 2006, February 2007, February 2008, January 2009, and February 2010 result from the Chinese New Year holiday, when industrial and commercial demand for electricity falls.

Equal Shares and Energy Efficient Dispatch in Guangxi

Using Guangxi as a case study, in this section we examine China's equal shares and energy efficient dispatch systems. Our emphasis here is on thermal, rather than total system, dispatch. Hydropower dispatch is subject to a number of non-power-related constraints, such as flood control and irrigation, and we did not have sufficient data to include these constraints in our analysis.

Equal Shares Dispatch

During 2005-2010 the GPGC's allocation of operating hours[10] across coal plants was, as expected, relatively uniform (Figure 36). Maintaining this level of uniformity in operating hours

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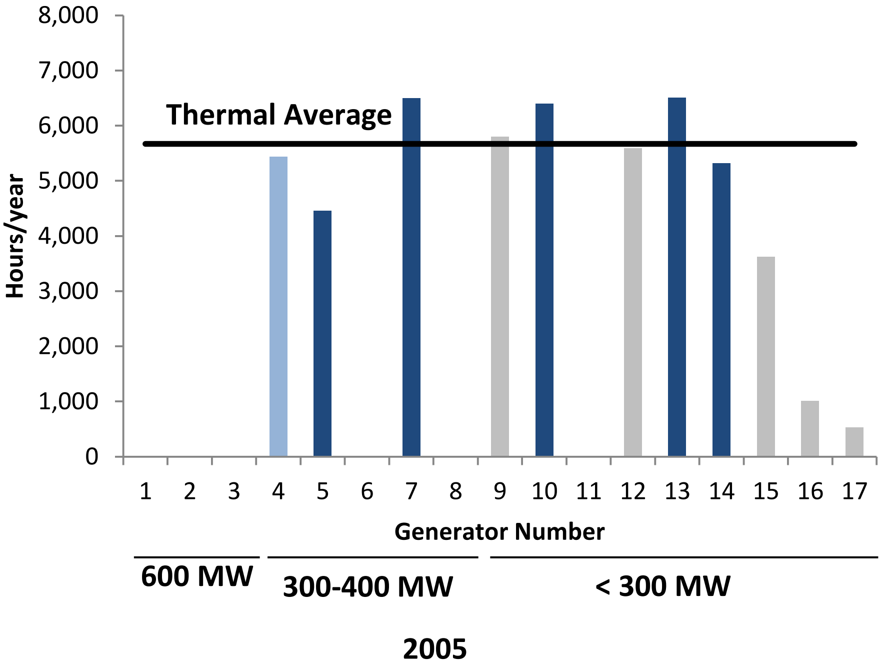
[10] Dispatch hours in the GPGC region, as in other parts of China, are tracked using adjusted annual operating hours (利用小时数). These values are not equivalent to annual generation divided by installed capacity (i.e., hours run at

is likely not a trivial scheduling and accounting exercise, requiring continual adjustments for changes in demand. The combination of economic downturn and high hydropower availability in 2008 and 2009, for instance, led to a 35% and 23% drop, respectively, in average annual operating hours for coal generators from 2005 levels.

Fairness plays a clear and central role in dispatch rules, and these rules, while flexible, do not appear to be arbitrary. For instance, power plant 4 (Laibin B), China's first build-operate-transfer (BOT) power plant, owned by Électricité de France, had higher operating hours maintained during the economic downturn in 2008 and 2009, which was likely in line with contractual obligations but further depressed operating hours for other generators. Alternatively, unlike reports during the economic downturn at the end of the 1990s, there was not any significant bias in the dispatch of national and provincial majority-owned power plants during the 2008-2009 downturn (Figure 37).[11]

Figure 36. Annual Operating Hours by Power Plant, in Order of Largest Unit, 2005, 2007, and 2009



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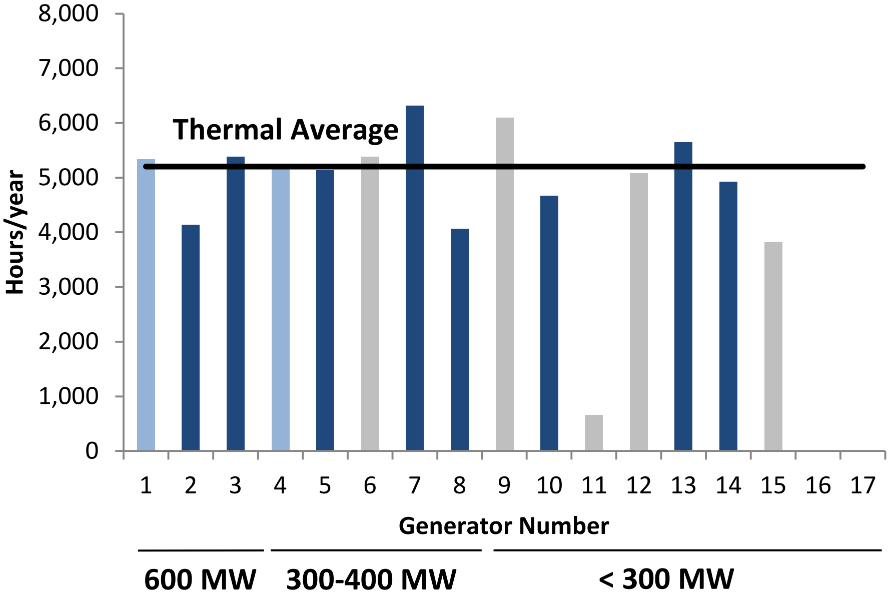
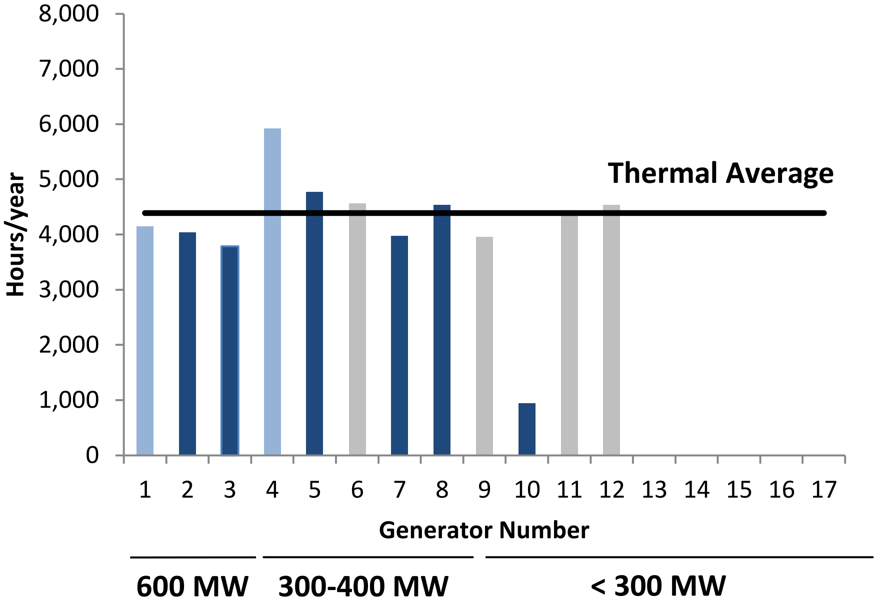
full load equivalent), and it is not clear how the GPGC adjusts this measure. In most cases the GPGC annual operating hour measure is consistent with a simple, unadjusted capacity factor. See the Supporting Material for further discussion on this topic.

[11] National majority-owned generators, in fact, had a higher average capacity factor than provincially majority-owned generators from January 2008 to August 2009, when capacity factors for thermal generators dipped system wide. Still, using a two-sample t-test differences in means between national and provincial generators are not statistically significant at a 95% level (p = 0.37). See the Supporting Material for a list of thermal power plants by majority owner.



2007

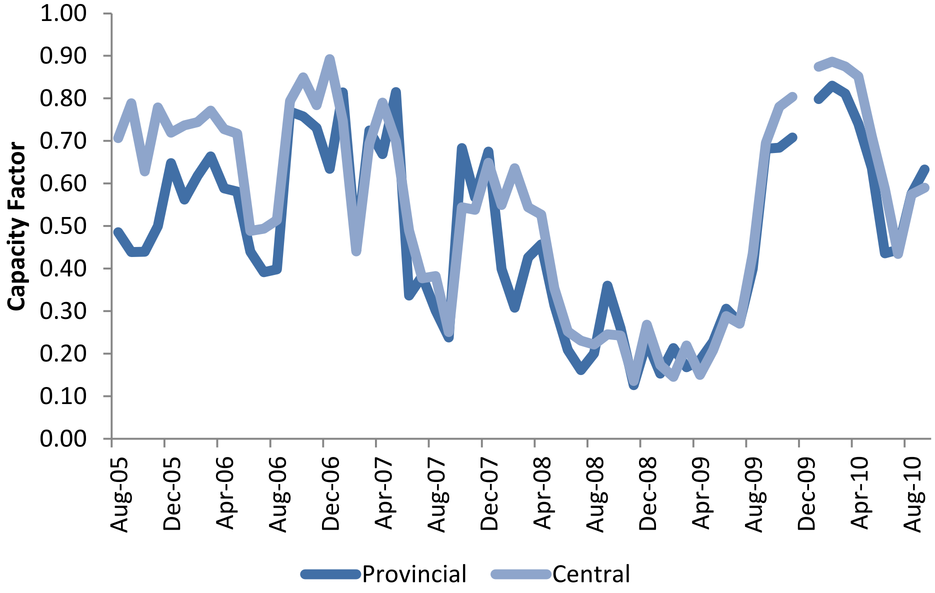


2009

Figure Key: dark blue = majority nationally-owned, gray = majority provincially-owned, light blue = majority internationally-owned

Notes: Gaps in annual operating hours occur as a result of either plants having not been built yet or as plants having been retired. For instance, in 2005 power plants 1-3 had not yet been built. In 2009, power plants 13-17 had been officially retired.

Figure 37. Capacity Factors for Provincial and Central Government Majority-Owned Power Plants, 2005-2010



Note: No data was available for December 2009.

Although the current system meets internally defined criteria for fairness, it does not create a stable investment environment, nor is it economically or environmentally efficient. Because wholesale rates are currently calculated using a fixed estimate of annual operating hours, if average operating hours fall below this level generators face a shortfall in average revenues. The downturn in 2008 and 2009, for instance, likely led to an average revenue deficiency of 2-3% for generators in Guangxi.[12] Operationally, Guangxi's three largest generators ran the same number of hours as generators with much higher heat rates and emissions levels (Table 14), indicating that there is likely scope for further reducing system costs and emissions.

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[12] If wholesale rates were set using 5,000 hrs/yr, for instance, the 2008-2009 downturn would have led to a 1,948 shortfall in operating hours. Over a 20-year amortization period, this translates into a shortfall in hours of 2.0%. Since levelized capital costs are calculated as annualized costs divided by operating hours, an hourly shortfall of 2% is equivalent to a revenue shortfall of 2%.

Table 14. Net Heat Rates by Generator Class in Guangxi

	Net Heat Rate (gce/kWh)					
	2007		2008		2009	
	Mean	Range	Mean	Range	Mean	Range
Large Unit (≥ 600 MW)	346	333-353	326	320-330	320	319-321
Mid-size Unit (300-400 MW)	346	338-359	343	334-354	344	326-348
Small Unit (< 300 MW)	426	367-533	378	361-435	376	362-384

Notes: The above heat rates are estimated based on a generation-weighted average of monthly reported values by power plant. Heat rates in China are measured in grams coal equivalent (gce) per kWh, where 1 gce = 29.31 kJ and 1 gce/kWh = 27.78 Btu/kWh (e.g., a heat rate of 320 gce/kWh is equivalent to 8,890 Btu/kWh). The higher heat rate for the "Large" category in 2007 is the result of all power plants in this category having just come online that year.

Energy Efficient Dispatch

To assess the effects of energy efficient dispatch, we examine how implementing this system in 2008 and 2009 would have changed coal use and wholesale costs in Guangxi. For this purpose, we created a basic model of thermal dispatch under the GPGC's authority, using monthly data on load shapes, thermal and hydropower generation, generator own-use and downtime, and reported heat rates. In keeping with the requirements of the energy efficient dispatch policy, our emphasis here is on reordering generating units in the dispatch stack rather than optimizing the system around average heat rates. A more detailed description of our approach is provided in the Supporting Material.

The results are shown in Table 15. In both years, energy efficient dispatch delivers a modest (2-4%) coal savings. In absolute terms, these savings would translate into 400-450 kt coal/yr and a CO_2 savings of roughly 1 $MtCO_2$/yr. Assuming all coal inputs are bought on the spot market (i.e., an upper bound), fuel cost savings would be around 250 million yuan, or 4-5 yuan per MWh and 1% of Guangxi's average wholesale generation price of 396 yuan/MWh in 2008.

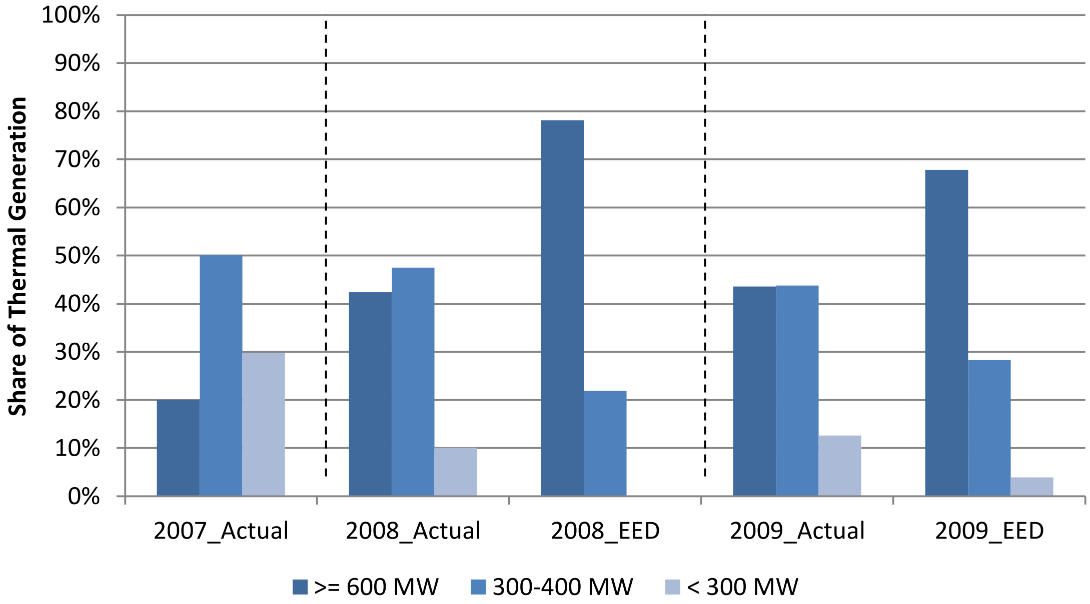
Table 15. Results for Energy Efficient Dispatch Implementation, 2008 and 2009

	Units	2008	2009
Reported actual average thermal net heat rate	gce/kWh	339	334
Estimated average thermal net heat rate for energy efficient dispatch	gce/kWh	328	325
Total coal savings	ktce / kt	310 / 450	290 / 420
CO2 savings	$MtCO_2$	1.25	1.16
Fuel cost savings, upper range	Myuan/yr	240	260
Unit fuel savings, upper range	yuan/MWh	5	4

Notes: Actual heat rate is an average annual heat rate based on a net generation-weighted average of monthly heat rates across generators. Conversion between ktce and kt assumes a *lower heating value for coal of 20 GJ/t, based on an average value of 19.7 GJ/t for thermal generators in Guangxi in 2008.* CO_2 *savings are based on a coal* CO_2 *emission factor of 2.77* gCO_2*/gce. Fuel savings are based on the April 2011 spot price of thermal coal (动力煤) at Qinhuangdao port, 780 yuan/t (data are from http://www.sxcoal.com). Unit fuel savings are based on total net generation under the provincial dispatch authority of 51.9 TWh in 2008 and 57.8 TWh in 2009.*

Savings are relatively small for two main reasons. First, due to the build out in large (≥ 600 MW) units since 2007, large and mid-size (300-400 MW) units already make up the lion's share of Guangxi's thermal generation mix (Figure 38). Second, the highest heat rates for smaller (< 300 MW) generators improved from 2007 to 2009 because of the retirement of older, inefficient units (Table 14).[13] Figure 38 shows that energy efficient dispatch would shift generation shares to larger units. Because the largest savings from reordering dispatch come from transferring generation from the smallest, most inefficient units to the largest, most efficient units, since the smallest units are already a small share of generation the benefits of energy efficient dispatch will be similarly small.

Figure 38. Share of Thermal Generation by Generator Capacity Class, 2007-2009 Actual (_Actual), 2008-2009 Estimated under Energy Efficient Dispatch (_EED)



Because of the structure of Guangxi's wholesale generation prices (Figure 39), changes in wholesale costs to grid companies, and by extension to ratepayers, are negligible. Aside from

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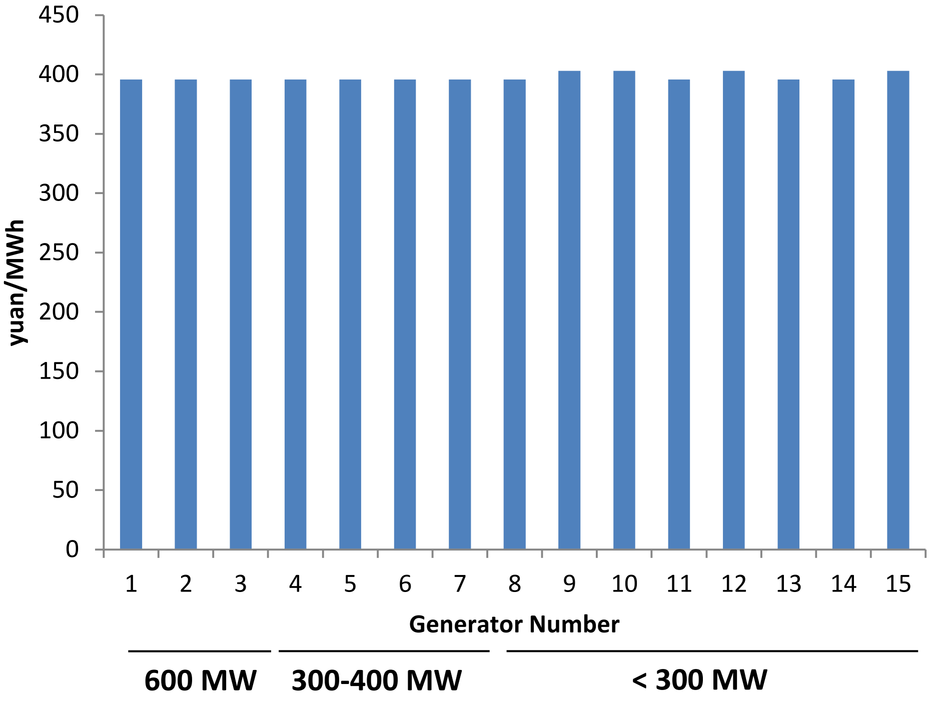
[13] Notably, reports on the impact of energy efficient dispatch typically fail to separate out these two effects. See, for instance, the China Southern Power Grid's official web page on energy efficient dispatch, http://www.csg.cn/zt/jnjp.aspx.

three generators that receive a 403 yuan/MWh (US$61/MWh) rate, all generators received a flat rate of 396 yuan/MWh (US$60/MWh) in 2008. In principle, the reallocation of operating hours to more efficient generators would reduce system costs, but without changes in wholesale prices the fuel savings from energy efficient dispatch would be internal transfers and would not be seen by ratepayers.

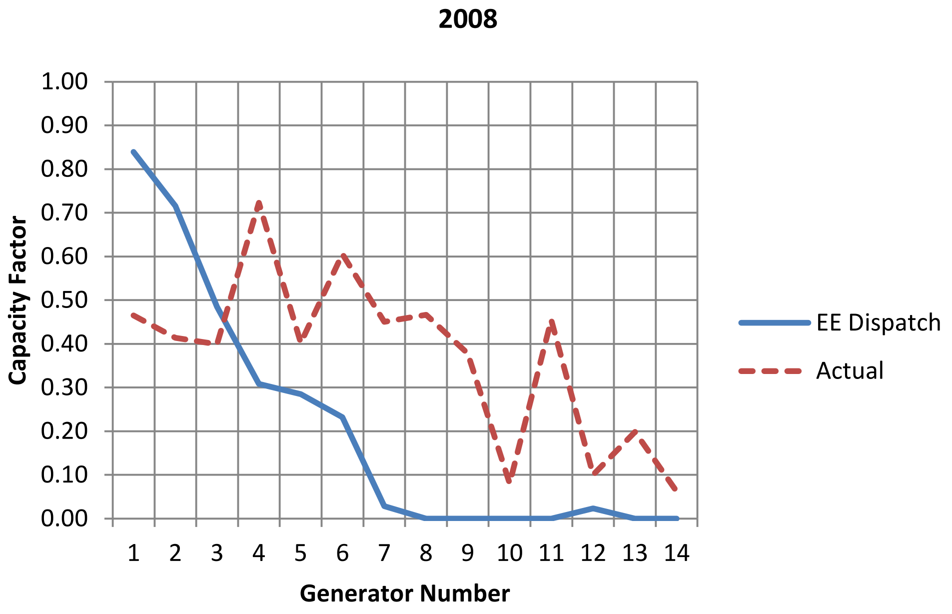
Figure 39. Wholesale Generation Prices by Power Plant, In Order of Largest Unit, 2008

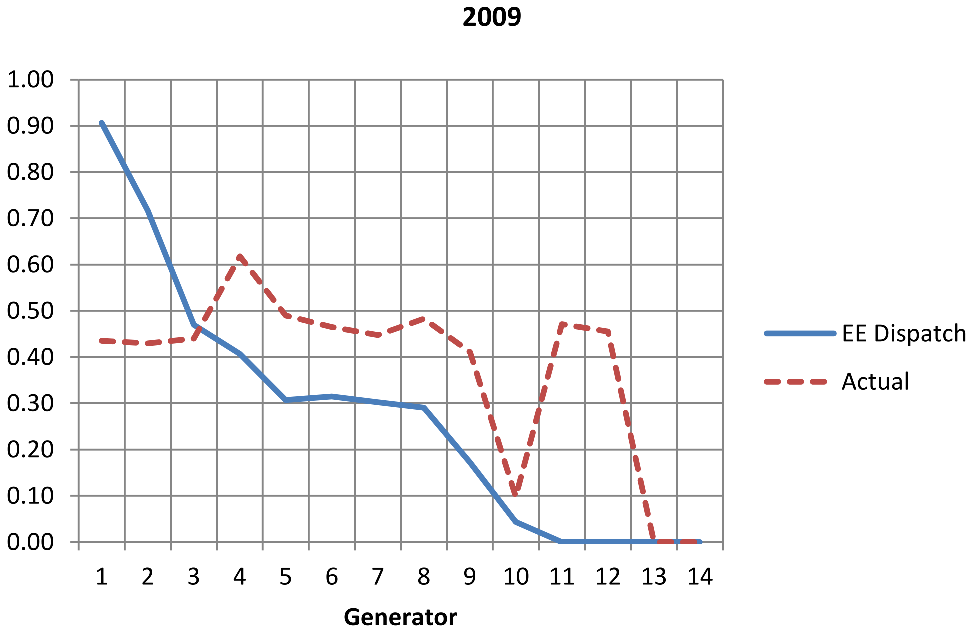


Source: Prices are from the Guigang Price Information Center, Online at: http://www.ggpi.gov.cn/shownews.asp?newsid=1276.

With energy efficient dispatch in China more generally, efficiency gains come through increasing capacity factors for larger coal-fired units, which in turn reduces capacity factors for mid-size and smaller units (Figure 40). In Guangxi, and in other provinces, there are political dimensions to this shift in operating hours. The largest three power plants in Guangxi are all majority-owned by national state-owned enterprises. All provincial generating companies would see their capacity factors fall to less than 40%. For both national and provincial mid-sized and smaller generators, assuming that they have little or no headroom under current rates and no mechanism to compensate them for lost revenues, energy efficient dispatch would lead to operating losses and likely strand at least some generation assets.

Figure 40. Capacity Factors for Thermal Generators, Actual and Modeled Estimates for Energy Efficient Dispatch, 2008 and 2009





This differential impact became apparent to authorities during the energy efficient dispatch pilots, and a 2009 adjustment to the policy, Announcement on Problems Related to Compensation for Energy Efficient Dispatch Pilots《关于节能发电调度试点经济补偿有关问题的通知》, attempted to address the problem by creating a mechanism that compensates generators for revenue shortfalls that result from changes in dispatch. The primary proposals for this mechanism have been systems for trading generation rights among power plants, but other proposals have included a dual-track generation pricing system, a surcharge on electricity rates, and ancillary services payments.[14] In pilot provinces, provincial government agencies were given latitude to decide an appropriate compensation mechanism, but more specific proposals have not been formally implemented.[15]

Energy Efficient Dispatch and Incentives for Efficiency

China's power system is still in the early stages of a transition toward more efficient operations and investment, with implications for the system's ability to cost-effectively deal with uncertainty in growth, more "peaky" demand, rising fuel costs, and greater intermittency in supply (Kahrl et al., 2011). In this section we evaluate whether energy efficient dispatch would lead to changes in incentives needed to transition toward more efficient operations and investment. Concluding that it would not, we explore the kinds of changes that would be necessary.

Table 16. Industry Structure and Pricing in U.S. Pre- and Post-Deregulation Electricity Sector, and in China's Quasi-Regulated Electricity Sector

	Industry Structure	Wholesale Generation Pricing	Wholesale T&D Pricing	Retail Pricing
U.S. Pre-Deregulation	Vertically integrated utility	Regulated cost of service	Regulated cost of service	Regulated, cost reflective
U.S. Post-Deregulation	Unbundled generation and T&D	Competitive contract or bid price	Regulated cost of service or nodal pricing	Cost reflective, mostly regulated
China	Unbundled generation and T&D	Administratively set benchmark price	Administratively set residual between retail prices and wholesale generation prices	Administratively set

The current incentive structure in the Chinese power sector is a legacy of central planning and incomplete reforms, in structure consistent with the international model of deregulation but in pricing still more akin to a centrally planned system, where prices are used for internal accounting rather than to reflect costs and provide an incentive framework (Table 16). With their roots in the centrally planned economy, China's administratively set wholesale and retail

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[14] For an overview, see Zhang (2009).

[15] For instance, SERC and the China Southern Power Grid convened a meeting in March 2011 to discuss appropriate compensation mechanisms. Only the two provinces that were included in the previous energy efficient dispatch, Guandong and Guizhou, had specific proposals. See http://www.serc.gov.cn/ywdd/201103/t20110330_14520.htm.

prices do not currently provide generators, grid companies, developers, or regulators with incentives for efficient dispatch and investment.

Energy efficient dispatch shifts costs and benefits among power sector actors but largely preserves the existing incentive structure. For example, the success of the energy efficient dispatch system depends on its administrative enforceability, as does the current system, rather than on links to grid company profits. Under energy efficient dispatch, generation investment would be skewed toward large units because they have a higher probability of receiving a stable number of annual operating hours, similar to the current system, even though this might not minimize investment costs. Energy efficient dispatch, in other words, is more akin to a quick fix rather than a longer-term reform strategy.

A longer-term reform strategy would require restructuring operations and investment incentives, which in turn would entail more fundamental pricing reforms and improved capacity planning. Efficient operations require more flexible and cost-reflective wholesale and retail pricing. Efficient investment requires that wholesale generation prices better reflect marginal capacity costs, which, in a system with regulated prices, requires more rigorous capacity planning to determine marginal avoided costs.

More Flexible, Cost-Reflective Pricing

In China's current system, generators are forced to absorb the bulk of additional costs from cycling, ancillary service provision, and higher fuel costs.[16] Formalizing these costs into wholesale prices would shift more of variable cost risk onto grid companies, which in turn would encourage grid companies to ensure more efficient use of generators. In an unbundled system with flat wholesale prices and only limited payments for ancillary services, grid companies are indifferent to how generators are dispatched.

To allow cost pass through for generators, regulators would also need to allow more responsive retail rates to allow grid companies to pass through higher costs onto ratepayers. For instance, current contract policy stipulates that grid companies should pay generators on a monthly basis, but these payments are based on a fixed wholesale generation price.[17] If monthly generator payments would be allowed to vary with changes in costs, without more flexibility in retail rates grid companies would, as generators currently are, be forced to absorb any cost increases.

Allowing more flexibility in retail rates would require fundamental changes in ratemaking. Retail electricity rates in China are currently not determined on a cost-of-service basis. To build

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[16] Payments for ancillary services are in the early stages of implementation. In 2009, SERC issued Implementation Guidelines for Ancillary Service Management 《并网发电厂辅助服务管理实施细则》, which requires regional grid companies to develop region-specific rules for compensating ancillary service provision. These rules are still being piloted.

[17] Monthly payments to generators are stipulated in SERC's 2008 Method for Settling Payments between Generators and Grid Companies 《发电企业与电网企业电费结算暂行办法》.

political support among ratepayers for a pricing system that better reflects costs, government agencies would need to make the regulation of grid company costs, presently a black box (Cai, 2010), transparent. A more flexible retail pricing system would also require devolving ratemaking authority to a local regulatory agency with a mandate to protect ratepayer interests. Currently, both wholesale and retail electricity rate setting is done at a national level by the NDRC, which is institutionally cumbersome and places electricity prices within the NDRC's sphere of competing priorities — industrial policy, state-owned enterprise management, and macroeconomic stability — which notably do not include ratepayer interests.

Capacity Pricing, Investment, and Planning

As illustrated above, dispatch reforms in China would segment thermal generators into baseload, load following, and peaking functions, transferring hours from small and mid-size units to the largest units and requiring changes in wholesale pricing to ensure generators can cover their fixed costs. Changes in wholesale pricing, whether explicit or implicit through transfer mechanisms, send signals for longer-term investment. However, because government agencies in China do not yet use optimal capacity planning methods, without changes in capacity planning developers and generating companies will not make investments that minimize system costs.

The most practical strategy to address increases in unit fixed costs associated with dispatch reforms would be to separate current wholesale rates into capacity (yuan/kW) and energy (yuan/kWh) payments, retaining the benchmark approach but separating generators by function (i.e., baseload, load following, and peaking).[18] Because China has unbundled generation and T&D without market mechanisms for price discovery, a benchmark approach to pricing would help to overcome the lack of transparency in wholesale generation costs. To ensure efficient investment in new capacity, planning and regulatory agencies would need to drive a wedge between existing and new capacity by setting capacity payments at current marginal cost.

Setting capacity payments at marginal cost would strand some investments, as payments required to cover the annualized capital costs of existing generators is higher than the capacity value of new generation. The average cost of a new thermal unit, for instance, is more than 20% cheaper than units built less than a decade ago.[19] Sunk investment costs could be recovered through rates or as a direct subsidy, and would be relatively small as most of China's generation

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[18] A system of capacity and energy payments, liang bu zhi (两部制上网电价) or "two-part pricing," was originally proposed under China's 2003 State Council Announcement on Electricity Price Reforms 《国务院办公厅关于印发电价改革方案的通知》, and was implemented in Northeast China. However, in the liang bu zhi system, capacity payments are made on a levelized (per kWh) basis (Zhang, 2009), which still requires some determination of annual operating hours.

[19] The average unit capital cost of new thermal projects in China reportedly fell from 4,808 yuan/kW to 3,708 yuan/kW (nominal) between 2001 and 2008 (SERC, 2009). This discrepancy is likely even larger for plants built before 2000. For instance, Zhou et al. (2000) report that capital costs for 300 MW and 600 MW units with flue gas desulfurization (FGD) units were 5,700 yuan/kW and 6,600 yuan/kW, respectively, in early 2000.

stock is of recent vintage. In Guangxi, these "transition" costs might be in the range of 0.5-2 billion yuan, which would be equivalent to around 1-3 yuan/MWh and on par with fuel savings from energy efficient dispatch.[20] In China, where power plants are financed through bank loans and where generation companies and banks are government owned and operated, recovering stranded costs may be as much a political as a financial consideration. In a high demand growth system like China's, the cost of dealing with legacy problems is, on a per MWh basis, much smaller than the cost of future inefficiency.

Absent markets, marginal capacity costs must be determined by regulatory agencies through a capacity planning process. Historically, capacity planning in China was done on the basis of an electricity elasticity of GDP (%ΔDemand/%ΔGDP), where new capacity requirements were calculated based on an assumed electricity elasticity, GDP growth rate, and number of annual operating hours. When demand growth is not uniform across hours (e.g., load shapes grow "peakier"), this approach leads to large swings in under and over capacity.[21] Additionally, the elasticity method does not account for the time-varying value of generation capacity. As long as capacity costs in some hours are lower than the cost of building a larger unit, exclusively building large, efficient coal units would lead to higher system costs even though it may minimize fuel costs.

Figure 41 provides a simple example of how building load following and peaking capacity, even though it might operate for a small number of hours, could lower system costs. The top curve shows a screening curve for a 300 MW subcritical coal unit (SUBC), a 600 MW supercritical coal unit (SUPC), and a 600 MW combined cycle gas turbine (CCGT), based on recent estimates of capital, fuel, and operations and maintenance costs. The bottom curve shows a load duration curve, normalized to a 5 TWh demand increment (~7% of 2009 net demand) and based on Guangxi's load shape in 2009. For this example, we assume that any incremental demand is met with thermal generation. With these estimates, the SUBC unit is never cost-effective, while the crossover point between the CCGT and SUPC units is around 980 hours. For Guangxi, this

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[20] Only five of the power plants currently operating in Guangxi were built before 2007: Liuzhou (2 x 220 MW), built in the early 1990s; Laibin B (2 x 360 MW), built in 2000; Beihai (2 x 300 MW), built in 2004; Heshan New (2 x 330 MW), built in 2004; and Tiandong New (2 x 135 MW), built in 2005. Liuzhou is likely already fully depreciated, but for the higher end of this range we assume conservatively that it is not, and that capacity payments are set 1,000 yuan/kW lower than capital costs for Liuzhou and Laibin B and 250 yuan/kW lower than capital costs for Beihai, Heshan New, and Tiandong New. Using a capital recovery factor of 0.09 (r = 7%, t = 20 years), these shortfalls would be 94 yuan/kW-yr and 24 yuan/kW-yr, respectively, or a total of 146 million yuan/yr. Spread across the 57,753 GWh in net electricity generation under provincial dispatch authority in 2009, and an even larger denominator as demand grows, this would amount to a temporary 3 yuan/MWh adder to rates.

[21] For instance, using 2009 as a base year (70,941 GWh of gross demand), an electricity elasticity of 1, and a GDP forecast of 7%, an electricity elasticity approach would predict 2010 energy demand of 75,906 GWh (+4,966 GWh). Assuming 5,300 annual operating hours, meeting this demand would require 940 MW of new capacity. Alternatively, assuming, for simplicity, that load shape does not change and that Guangxi is only capacity constrained for 600 hrs/yr (roughly 4 hrs/day for 5 months), new capacity requirements would be only about 130 MW (see the load duration curve for a visualization). The electricity elasticity approach would overestimate capacity requirements by more than 7 fold.

implies that building CCGT units would be more cost effective for about 150 MW (18%) and 39 GWh (0.8%) for a 5 TWh increment in thermal demand. Building CCGT rather than SUPC units to meet peak demand in those 980 hours would, for each 5 TWh demand increment, save a modest 1.2 million yuan/yr in annual system costs.[22]

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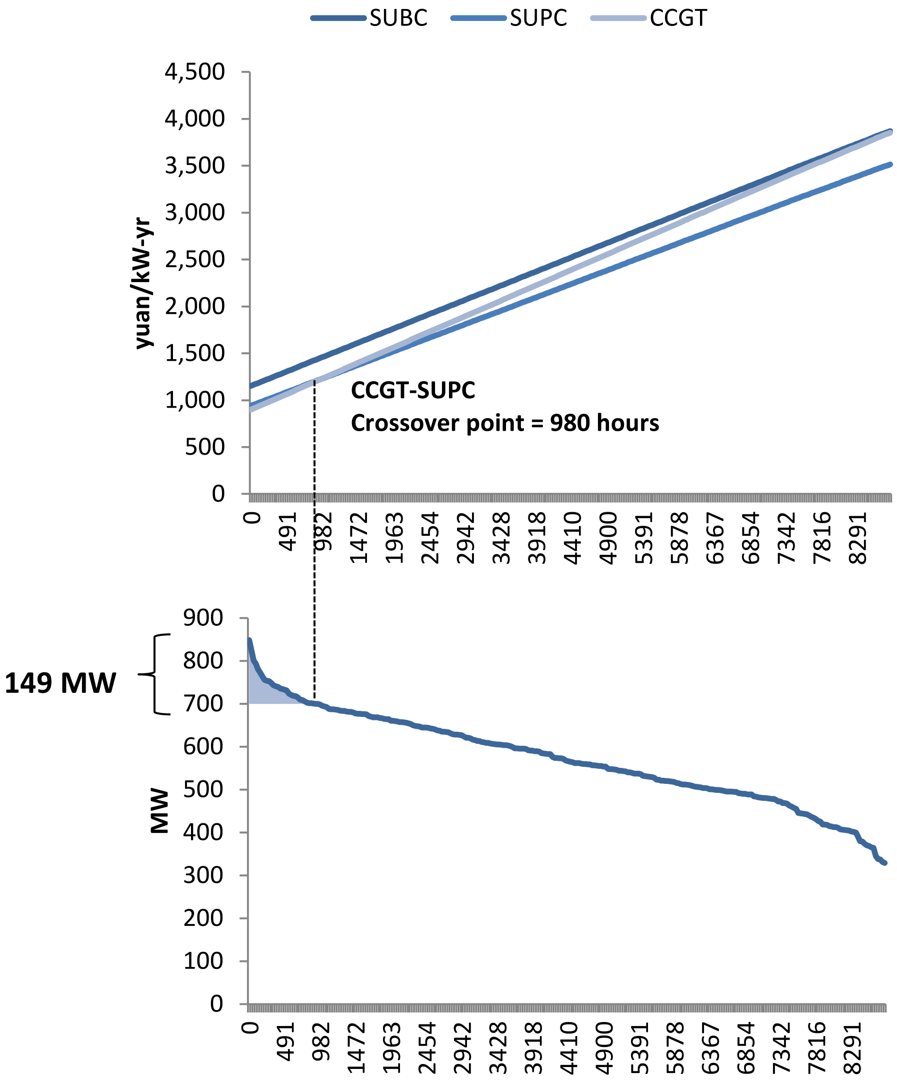
[22] This example assumes that generators are being run at full load, which will not be the case, particularly during days with high peak demand. Accounting for the efficiency penalty of coal units run at partial load would make gas attractive for at least part of the intermediate portion of the load duration curve, in addition to the peak. For cost estimates, assumptions, and further discussion on this example, see the Supporting Material.

Figure 41. Load Duration Curve for 5 TWh of Incremental Thermal Demand in Guangxi and Screening Curve for 300 MW Subcritical Coal Unit (SUBC), 600 MW Supercritical Coal Unit (SUPC), and 600 MW Combined Cycle Gas Turbine (CGGT)



This example also illustrates the relatively unique economics of power generation in China. Whereas in much of the world, investment costs for load following and peaking units are significantly lower than for baseload generation — gas units are less than half of the cost of a new coal unit in the U.S., for instance[23] — in China investment costs for advanced coal units are

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[23] In its 2010 Electricity Market Module, the U.S. Energy Information Administration (EIA) estimates that base overnight capital costs for new scrubbed coal, conventional combined cycle gas turbines, and conventional combustion turbines of $2,073/kW, $937/kW, and $653/kW, respectively (EIA, 2010).

reportedly lower than smaller coal units and only slightly higher than gas units (see Supporting Material). The lack of a larger difference between capital costs for large coal and smaller coal and gas units may be due to the Chinese central government's strong policy support for supercritical coal technology, the high cost of imported gas units, or to a history of granular planning and administrative pricing.

Conclusions and Discussion

This paper provides an empirical analysis of China's current electricity dispatch system, equal shares dispatch, and a proposed alternative, energy efficient dispatch. Under equal shares dispatch, all thermal generators receive roughly the same number of annual operating hours, regardless of marginal cost. Energy efficient dispatch would change this system by prioritizing daily unit commitment for conventional thermal generators by heat and emissions rates. Using Guangxi Zhuang Autonomous Region as a case study, we examined how energy efficient dispatch would impact coal use and wholesale generation prices, and whether energy efficient dispatch could be an important lever for driving the transition to a lower cost, more efficient, cleaner power system in China.

Through changes in unit commitment, energy efficient dispatch would lead to a small (2-4%) reduction in heat rates and virtually no impact on wholesale generation costs under the current benchmark price system. Instead, energy efficient dispatch would shift hours from both small (< 300 MW) and mid-size units (300-400 MW) to larger (≥ 600 MW) units, segmenting generators into the baseload, load following, and peaking functions found in most other power systems. Without changes in wholesale generation prices, which the energy efficient dispatch policy does not stipulate, this segmentation would lead to a windfall for larger generators and a revenue shortfall for small and mid-sized generators.

The transfer mechanisms being discussed to redistribute revenues among generators would not address the need to restructure incentives to encourage efficient operations and investment through price signals rather than by administrative means. Incentivizing efficient operations will require grid companies to absorb a greater share of fuel price risk, but will also require creating mechanisms that allow them to pass these costs through to retail rates. The political feasibility of allowing retail rates to be more responsive to changes in average cost will depend on the extent to which ratemaking can be made more transparent and legitimately cost-reflective.

Without changes in capacity planning, dispatch reforms in China would concentrate investment in large, efficient generators, which may reduce system fuel costs but will lead to higher investment and total costs. Balancing areas in China are by no means capacity constrained in all hours, and some amount of load following and peaking generation is economically efficient. However, without appropriate price signals and a more rigorous capacity planning process, smaller capacity, and in many cases more flexible, units will not be built. Indeed, our illustrative gas-coal screening curve suggests that the relative lack of natural gas capacity in the Chinese power sector may be more a symptom of coarse capacity planning rather than relative technology costs. In China, gas currently competes with coal on a time averaged rather than a time varying basis.

Because it lacks the support of accompanying price or planning reforms, we argue that China's energy efficient dispatch policy will not provide the scaffolding for a more efficient power system. Instead, the significant administrative effort required to implement and regulate energy efficient dispatch are a distraction from the more fundamental changes in incentives needed in China's power sector. Our analysis indicates that cost savings from more efficient dispatch and capacity planning will, at least in the short term, be relatively small. The lack of larger corresponding bill savings will make it difficult to create a public constituency for pricing reforms. Instead, China's power sector reforms will require political will built on a vision of institutions that support more efficient planning, pricing, and dispatch.

Challenges to reform in the Chinese power sector are considerable. China's reform problem is not that of an all-powerful state defining optimal policy strategies, but rather that of a fractured polity where government agencies and regulators with ambiguous powers and incentives seek to create consensus among competing, powerful corporate interests, often with only subsidiary consideration of the public interest. As with its economic reform process more broadly (Wong, 2009), China's power sector reforms have shied away from making proactive trade-offs, which means that regulators have never developed the stakeholder processes and tools commonly used in other countries to transparently allocate costs and benefits among corporate actors, and between corporate actors and ratepayers. To that extent, the road forward in China's power sector reforms will need a greater bottom-up emphasis: on establishing more formal processes and mechanisms for transparency, building supporting information systems, and developing institutional and analytical capacity.

Appendix: Supporting Material and Dispatch Model Documentation

Annual Operating Hours

As described in the main text, accounting for the equal shares dispatch system is done through 'annual operating hours' (利用小时数), which are essentially discounted capacity factors multiplied by the number of hours in a year

$$AOH = \alpha CF \cdot h$$

- AOH is annual operating hours, in hrs/yr
- α is a discount factor,
- CF is a capacity factor, defined as the fraction of capacity utilization, or equivalently total annual generation divided by rated capacity divided by the number of hours per year (GEN/CAP/h)
- h is the total number of hours in a year, 8,760 in a normal year and 8,784 in a leap year

If the discount factor is 1, then AOH and CF are equivalent measures. That they are not suggests that the annual operating hour metric in China is discounted. From the Guangxi Power Grid Corporation's (GPGC's) reports, it is unclear how the discount factor is determined. From anecdotal evidence, we expected that discounting would have been done to penalize generators for unplanned downtime, but the two below figures provide conflicting evidence. Without a clearer description of discounting rules, it is not possible to determine how the discount factor is calculated. Ultimately, the AOH and CF measures are relatively consistent and proximate, and we use capacity factor and annual operating hours interchangeably in the text.

Figure 42. Capacity Factors based on Unadjusted Capacity Factors and Official Annual Operating Hours for Thermal Power Plants in Guangxi, 2008

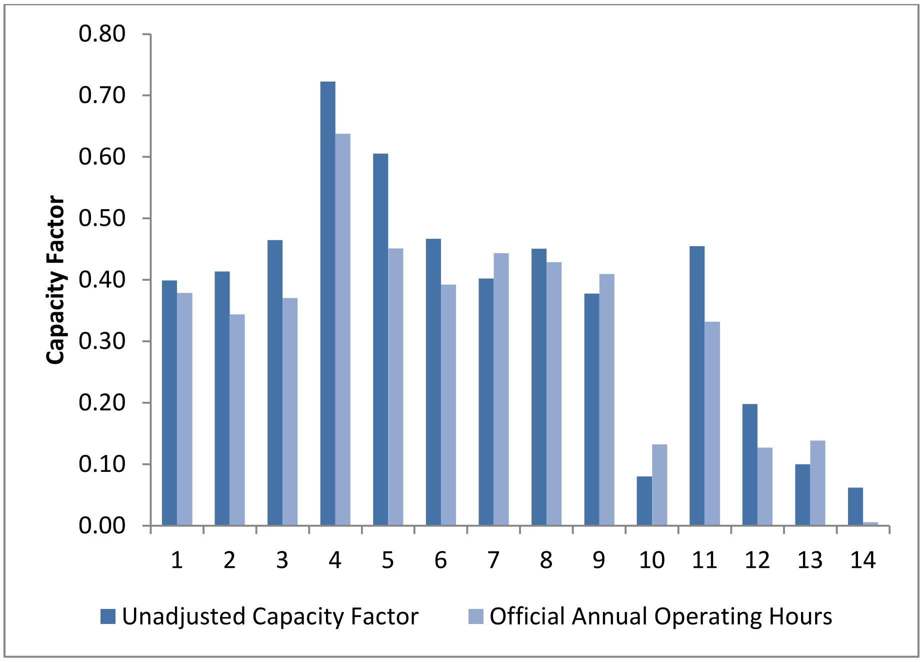
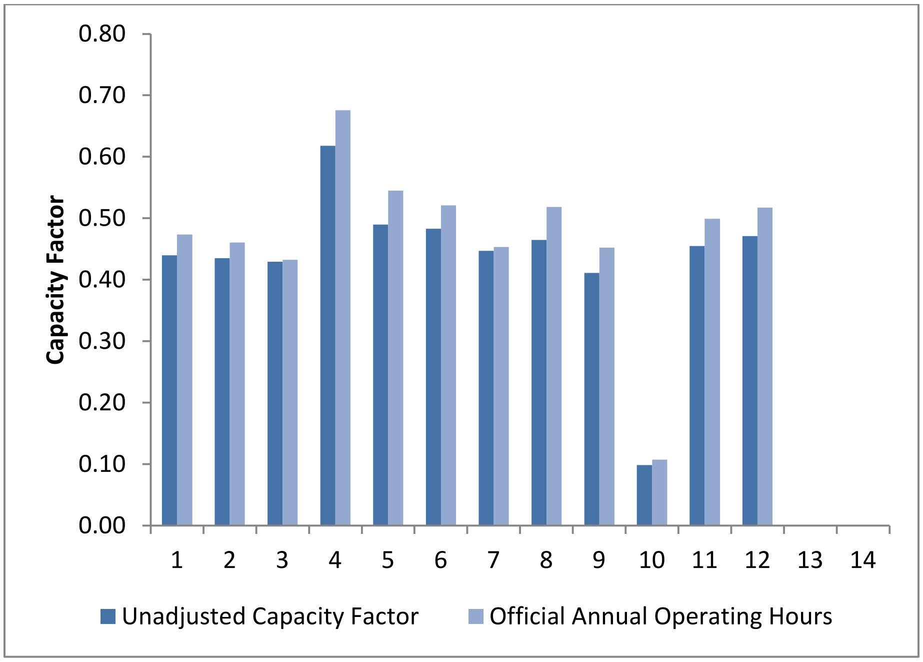


Figure 43. Capacity Factors based on Unadjusted Capacity Factors and Official Annual Operating Hours for Thermal Power Plants in Guangxi, 2009



Power Plant Ownership

In the main text we show that differences in capacity factors are not statistically significant between nationally and provincially majority-owned coal-fired power plants. In Table 17 we list coal-fired power plants in Guangxi by majority owner and ownership type. Coal-fired power plants are owned by a mixture of a provincial investment group, the former provincial hydroelectric utility, three of China's "big five" national generating companies, a national investment company, a Hong Kong utility, and a French utility.

Table 17. Power Plants by Majority Owner and Ownership Type

Plant Name	Majority Owner	Type
Liuzhou	Guangxi Investment Group Co., Ltd	Provincial
Laibin A	Guangxi Investment Group Co., Ltd	Provincial
Laibin Extension	Guangxi Investment Group Co., Ltd	Provincial
Laibin B	Électricité de France	International
Tiandong New	Guangxi Water Conservancy & Electric Power Construction Group Co., Ltd.	Provincial
Heshan	China Datang Corporation	National
Heshan New	China Datang Corporation	National
Beihai	State Development and Investment Corp.	National
Yongfu	China Guodian Corporation	National
Yongfu Extension	China Guodian Corporation	National
Fangchenggang	China Light and Power	International

Guigang	China Huadian Corporation	National
Qinzhou	State Development and Investment Corp.	National
Tianyang	Guangxi Investment Group Co., Ltd	Provincial
Shanglin		Provincial
Xingan		Provincial

Notes: We were not able to determine who owned the Shanglin and Xingan power plants, but were able to determine that these were not nationally majority-owned. Both of these power plants had been retired by the end of 2007.

Dispatch Model Development and Assumptions

This section describes the approach and assumptions used in creating our model of thermal dispatch under the GPGC's control. The section is divided into six sub-sections:

- Daily Load Shape Adjustments
- Net Thermal Load Curve
- Max Capacity Factors
- Heat Rates
- Dispatch
- Comparing Savings Magnitudes

Daily Load Shape Adjustments

The GPGC reports include "typical" daily load shapes for each month. We assume that each typical daily load shape represents an average across the month, which allows us to create monthly load shapes using 288 unique data points (i.e., 24 hours x 12 months).

The daily peak of these monthly load shapes is not consistent with reported annual generation, and we adjust the peak using the following steps to ensure that the two are consistent.

First, we normalize daily load shapes to the daily load peak

$$NL_{h,m,y} = \frac{L_{h,m,y}}{\max(L_{h,m,y})}$$

- $NL_{h,m,y}$ is the normalized load in each hour h, for month m in year y
- $L_{h,m,y}$ is the reported load in each hour h, for month m in year y

We then adjust the load shapes in each month so that the area under the load shape is consistent with total purchased generation

$$ALP_{m,y} = \frac{GEN_{m,y}}{\sum_h NL_{h,m,y} \cdot dy_{m,y}}$$

- $ALP_{m,y}$ is the adjusted load peak in month m and year y
- GEN_m is the total generation purchased by the GPGC (generation + imports –exports) in month m and year y
- $NL_{h,m,y}$ is the normalized load in hour h, month m and year y
- $dy_{m,y}$ is the number of days in year y

Using the adjustment factor and normalized load, we calculate final load as

$$FL_{h,m,y} = ALP_{m,y} \cdot NL_{h,m,y}$$

- $FL_{h,m,y}$ is the final load in hour h, month m and year y
- $ALP_{m,y}$ is the adjusted load peak in month m and year y
- $NL_{h,m,y}$ is the normalized load in hour h, month m and year y

Net Thermal Load Curve

We assume that hydropower is only constrained by total monthly generation, and that, to the extent possible, all intermediate generation is met with hydropower. This is equivalent to subtracting a constant thermal load, $Th.L_m$, from the daily load shape

$$Th.L_{h,m,y} = \frac{1}{24}\left(\sum_h FL_{h,m,y} - \frac{Hp.GEN_{m,y}}{dy_{m,y}}\right)$$

- $Th.L_{h,m,y}$ is constant thermal load in hour h, month m and year y
- $FL_{h,m}$ is final load in hour h in month m in year y
- $Hp.GEN_m$ is total net hydropower generation in month m in year y
- dy_m is the number of days in month m in year y

In all periods in both 2008 and 2009, Guangxi has sufficient hydropower generation to cover all intermediate and peak load. This approach represents a best case scenario. In reality, it is unlikely that the GPGC would be able to meet all intermediate and peaking load with hydropower.

Max Capacity Factors

We calculate maximum capacity factors for each thermal generator for each month using reported annual averages of generator own-use and monthly planned and unplanned downtime.

GPGC reports on generator own-use are incomplete for 2009, including only data from April to November. To overcome gaps in data, we use annual averages for generator own-use for both 2008 and 2009, weighting reported monthly values using gross generation

$$\overline{OU}_{i,y} = \omega_{i,m,y} OU_{i,m,y}$$

where weights are calculated using

$$\omega_{i,m,y} = \frac{G.GEN_{i,m,y}}{\sum_m G.GEN_{i,m,y}}$$

- $OU_{i,y}$ is average annual own-use for generator i in year y
- $\omega_{i,m,y}$ is the gross generation share of thermal generator i in month m and year y
- $OU_{i,m,y}$ is reported own-use for generator i in month m in year y
- $G.GEN_{i,m,y}$ is thermal generator i's gross generation in month m and year y

Table 18. Average Annual Generator Own-Use in 2008 and 2009 (mean ± s.d.)

No.	Plant Name	2008	2009
1	Liuzhou	8.37 ± 0.5	8.67 ± 0.3
2	Laibin A	9.20 ± 0.2	n/a
3	Laibin Extension	7.03 ± 0.9	6.66 ± 0.5
4	Laibin B	7.48 ± 0.3	7.89 ± 0.5
5	Tiandong New	8.73 ± 0.4	8.69 ± 0.3
6	Heshan	10.16	n/a
7	Heshan New	8.92 ± 0.5	8.09 ± 0.0
8	Beihai	6.00 ± 1.0	6.92 ± 1.0
9	Yongfu	9.03 ± 0.7	8.08 ± 0.2
10	Yongfu Extension	6.82 ± 0.6	5.93 ± 0.4
11	Fangchenggang	7.19 ± 0.6	5.77 ± 0.6
12	Guigang	6.37 ± 0.7	5.46 ± 0.5
13	Qinzhou	5.22 ± 0.8	5.49 ± 0.3
14	Tianyang	9.51 ± 0.5	8.91 ± 0.2

Notes: Heshan only operated for one month in 2008. Laibin A and Heshan were officially retired in 2009.

Standard deviations for generator own-use in Table 18 are weighted using gross generation

$$\sigma_{OU_{i,y}} = \sqrt{\sum_m \omega_{i,m,y}\left(OU_{i,m,y} - \overline{OU}_{i,y}\right)^2}$$

The GPGC reports list generator downtime by month, including normal repairs, unanticipated equipment failures, and coal shortages. Some double counting takes place between monthly reports. After cleaning this data to remove duplicates, we create an i x 12 availability matrix (i generators)

$$\theta_{i,m,y} = 1 - \left(\frac{\sum_j U_{i,j,m,y} \cdot od_{i,j,m,y}}{CAP_{i,m,y} \cdot dy_{m,y}}\right)$$

- $\theta_{i,m,y}$ is the availability coefficient for thermal generator i in month m and year y
- $U_{i,j}$ is the capacity of unit j for thermal generator i in month m and year y
- $od_{i,j}$ is the number of outage days (fraction) reported for unit j, generator i, month m, year y
- $CAP_{i,m,y}$ is the total capacity of generator i in month m and year y
- $dy_{m,y}$ is the number of days in month m and year y

Table 19. Generator Downtime Matrix for 2008

	Month											
No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	1.00	0.50	0.96	1.00	1.00	0.98	0.52	0.60	0.79	0.98	1.00	1.00
2	1.00	0.02	0.89	0.96	0.88	0.67	0.00	0.81	0.81	1.00	1.00	0.98
3	0.68	0.68	0.78	1.00	1.00	0.88	0.50	0.89	0.61	1.00	0.94	1.00
4	0.95	0.25	0.78	1.00	0.93	0.88	0.63	0.44	0.82	0.83	1.00	1.00
5	0.31	0.20	0.50	0.77	0.84	0.00	0.00	0.00	0.56	0.00	1.00	1.00
6	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.67
7	0.76	0.79	0.94	0.96	0.97	1.00	0.76	0.92	0.67	0.56	1.00	1.00
8	0.97	0.95	0.75	1.00	1.00	1.00	0.62	0.80	1.00	1.00	1.00	0.95
9	0.98	0.50	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10	0.80	0.58	1.00	1.00	0.82	0.98	0.50	0.98	1.00	0.86	1.00	1.00
11	0.90	0.69	0.94	0.73	0.52	0.95	1.00	0.97	0.91	1.00	1.00	1.00
12	1.00	1.00	1.00	0.90	0.72	0.72	0.55	0.50	0.50	0.88	1.00	1.00
13	0.73	0.78	0.65	0.87	1.00	0.92	0.85	0.98	0.86	0.97	1.00	1.00
14	0.87	0.51	0.83	0.79	0.69	1.00	0.89	1.00	1.00	1.00	1.00	0.88

Note: Plant number (no.) in the above table matches the power plants in Table 18.

Table 20. Generator Downtime Matrix for 2009

	Month											
No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	1.00	1.00	1.00	1.00	0.60	0.62	1.00	1.00	1.00	0.97	0.91	1.00
2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.89	1.00	1.00
3	1.00	1.00	1.00	1.00	1.00	1.00	0.67	1.00	1.00	1.00	1.00	1.00
4	1.00	1.00	1.00	1.00	0.55	0.88	1.00	1.00	0.97	1.00	1.00	1.00
5	0.94	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	1.00
6	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
7	1.00	1.00	1.00	1.00	1.00	1.00	0.65	0.96	1.00	1.00	1.00	1.00
8	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.13	1.00	0.98	0.90	1.00
9	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10	1.00	1.00	1.00	1.00	0.74	0.92	1.00	1.00	1.00	1.00	1.00	1.00
11	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
12	1.00	0.91	0.71	1.00	1.00	1.00	1.00	0.88	1.00	1.00	1.00	1.00
13	1.00	0.98	1.00	1.00	1.00	0.75	0.76	0.89	0.88	0.98	0.87	1.00
14	1.00	1.00	0.76	1.00	1.00	1.00	1.00	1.00	0.88	1.00	1.00	1.00

Note: Plant number (no.) in the above table matches the power plants in Table 18.

We calculate the maximum capacity for each power plant in each time period as

$$MCF_{i,m,y} = \theta_{i,m,y}\frac{\left(1-\overline{OU}_{i,y}\right)}{100}$$

which gives the n x 12 maximum capacity factor matrices shown in Table 21 and Table 22.

Table 21. Maximum Capacity Factor Matrix for 2008

	Month											
No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	0.92	0.46	0.88	0.92	0.92	0.90	0.47	0.55	0.72	0.90	0.92	0.92
2	0.91	0.02	0.80	0.88	0.80	0.61	0.00	0.73	0.73	0.91	0.91	0.89
3	0.63	0.63	0.73	0.93	0.93	0.82	0.46	0.83	0.56	0.93	0.88	0.93
4	0.88	0.23	0.72	0.93	0.86	0.82	0.58	0.41	0.76	0.77	0.93	0.92
5	0.28	0.18	0.45	0.70	0.76	0.00	0.00	0.00	0.51	0.00	0.91	0.91
6	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.60
7	0.69	0.72	0.85	0.88	0.88	0.91	0.69	0.84	0.61	0.51	0.91	0.91
8	0.91	0.89	0.70	0.94	0.94	0.94	0.58	0.75	0.94	0.94	0.94	0.89
9	0.90	0.45	0.89	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
10	0.74	0.54	0.93	0.93	0.76	0.92	0.47	0.91	0.93	0.80	0.93	0.93
11	0.83	0.64	0.87	0.68	0.48	0.88	0.93	0.90	0.85	0.93	0.93	0.92
12	0.94	0.94	0.94	0.84	0.68	0.67	0.52	0.47	0.47	0.82	0.94	0.94
13	0.69	0.74	0.61	0.82	0.95	0.87	0.81	0.93	0.82	0.92	0.94	0.94
14	0.78	0.46	0.75	0.71	0.63	0.90	0.80	0.90	0.90	0.90	0.90	0.80

Note: Plant number (no.) in the above table matches the power plants in Table 18.

Table 22. Maximum Capacity Factor Matrix for 2009

	Month											
No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	0.91	0.91	0.91	0.91	0.55	0.56	0.91	0.91	0.91	0.88	0.83	0.91
2	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.81	0.91	0.91
3	0.93	0.93	0.93	0.93	0.93	0.93	0.63	0.93	0.93	0.93	0.93	0.93
4	0.92	0.92	0.92	0.92	0.51	0.81	0.92	0.92	0.89	0.92	0.92	0.92
5	0.85	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.84	0.91
6	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
7	0.92	0.92	0.92	0.92	0.92	0.92	0.59	0.88	0.92	0.92	0.92	0.92
8	0.93	0.93	0.93	0.93	0.93	0.93	0.00	0.13	0.93	0.92	0.84	0.93
9	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
10	0.94	0.94	0.94	0.94	0.70	0.87	0.94	0.94	0.94	0.94	0.94	0.94
11	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94
12	0.95	0.86	0.67	0.95	0.95	0.95	0.95	0.83	0.95	0.95	0.95	0.95
13	0.95	0.93	0.95	0.95	0.95	0.71	0.72	0.84	0.83	0.92	0.82	0.95
14	0.91	0.91	0.70	0.91	0.91	0.91	0.91	0.91	0.80	0.91	0.91	0.91

Note: Plant number (no.) in the above table matches the power plants in Table 18.

Heat Rates

We use fixed, weighted average annual heat rates in our dispatch model

$$\overline{HR}_{i,y} = \varphi_{i,m,y} HR_{i,m,y}$$

weighted here by net, rather than gross, generation

$$\varphi_{i,m,y} = \omega_{i,m,y} \frac{\left(1 - OU_{i,m,y}\right)}{100}$$

- $HR_{i,y}$ is an annual average heat rate for generator i in year y
- $\phi_{i,m,y}$ is the net generation share of thermal generator i in month m and year y
- $\omega_{i,m,y}$ is the gross generation share of thermal generator i in month m and year y
- $OU_{i,m,y}$ is average annual own-use for generator i in month m and year y

Heat rate standard deviations are calculated using net generation weights

$$\sigma_{HR_{i,y}} = \sqrt{\sum_{m} \varphi_{i,m,y}\left(HR_{i,m,y} - \overline{HR}_{i,y}\right)^2}$$

The GPGC reports include generator-specific heat rates by month, with significant monthly variation, as shown in Table 23.

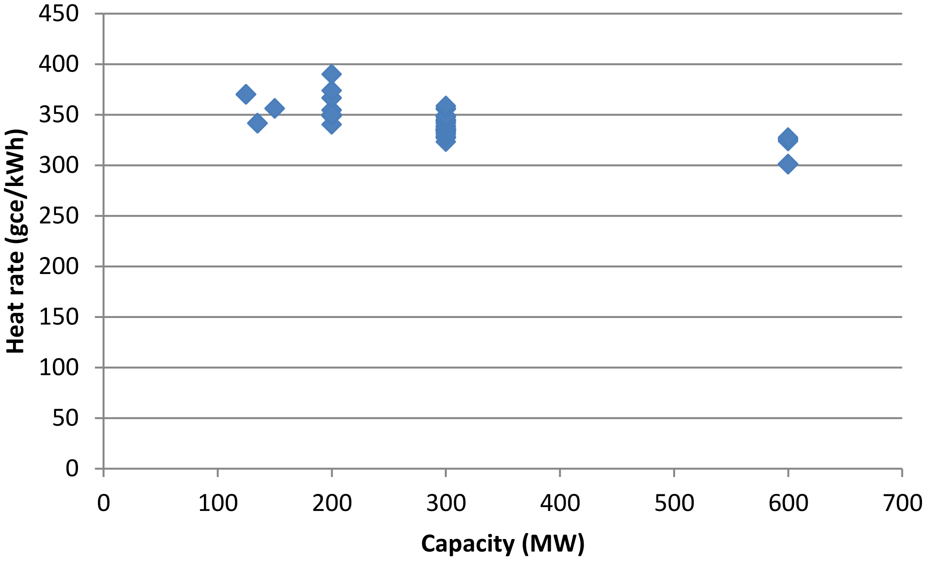
Table 23. Capacity and Net Heat Rate by Power Plant, 2008 and 2009 (mean ± s.d.)

No.	Plant Name	Capacity	2008	2009
1	Liuzhou	2 x 220 MW	361 ± 7	362 ± 0.4
2	Laibin A	2 x 125 MW	402 ± 12	n/a
3	Laibin Extension	2 x 330 MW	354 ± 13	348 ± 4
4	Laibin B	2 x 360 MW	334 ± 10	326 ± 9
5	Tiandong New	2 x 135 MW	408 ± 16	384 ± 9
6	Heshan	1 x 110 MW	435	n/a
7	Heshan New	2 x 330 MW	344 ± 9	336 ± 3
8	Beihai	2 x 300 MW	343 ± 10	338 ± 10
9	Yongfu	2 x 142 MW	391 ± 5	379 ± 7
10	Yongfu Extension	2 x 300 MW	346 ± 4	337 ± 2
11	Fangchenggang	2 x 630 MW	330 ± 8	321 ± 7
12	Guigang	2 x 630 MW	328 ± 9	318 ± 6
13	Qinzhou	2 x 600 MW	320 ± 12	319 ± 5
14	Tianyang	2 x 150 MW	399 ± 12	387 ± 9

Notes: Heshan only operated for one month in 2008. Laibin A and Heshan were officially retired in 2009. Fangchenggang and Guigang added 60 MW of capacity each in 2009, which is included in the above table.

Given that thermal units in Guangxi do not yet have heat rate monitoring devices, these heat rates are likely calculated based on reported coal consumption. It is unclear from the GPGC reports whether the primary driver of monthly variance in heat rates is reporting accuracy or changes in monthly average load factors. The latter are not included in the GPGC reports. Though their monthly values vary significantly, averaged over the year heat rates in Guangxi are consistent measured values elsewhere. For instance, Figure 44 shows measured heat rates for Guizhou, where most thermal power plants now have real-time heat rate monitoring devices.

Figure 44. Measured Heat Rates by Generator Capacity Class, Guizhou Province, April 2010



Notes and Source: Heat rates for generators < 200 MW are based on manufacturer specifications rather than real-time measurements. Data are from http://202.101.77.223/upload/2010_04/10042216259232.pdf.

This annual average heat rate approach commits us to the assumption that generator-specific heat rates do not change with generator reordering. This assumption, though perhaps unrealistic, does not necessarily increase the uncertainty in our analysis. Because the GPGC reports do not provide information on average load factors, it is unclear what average load levels monthly heat rates reflect and there is not sufficient information to estimate how heat rates would change with load factor improvements. The average heat rate assumption allows us to focus on reordering the dispatch stack, which is the focus of the energy efficient dispatch policy.

System-wide, the annual average heat rate for thermal generators is a weighted average across generators

$$\overline{HR}_y = \sum_i \tau_{i,y} \sum_m \varphi_{i,m,y} HR_{i,m,y}$$

where τ is an additional weighting factor

$$\tau_{i,y} = \frac{N.GEN_{i,y}}{\sum_i N.GEN_{i,y}}$$

- $\tau_{i,y}$ is generator i's share of total net generation in year y
- $N.GEN_{i,y}$ is generator i's net generation in year y

Assuming no correlation in the variance of monthly heat rates across generators, the standard deviation of system average heat rates is

$$\sigma_{HR_y} = \sqrt{\sum_i \tau_{i,y}\left(HR_{i,y} - \overline{HR}_y\right)^2 + \sum_m \varphi_{i,m,y}\left(HR_{i,m,y} - \overline{HR}_{i,y}\right)^2}$$

Standard errors are

$$se_{HR_y} = \frac{\sigma_{HR_y}}{\sqrt{n \cdot 12}}$$

- n is the number of generators
- 12 is for the 12 months in a year

Table 24. Average Annual Thermal Heat Rates, 2008 and 2009 (mean ± s.e.)

	2008	2009
Average Annual Thermal Heat Rate	339 ± 3	334 ± 2

Dispatch

Thermal units are dispatched in each hour to meet demand for thermal generation

$$Th.GEN_{n,h,m,y} = \max\left(\min\left(Th.L_{h,m,y} - \sum_{i=1}^{n-1} Th.GEN_{i,h,m,y}\,, CAP_{i,m,y} \cdot MCF_{i,m,y}\right), 0\right)$$

- $Th.GEN_{n,h,m,y}$ is thermal generation for generator n in hour h, month m and year y
- $Th.L_{h,m,y}$ is net thermal load in hour h, month m, and year y
- $Th.GEN_{i,h,m,y}$ is thermal generation for the previous n-1 generators in hour h, month m, year y
- $CAP_{i,m,y}$ is the rated capacity of generator i in month m, year y
- $MCF_{i,m,y}$ is the maximum capacity factor for generator i, month m, year y

We use a common rule-of-thumb in China that units cannot be operated at lower than 50% load. In meeting this requirement, we allow power plants with multiple units to have these units operated separately. With our assumption about hydropower dispatch, this approach leads to a “swing” generator in each month that is run at partial load, while other generators are run at full load.

A system-wide, energy efficient dispatch heat rate for thermal generators, EED.HR, can then be calculated from the reordering of the dispatch stack and the average annual heat rates from above

$$EED.\overline{HR}_y = \gamma_{n,y}\overline{HR}_{i,y}$$

where γ is a weighting factor

$$\gamma_{n,y} = \frac{\sum_m \sum_h Th.GEN_{n,h,m,y} \cdot d_{m,y}}{\sum_n \sum_m \sum_h Th.GEN_{n,h,m,y} \cdot d_{m,y}}$$

and $d_{m,y}$ is the number of days in month m and year y.

In addition to heat rate impacts of in generator load, described above, this approach does not account for transmission constraints. Transmission constraints are a particularly salient issue in China because smaller power plants were historically built near cities and towns and served this load directly. Reducing the use of or closing these smaller plants will require investments in transmission lines and transformer capacity to transfer load to other power plants and minimize impacts on grid power flow (Wan, 2007).

Comparing Savings Magnitudes

The small magnitude of savings from reordering the dispatch stack that we find in this analysis is consistent with a simple, more aggregate analysis and with reported actual values.

Average thermal heat rate is a weighted average of heat rates across generators. For three size classes of generators, for instance, the average heat rate is

$$HR_{AVG} = \omega_1 HR_1 + \omega_2 HR_2 + \omega_3 HR_3$$

where ω_1, ω_2, and ω_3 are generator class 1, 2, and 3’s share of total net generation.

Assuming no changes in average heat rates by generator class, a reweighting of generator classes in the generation mix changes the average heat rate by

$$\Delta HR_{AVG} = \Delta\omega_1 HR_1 + \Delta\omega_2 \alpha_2 HR_1 + \Delta\omega_3 \alpha_3 HR_1 = HR_1(\Delta\omega_1 + \Delta\omega_2 \alpha_2 + \Delta\omega_3 \alpha_3)$$

where

$$\alpha_2 = \frac{HR_2}{HR_1}$$

and

$$\alpha_3 = \frac{HR_3}{HR_1}$$

Jiangsu Province provides a simple numerical example. Jiangsu was one of the five provinces included in the energy efficient dispatch pilot. As part of its policies to transfer operating hours to larger generators, Jiangsu required units less than 200 MW to transfer 50% of their planned hours to units at or larger than 600 MW. Reported installed capacity for these units and rule-of-thumb heat rates for each unit are shown in the below table. In an equal shares dispatch system, capacity and generation shares are identical. If smaller units were to transfer 50% of their hours to 600 MW or larger generators, the generation share of smaller units would fall by half.

Generator Class	**Average Heat Rate (gce/kWh)**	**Installed Capacity (GW)**	**Share of Generation Pre-EED (%)**	**Share of Generation Post-EED (%)**
< 300 MW	380	9.4	22%	11%
300-400 MW	350	33.6	78%	89%
600	330			

Source: These data are based on http://diangong.jdzj.com/article/2011-3-26/25461-1.htm.

Because $\Delta\omega_2$ is zero in this case, assuming that own-use is the same across generators, average heat rates change by

$$\Delta HR_{AVG} = 330(0.11 - 0.11 \cdot 1.15) = -5.5\ gce/kWh$$

Determining percentage change requires knowing HR_{AVG}, which in turn requires knowing ω_1 and ω_2. Generation shares of 300 MW and larger units were not reported. If 600 MW or larger units accounted for 50% of 300 MW or larger capacity, HR_{AVG} is

$$HR_{AVG} = 0.39 \cdot 330 + 0.39 \cdot 350 + 0.22 \cdot 380 = 349\ gce/kWh$$

In other words, the Jiangsu policy would reduce average heat rates from an initial 349 gce/kWh to 343 gce/kWh, or a reduction of 1.6%. Transferring all of the hours from generators less than 300 MW to the largest generators would reduce average heat rates by 11 gce/kWh, or just over 3%.

As a second example, in Guizhou Province energy efficient dispatch reportedly reduced average heat rates from 330 gce/kWh to 322 gce/kWh (by 2.4%).[24] However, this report does not isolate the effects of new generators added from 2007-2009. When this effect is accounted for, heat rate improvements from reordering generators would be even smaller.

Load Duration Curve and Screening Curve Assumptions

Normalized Load Duration Curve

Because of data limitations, the load duration curve (LDC) shown in the main text is estimated using the typical daily load shapes mentioned above. As with the above, this means that the LDC has only 288 unique data points, and that each point represents between 28 and 31 days per year.

To normalize this curve to a demand increment, we shift the LDC by a constant

$$\mu \sum_p L_p d_p = \Delta D$$

- μ is a constant
- p is the number of periods, 12 x 24 = 288
- L_p is load in period p
- d_p is the number of days in period p
- ΔD is the demand increment

Solving for the constant gives

$$\mu = \frac{\Delta D}{\sum_p L_p d_p}$$

or, in the example given in the text

$$\mu = \frac{5 \times 10^6 \ MWh}{58 \times 10^6 \ MWh} = 0.09$$

Normalized load (NL) in period p is then

$$NL_p = \mu L_p$$

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[24] Reported in http://gz.offcn.com/Html/News/zhxw/4086.html.

Screening Curve

The cost assumptions for the screening curve shown in the main text are shown in the table below, drawing from a November 2010 report by Qinghua University for the State Electricity Regulatory Commission. All labor costs are included in "other fixed costs" as a fixed cost rather than as a variable cost, which explains why these are higher than typical values. A new coal-fired power plant in China might have 200-300 employees, which is several fold more than a comparable power plant in the U.S.

Table 25. Screening Curve Assumptions

	Unit	Subcritical (SUBC) 300 MW	Supercritical (SUPC) 600 MW	Natural Gas (CCGT) 600 MW
Unit capital cost	yuan/kW	4,057	3,675	3,249
Annualized capital cost	yuan/kW-yr	445	403	357
Other fixed costs	yuan/kW-yr	707	537	541
Other variable costs	yuan/kWh	0.021	0.018	0.020
Fuel price	yuan/t or yuan/m^3	600	600	1.6
LHV fuel	GJ/t or MJ/m^3	20	20	38.3
Heat rate	gce/kWh (η_{th} % in paren.)	330 (37%)	315 (39%)	260 (47%)

Notes: To annualize capital costs we use a capital recovery factor with r = 7% and t = 15 years across all technologies. Other variable costs include desulfurization costs and pollution fees.

We use a coal price of 600 yuan/t. Many generation cost comparisons in China use spot prices for coal, but contract prices are likely to be significantly lower than spot prices. Spot prices for thermal coal were 780 yuan/t in April 2011 at the coal hub of Qinhuangdao (http://www.sxcoal.com). 600 yuan/t would be 23% lower than the spot price. For gas prices, we use the value from the report.

Total fixed costs (TFC) for each technology j in the screening curve are the sum of annualized capital costs (ACC) and other fixed costs (OFC)

$$TFC_j = ACC_j + OFC_j$$

Total variable costs (TVC) for each technology j in the screening curve are the sum of other variable costs (OVC) and fuel costs (FC)

$$TVC_j = OVC_j + FC_j$$

Fuel costs are

$$FC_j = \frac{FP_k \cdot 29.31 \cdot HR_j}{LHV_k \cdot 10^6}$$

- FC_j is fuel cost for technology j
- FP_k is the fuel cost for fuel k
- 29.31 is a conversion factor, 1 ton standard coal equivalent = 29.31 GJ
- HR_j is the heat rate for technology j
- LHV_k is the lower heating value for technology k

It is worth noting how much higher the energy prices we use in this example are than those in the U.S. For coal, a significant portion of the difference is transport costs. For natural gas, government controls and distribution costs both play a role.

Table 26. Energy Prices (US$/GJ), China from Table 25 and U.S. 2009

	China	**U.S.**
Coal	$4.63	$2.09
Natural Gas	$6.44	$4.55

Sources: U.S. thermal coal prices are based on a delivered price of $2.21/MMBTU in 2009, from the EIA (http://tonto.eia.doe.gov/energyexplained/index.cfm?page=coal_prices). U.S. gas prices are based on a delivered electric power price of US$4.93/MCF (http://tonto.eia.doe.gov/dnav/ng/ng_pri_sum_dcu_nus_a.htm). The table uses a 1 May 2011 exchange rate of 6.49 yuan/$, from oanda.com.

Crossover Point and Savings from CCGTs

Because our LDC is in terms of periods p rather than hours, our screening curve is scaled according to the same periods. The crossover points between any two lines on the screening curve are the p values where the lines intersect

$$FC_1 + VC_1 p = FC_2 + VC_2 p$$

or

$$p^C = \frac{FC_2 - FC_1}{VC_1 - VC_2}$$

- FC is the total fixed costs for technologies 1 and 2
- VC is the total variable costs for technologies 1 and 2

- p is a given period, from 1 to 288
- p^C is the period where the two technologies intersect

Savings from using the CCGT rather than the SUPC are the area between the two curves, multiplied by the corresponding area under the LDC

$$\sum_{p=1}^{p^C}\left[\left(SUPC.FC + SUPC.VC \cdot \sum_{o=1}^{p} d_o\right) - \left(CCGT.FC + CCGT.VC \cdot \sum_{o=1}^{p} d_o\right)\right] \cdot \left[NL_p - NL(p^C)\right] \cdot d_p$$

- SUPC.FC is total fixed costs for the supercritical unit
- SUPC.VC is total variable costs for the supercritical unit
- CCGT.FC is total fixed costs for the combined cycle gas turbine
- CCGT.VC is total variable costs for the combined cycle gas turbine
- NL_p is normalized load in period p
- $NL(p^C)$ is the normalized load at the crossover point in period p^C
- d is the number of days in each period

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Chapter 6

Greenhouse Gas Emissions from Nitrogen Fertilizer Use in China[1]

Synthetic nitrogen (N) fertilizers have played an important role in maintaining China's food security over the past three decades. In contrast to its low levels of synthetic N fertilizer production and use in the early 1970s, China is now the world's largest producer and consumer of N fertilizers. In the 1990s, the scientific community began to raise concerns over the potential overuse and environmental impacts of N fertilizer application in China, and since then a growing body of research has identified the need to improve N fertilizer use efficiencies.

While a significant portion of these concerns have centered around N fertilizers as a non-point source of water-borne pollution, application of N fertilizers in China is also a major driver of energy use and greenhouse gas (GHG) emissions. In addition to reducing water-borne pollution and other ecological impacts associated with anthropogenic reactive nitrogen, improving N fertilizer use efficiency could free up scarce energy resources, reduce GHG emissions, and contribute to poverty reduction goals by reducing input costs to farmers.

This paper estimates: a GHG emission factor for synthetic N fertilizer application; the scale of energy use and GHG emissions embodied in N fertilizer application; and GHG emission reductions from improvements in N fertilizer production and use efficiency in China. The paper concludes with thoughts on the costs and financing of a fertilizer efficiency program, and how a GHG mitigation framework might contribute to program design and funding.

Because our focus here is on chemical rather than organic N fertilizers, we use the term 'N fertilizer' to refer exclusively to synthetic N fertilizers in the text below. Additionally, our emphasis here is on N fertilizer use in agriculture, and the use of the phrase 'N fertilizer application' refers to application on cropland.

Use and Overuse of Nitrogen Fertilizers in China

China is the world's largest producer and consumer of synthetic N fertilizers, accounting for an estimated 31% of world consumption in 2005 (FAOSTAT). Increasing the use of chemical fertilizers was a key part of the Chinese government's efforts to expand food production and ensure an adequate food supply, beginning in the early 1970s (Naughton, 2007). From 1970 to

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[1] This chapter was originally published as Kahrl, F., Li, Y., Su., Y, Tennigkeit, T., Wilkes, A., Xu, J., 2010. Greenhouse gas emissions from nitrogen fertilizer use in China. Environmental Science & Policy 13, 688-694.

2008, chemical fertilizer use increased from 2.4 Mt yr^{-1} to 60.1 Mt yr^{-1} (total nutrients), a 25 fold increase (NBS, various years).[2] In the 1990s concerns began to emerge over the overuse and environmental impacts of N fertilizers in China. Since that time, a substantial literature has emerged on the ecological implications, and, to a lesser extent, behavioral drivers of N fertilizer use (Zhang et al., 1996; Yong and Zhang, 1999; Xing and Zhu, 2000; Zhu and Chen, 2002; Ju et al., 2004; Cui et al., 2006; He et al., 2007; Lin et al., 2007; Wang et al., 2007; Huang et al., 2008; Ju et al., 2009; Han and Zhao, 2009).

A key argument implicit across much of this literature is that, at an aggregate level, the marginal productivity of N fertilizer use in China is declining. Zhu and Chen (2002) argue that, although increased use of N fertilizers contributed to the substantial increase in China's agricultural output from the 1970s to the 1990s, the marginal contribution of N fertilizer to food production (narrowly defined)[3] has declined at an increasing rate since the 1950s. Ju et al. (2009) report that N fertilizer application increased by 271% from 1977-2005, while grain yields increased by only 98% and total grain output increased by only 71%.

Although these descriptions capture what is likely an aggregate trend of declining marginal productivity of N fertilizer application in China, it is important to note that neither includes fertilizer use for cash crops, and thus both may be neglecting the influence of a significant structural shift from grain to cash crops that occurred in China beginning in the 1990s (Figure 45). As grain crops typically use less fertilizer per area vis-à-vis cash crops (Ju et al., 2004; Zhang et al., 2007),[4] shifts in cropping patterns may explain some of the apparent declining marginal productivity of fertilizer inputs vis-à-vis staple crops. Zhang et al. (2007) report that cash crops accounted for 50% of fertilizer use in China in 2005.

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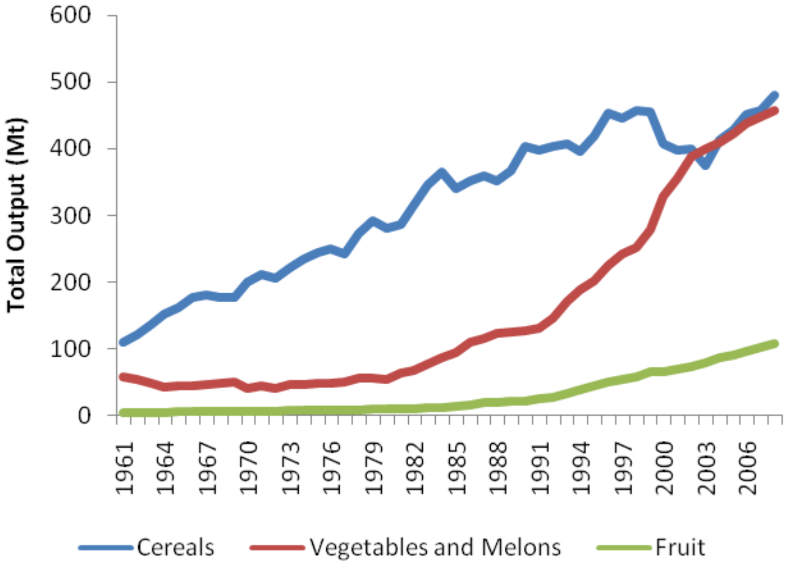
[2] NBS data are from China Data Online.

[3] This definition only includes crops reported in the *China Statistical Yearbook* series: cereals, pulses, potato, and sweet potato.

[4] See also FAO FertiStat Fertilizer Use Statistics, online at: http://www.fao.org/ag/agl/fertistat/index_en.htm.

Figure 45. Cereals, Vegetables and Melons, and Fruit Production in China, 1961-2008



Source: Data are from FAOSTAT

Table 27. Estimates of N Fertilizer Use in Different Cropping Systems and Regions of China

Region	Crop(s)	Fertilizer Use	Source
Jiangsu Province	Paddy rice	300-350 kgN ha^{-1}	Lin et al., 2007
Beijing Municipality	Winter wheat Summer maize	309 kgN ha^{-1} yr^{-1} 256 kgN ha^{-1} yr^{-1}	Zhao, 1997, c.f. Zhao et al., 2006
Henan Province **Shandong Province**	Multiple crops Multiple crops	587 kgN ha^{-1} yr^{-1} 652 kgN ha^{-1} yr^{-1}	Gao et al., 1999, c.f. Zhao et al., 2006
Shandong Province	Winter wheat	369 kgN ha^{-1} yr^{-1}	Cui et al., 2006
Yunnan Province	Summer maize	360 kgN ha^{-1} yr^{-1}	Authors, 2008 unpublished surveys (n = 458)

Nevertheless, there is a growing body of field-based evidence to suggest that N fertilizer application for grain crops in China exceeds optimal levels, that the marginal product of N fertilizer for grain crops is low, and that N fertilizer use could be reduced without adversely affecting grain yield. Table 27 catalogues a number of fertilizer use estimates across different regions of China. Although optimal N fertilizer use levels are site specific, these estimates compare against a range of around 150-200 kgN ha^{-1} considered optimal for grain crops in China (Zhu and Chen, 2002; Ju et al., 2004; Ju et al., 2009). While the majority of research on N inputs in China has focused on grain crops, N use efficiency for vegetables and fruit may be similarly low.

A growing number of studies confirm the potential for reducing N fertilizer application rates without reducing yield. In a 16-village experiment in Guangdong, Hunan, Hubei, and Jiangsu Provinces, Huang et al. (2008) report a 23% reduction in total fertilizer use as part of a training project to encourage farmers to use less fertilizer. Based on field trials in Jiangsu Province, Ju et al. (2009) estimate that total fertilizer use could be reduced by 30-60% without compromising yield. While these studies suggest the potential for significant improvements in N fertilizer use efficiency in China, how to achieve these improvements on a large scale remains an open question.

Energy Use and GHG Emissions from N Fertilizer Application in China

Rising N fertilizer use in China has contributed to a number of environmental problems (Zhang et al., 1996; Yong and Zhang, 1999; Domagalski, 2007; Guo et al., 2010), including an increase in GHG emissions. The use of fertilizer induces process-based and combustion CO_2 emissions from the production of ammonia, combustion CO_2 emissions from the synthesis of N fertilizers from ammonia, and N_2O emissions from the denitrification of N inputs.

Ammonia and fertilizer production in China are more energy and CO_2 intensive than the global average. While natural gas is the primary feedstock and source of process energy used for ammonia and N fertilizer production in most of the world, in China anthracite coal is the primary feedstock for ammonia synthesis and coal and electricity provide the bulk of process energy used in both ammonia and N fertilizer production. Additionally, for historical reasons a large number of China's ammonia-fertilizer producers are small and medium sized (Wong, 1986; Li, 2001; Zhang et al., 2009), and tend to be less energy efficient than larger facilities (Cao et al., 2008).

In this paper we develop a GHG emission factor for applied nitrogen (in $tCO_2e\ tN^{-1}$) in Chinese agriculture using: China-specific estimates of energy use in ammonia synthesis; China-specific estimates of energy use in the synthesis of China's two main N fertilizers — urea and ammonium bicarbonate (ABC) — from ammonia; and more generic N_2O emission factors using China-specific coefficients where available. A detailed accounting of the data and assumptions used in calculating the total GHG emission factor is provided in the Appendix. From estimates of total specific energy use ($GJ\ tN^{-1}$) and the GHG emission factor for applied nitrogen, we use data on N fertilizer application in Chinese agriculture to calculate total energy use and GHG emissions in 2005. The estimates here are not lifecycle GHG emissions, as consensus estimates of GHG emissions embodied in upstream (e.g., coal mining) and downstream (e.g., transport) activities are not available for China. For context, Gellings and Parmenter (2004) report that packing, transport, and application can account for around 10% of the energy required to produce, distribute, and apply N fertilizer.

Actual use of N fertilizers in China is difficult to assess with a high level of accuracy. FAO estimates that China's total N fertilizer consumption was 30.2 MtN in 2005 (FAOSTAT). The IFA estimates that N fertilizer consumption in China was 29.7 MtN in 2005 (IFA website). Official statistics from the China Statistical Yearbook report that total application of N-based and compound fertilizers was 22.3 MtN and 13.0 Mt total nutrients, respectively, in 2005 (NBS, 2006), but the composition of compound fertilizers is not published as part of these statistics. At an average of 40% elemental N in compound fertilizer nutrients,[5] total N application in China would have been 27.5 MtN in 2005. The difference in these values, though significant, is comparatively small, and we use the FAO's 30.2 MtN estimate in the remainder of this paper. Because our interest is in N fertilizer used for crop production, we draw from an estimate from Zhang et al. (2007) to scale down total N fertilizer consumption by the percentage used in agriculture (~90%), which gives a final N fertilizer use on cropland in 2005 of 27 MtN.

Using data and assumptions described in detail in the Appendix, we calculate embodied energy use per N applied for ammonia production (77 GJ tN^{-1}) and fertilizer synthesis (30 GJ tN^{-1}). Multiplying these values by total N fertilizer application (27 MtN), we estimate that N fertilizer application in China induced primary energy use of 2.9 EJ, or 4.4% of China's total primary energy use of 65.6 EJ in 2005 (NBS, 2009). Household energy use accounted for only 6.9 EJ (10%) of China's total energy use in 2005 (NBS, 2009), which implies that the energy embodied in fertilizer use is roughly 40% as large as total household energy use.

Table 28. GHG Emissions Estimates from N Fertilizer Use in 2005 (in $MtCO_2e$)

	N_2O Range	
	Default N_2O	**High N_2O**
Embodied Ammonia	180	180
Fertilizer Manufacture	70	70
N_2O Emissions	140	580
Total	**390**	**830**

See the Appendix for a more detailed description of assumptions behind these estimates.

Multiplying total N fertilizer application in agriculture (27 MtN) by our estimated GHG emission factor for applied N (15-31 $tCO_2e\ tN^{-1}$), we estimate that the application of N fertilizers in China led to emissions of 400-840 $MtCO_2e$ in 2005 (Table 28), equivalent to 8-16% of China's energy-related CO_2 emissions (5 101 $MtCO_2$, IEA [2007]) in that year. Although total GHG emissions and energy-related CO_2 emissions are not strictly comparable, China has not conducted a GHG emissions inventory since 2000 (1994 GHG emissions) and the IEA estimate provides a useful reference point. The significant range in our estimated GHG emission factor for applied N is driven by uncertainty in N_2O emission factors, emphasizing the need for further research to better understand direct and indirect N_2O emissions.

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[5] For instance, in a 15-15-15 NPK fertilizer N would constitute 44% of total nutrients. By contrast, Lu et al. (2008) assume that N is 30% of total NPK nutrients.

Reducing GHG Emissions from N Fertilizer Application in China

A number of unknowns make baseline demand for N fertilizers in China difficult to forecast. Population growth and continued changes in the composition of diets in China will induce higher demand for fertilizers, while changes in relative factor prices associated with rural socioeconomic restructuring (e.g., urbanization) will likely lead to changes in fertilizer use practices and potentially a decline in baseline fertilizer use. A detailed forecast of N fertilizer use in China is beyond the scope of this paper, and we use a more heuristic approach here. Growth in N fertilizer consumption (total N nutrients in pure N and compound fertilizers) in China has slowed dramatically since the 1980s, to around 2% yr^{-1} from 2000-2008 (NBS, 2009). Zhang et al. (2009) cite a Ministry of Agriculture forecast of 1.6% yr^{-1} growth in N fertilizer demand in China between 2010 and 2030, which is somewhat higher than FAO's (2000) forecast of 1% yr^{-1} growth in total fertilizer use in the East Asia region to 2015 and 0.8% yr^{-1} to 2030. At a conservative 1.5% yr^{-1} average growth over 2005-2020 China's demand for N fertilizer in agriculture would reach 34 MtN by 2020.

Based on He et al. (2007), Huang et al. (2008), Xu et al. (2009), and Wen (2010), we assume that achieving a 20-30% reduction in baseline N fertilizer use through improvements in use efficiency could be feasible over the next decade. A 20-30% reduction vis-à-vis a baseline of 34 MtN would lead to a decrease of 7-10 MtN in N fertilizer application in China by 2020 (50-80 kgN ha^{-1} based on China's cultivated land in 2005 [NBS, 2006]). As long as N fertilizer demand growth is below about 1.5% yr^{-1}, a 20-30% reduction in N fertilizer use levels would mean a decline in absolute levels of N fertilizer use over 2005 levels by 2020, requiring a major readjustment process for China's N fertilizer industry given that it was already overcapacity in early 2010.

At our estimated 2005 GHG emission factor for applied N (15-31 $tCO_2e\ tN^{-1}$), a 7-10 MtN reduction in N fertilizer use by 2020 would lead to GHG emission reductions of 100-310 $MtCO_2e\ yr^{-1}$. These reductions would be equivalent to a 2-7% reduction in the IEA's (2007; 2009) Reference Case estimate of the growth in China's energy-related CO_2 emissions from 2005-2020 (4,482 $MtCO_2$). As with end use efficiency more generally, reductions in demand do not lead to linear reductions in supply-side GHG emissions, and it is possible that surplus N fertilizer production resulting from offset demand in China would be exported abroad. A fuller treatment of this issue would require an analysis of global fertilizer markets and a more complete understanding of supply elasticities in China's ammonia and fertilizer industries. While an important consideration, such a treatment is beyond the scope of this paper.

Significant reductions in CO_2 intensity are possible in China's ammonia and fertilizer industries through equipment efficiency improvements, fuel switching, industry restructuring, and, more passively, reductions in the CO_2 intensity of electricity generation (Cao, 2008; Zhou, 2010). China's National Development and Reform Commission (NDRC) has set a target for energy use in large ammonia plants to fall from 1 210 ktce tNH_3^{-1} (35.5 GJ tNH_3^{-1}) in 2005 to 1 000 ktce tNH_3^{-1} (29.3 tNH_3^{-1}) in 2020, an improvement of 17% (NDRC, 2004). However, given its large number of less efficient, small- and medium-sized ammonia plants, average specific energy use in ammonia plants in China was 59.4 GJ tNH_3^{-1} in 2005 (see Appendix), and larger improvements in efficiency are likely possible. For example, reaching the International Fertilizer Association's (IFA's) estimated 2008 global average of 36.6 GJ tNH_3^{-1} (IFA, 2009) would require a 38% improvement in aggregate efficiency.

Energy use in fertilizer synthesis in China is also significantly higher than in OECD countries. Urea manufacturing in the U.S. and EU, for instance, require an estimated 2.5-2.8 GJ t^{-1} (USDOE, 2000; Worrell et al., 2000) and 3.2-4.6 GJ t^{-1} (Gerlagh and van Dril, 1999) of primary energy, respectively. For China we estimate that urea manufacturing requires, on average and across fuels, 12.2 GJ t^{-1} (see Appendix). Although structure of technologies in China's fertilizer industry is, to some extent, constrained by natural resources and history, comparisons with OECD countries suggest that major gains in efficiency are possible through either industry restructuring (e.g., forcing small plants out of business) or facility upgrades (e.g., retrofitting new technologies). Fertilizer is considered to be a "high energy consuming" industry in China, and the need to improve the energy efficiency of N fertilizer production is increasingly recognized.

Possibilities for fuel switching in ammonia and fertilizer manufacturing in China are less clear. A shift to natural gas as both a feedstock and energy source would reduce the energy and CO_2 intensity of N fertilizer production, but may not be compatible with China's natural resource endowment. China has relatively limited natural gas reserves (1% of the world's proven reserves in 2007) but has an abundant supply of coal (14% of total proven coal reserves) (BP, 2009). Whether scarce natural gas resources have a higher social and environmental value in ammonia and fertilizer production or in other uses is ultimately a question to be determined by policy. In its 2007 Natural Gas Use Policy, the NDRC listed ammonia production in its "restricted use" category (NDRC, 2007). Without fuel switching from coal to natural gas, with current technologies there are limits to efficiency improvements in ammonia and fertilizer manufacturing (Zhou et al., 2010).

As an anchor point, drawing on Cao et al. (2008) we assume that 25% improvements in aggregate energy efficiency, with no changes in the composition of fuel use, would be feasible in both ammonia and fertilizer manufacturing by 2020. Based on the IEA's (2007) Alternative Policy Scenario, we assume that a 25% reduction in the CO_2 intensity of electricity generation over 2005 levels would be feasible by 2020. With these improvements, the combined emission factor for ammonia and fertilizer CO_2 emissions embodied in N fertilizer use could be reduced from 9.3 tCO_2 tN^{-1} in 2005 to 6.5 tCO_2 tN^{-1} (i.e., by 30%) in 2020 (Table 29), a level more on par with that in OECD countries (Lal, 2004).

Table 29. 2005 Aggregate Energy and Emissions Intensities, Efficiency/Intensity Improvements, and Implied Energy and Emissions Intensities in 2000

	2005	%Efficiency Intensity Improvement	Implied 2020
Specific energy use in ammonia synthesis	59.4 GJ tNH_3^{-1}	25%	44.5 GJ tNH_3^{-1}
Specific energy use in fertilizer manufacture	29.5 GJ tN^{-1}	25%	22.1 GJ tN^{-1}
CO_2 intensity of net electricity consumption	1.04 $kgCO_2$ kWh^{-1}	25%	0.78 $kgCO_2$ kWh^{-1}
Total emission factor for embodied ammonia and fertilizer energy use	9.3 tCO_2 tN^{-1}	30%	6.5 tCO_2 tN^{-1}

See the Appendix for a more detailed description of assumptions behind these estimates.

In tandem, improvements in N fertilizer production (as detailed in Table 29) and use efficiency (i.e., a 20-30% reduction in N use) would lead to GHG emissions reductions of 180-380 $MtCO_2e$, vis-à-vis a baseline based on 1.5% yr^{-1} N fertilizer demand growth, by 2020 (Figure 46). This range of emission reductions is equivalent to 4-8% of the IEA's afore-mentioned forecast of energy-related CO_2 emissions growth in China between 2005 and 2020 (4,482 $MtCO_2$). At these levels, increases in the efficiency of N fertilizer production and use could be an important mitigation strategy in China.

Figure 46. Reductions in 2020 GHG Emissions with a 20-30% Reduction in N Fertilizer Use and Improvements in Fertilizer Production Efficiency (in $MtCO_2e$)

	Fertilizer Use Reduction		Production Efficiency		Total	
Reduction %	**20%**	**30%**	**20%**	**30%**	**20%**	**30%**
N_2O Low	100	150	80	70	180	220
N_2O High	210	310	80	70	290	380

See the Appendix for a more detailed description of assumptions behind these estimates.

Fertilizer Efficiency Program Cost and Financing

Much of the discussion on improving the efficiency of N fertilizer use in China has focused on the importance of removing fertilizer subsidies. While price and fiscal reforms are important, we argue that a program to improve N fertilizer use efficiency in China on a large scale would require non-trivial investments in agricultural extension and physical infrastructure (e.g., irrigation infrastructure). The cost implications of these two strategies are different. If reducing fertilizer use is as simple as removing subsidies and raising awareness, the direct costs of a large-scale fertilizer efficiency program could be small. If, however, such a program requires significant investment, then program design, costs, and financing become more important considerations.

We begin with an assumption that, given their constraints (e.g., labor endowment, amount and timing of water availability) and risk preferences, farmers are currently using optimal levels of N fertilizer. In other words, farmers have experimented with different levels of N fertilizer use and current levels of use provide the desired yield effects at an acceptable cost. In this case, the cost of reducing fertilizer would be the marginal value of applied fertilizer, which is equal to its unit cost per area.

Using estimates for cultivated land (130 Mha [NBS, 2005]) and N fertilizer used in agriculture (27 MtN), average N fertilizer use in China was 210 kgN ha^{-1} yr^{-1} in 2005. Reducing N fertilizer use by 20% would require a roughly 40 kgN ha^{-1} yr^{-1} decrease in average N use levels. Urea costs in China in 2009 were around 2 yuan kg^{-1}, or equivalently around 4 yuan kgN^{-1}. Assuming, for the sake of illustration, that per N urea costs are representative of N fertilizer costs, at 4 yuan kgN^{-1} the value of this reduction to farmers would be 160 yuan ha^{-1} yr^{-1}, or US$40 tCO_2e^{-1} using our default N_2O GHG emission factor (15 tCO_2e tN^{-1}). If the cost of a fertilizer efficiency program is the cost of replacing the value of N fertilizer use, total program costs would be around 20 billion yuan yr^{-1} (160 yuan ha^{-1} yr^{-1} multiplied by 130 Mha), or around US$3 billion yr^{-1}.

An alternative way of approaching this problem would be to assume that, while fertilizer use may be optimal given constraints and risk preferences, operating conditions are far from optimal. Investments to improve operating conditions, for instance through investments in agricultural extension services or physical infrastructure, could ease constraints, lower risk, and improve fertilizer use efficiencies. Fertilizer efficiency program costs, then, would be the cost of these investments rather than the value of fertilizer reductions.

GHG mitigation provides a useful framework for thinking about investment levels. At a cost of 68 yuan tCO_2^{-1} (US$10 tCO_2^{-1}), a fertilizer efficiency program that achieves 20% reductions in annual N fertilizer use from 2005-2020 would generate revenues (e.g., through an offset program) of about 40 yuan ha^{-1} yr^{-1}, or total revenues of around 80 billion yuan (US$12 billion) over 15 years. Allocated over China's 2 859 counties (NBS, 2008), 80 billion yuan (3-4 billion yuan yr^{-1}) would mean payments of about 30 million yuan (2 million yuan yr^{-1}) per county. If this level of investment would be sufficient to provide incentives for improvements in fertilizer use efficiency, total program costs would be much lower than the value of N fertilizer reductions and would save farmers up to 20 billion yuan yr^{-1} in fertilizer expenditures. Depending on the trade-offs between industry impacts and higher rural consumption, a fertilizer efficiency program could be net positive, with economy-wide benefits exceeding costs. Additionally, if US$10 tCO_2^{-1} is cost-effective relative to other GHG emission reduction options in China, a domestic offset program could provide the necessary funding.

The above discussion highlights four important points:

1) In designing a fertilizer efficiency program it is important to consider the marginal costs and benefits of current levels of N fertilizer use. We argue that simply removing subsidies and conducting a broad information campaign is unlikely to address root drivers of inefficiency in N fertilizer use.
2) Instead, and much like energy efficiency (Blumstein et al., 1980), it is more likely that there are a number of barriers to higher N fertilizer efficiency levels in China, and that public sector investments will be required to overcome these barriers.
3) Even without considering "external" costs (e.g., eutrophication, nitrate pollution, and climate change), the cost of a fertilizer efficiency program could be much smaller than the total net savings to farmers if well designed.
4) If the mitigation costs of N fertilizer reductions are lower than mitigation costs elsewhere in the economy (e.g., in steel production), a domestic GHG offset scheme could provide the funds needed for implementing a fertilizer efficiency program.

Conclusions

There is a growing body of evidence that suggests that the efficiency of N fertilizer use in China is low, and that through efficiency improvements the use of N fertilizer could be significantly reduced without affecting yields. Because N fertilizer use in China is a major source of embodied CO_2 and N_2O emissions, a large-scale program to improve N fertilizer efficiency could be an important part of a larger strategy to make the Chinese economy more resource and emissions efficient over the next decade.

This paper examines the potential for reducing GHG emissions through improvements in N fertilizer use efficiency. Using China-specific energy use estimates for ammonia and fertilizer synthesis and more generic approach for N_2O, we calculate an emission factor range of 15-31 $tCO_2e\ tN^{-1}$, with the significant range driven by uncertainty in N_2O emissions.

Using the 15-31 $tCO_2e\ tN^{-1}$ emission factor, we estimate that N fertilizer application on cropland led to GHG emissions of 390-890 $MtCO_2e$, equivalent to 8-16% of China's 2005 energy-related CO_2 emissions. Using assumptions about N fertilizer demand growth to 2020, we estimate that a 20-30% reduction vis-à-vis 2020 baseline N fertilizer demand growth would lead to GHG emission reductions of 100-310 $MtCO_2e$ in 2020, equivalent to 2-7% of the IEA's IEA's forecasted growth in energy-related CO_2 emissions in China between 2005 and 2020.

Due to China's natural resource endowment and for historical reasons, ammonia and fertilizer production are much more energy and CO_2 intensive in China than in OECD countries. If 20-30% reductions in N fertilizer use are combined with 25% energy efficiency improvements in ammonia and fertilizer production and a 25% decline in the CO_2 intensity of electricity generation, total GHG emission reductions would reach 180-380 $MtCO_2e$ by 2020, or 4-9% of the IEA's forecasted growth in energy-related CO_2 emissions in China between 2005 and 2020.

To a greater extent than in OECD countries, improving efficiency in N fertilizer production and use could be an important mitigation strategy in China.

A fertilizer efficiency program must address the root drivers of inefficient N fertilizer use in China. There are likely a number of barriers to higher use efficiencies for N fertilizers, and removing these barriers will require government policy intervention. Even if substantial investments from the public sector are required, the net economy-wide benefits of a fertilizer efficiency program (stimulus from savings to farmers minus direct and indirect program costs) may still be positive, even without including environmental externalities. Including one such externality — the cost of climate change mitigation — could provide an additional avenue for raising investment funds for a fertilizer efficiency program. If the costs of reducing N fertilizer use are lower than mitigation costs elsewhere in the economy, a domestic offset program could be an important source of program funding.

Appendix: Methods for Calculating Ammonia and Fertilizer Emission Factors

The production and use of synthetic N fertilizers generates:

- CO_2 emissions in the process of producing hydrogen for ammonia synthesis;
- CO_2 from the energy used to run ammonia plants;
- CO_2 from the energy used to produce nitrogen fertilizers from ammonia; and
- N_2O emissions from nitrification-dentrification.

This section describes calculations for GHG emissions from each of these sources. Although combustion to produce energy for ammonia production or final fertilizer production generates non-CO_2 trace gas and aerosol emissions, we assume these are small relative to CO_2 emissions. Also, as described in the main text, the GHG emission factor developed below does not include emissions from upstream (e.g., coal mining) or downstream (e.g., transport) activities.

Ammonia Synthesis

Ammonia is the source of the vast majority of nitrogen in N fertilizers. The hydrogen feedstock for ammonia is typically produced through catalytic steam reforming with natural gas (here idealized as CH_4) as a feedstock

$$\mathrm{CH_4 + H_2O \rightarrow CO + 3\ H_2}$$

Subsequently a gas shift reaction in high- and low-temperature shift converters converts the CO to CO_2 and produces more hydrogen

$$\mathrm{CO + H_2O \rightarrow CO_2 + H_2}$$

Ammonia (NH_3) is produced through the Haber-Bosch process, reacting the hydrogen produced from the above two reactions with nitrogen derived from air

$$3\ \mathrm{H_2} + \mathrm{N_2} \rightarrow 2\ \mathrm{NH_3}$$

The net reaction produced by the steam reforming and shift converter reactions

$$\mathrm{CH_4} + 2\ \mathrm{H_2O} \rightarrow \mathrm{CO_2} + 4\ \mathrm{H_2}$$

generates CO_2 emissions (1.0 gCO_2 gNH_3^{-1} for the above reactions), which is removed from the gas stream and can be used as a feedstock in urea production in joint ammonia-urea plants, sold for other industrial use, or released to the atmosphere. Even if used as a feedstock for other processes, the process CO_2 emissions from ammonia production are ultimately transferred to the atmosphere.

In China, and different than in most countries, anthracite coal is the main feedstock for the hydrogen used in ammonia synthesis, rather than natural gas. With an anthracite feedstock, coal gasification, rather than steam reforming, is used for hydrogen separation

$$\mathrm{Anthracite} + [\mathrm{Air}\ or\ (\mathrm{O_2} + \mathrm{H_2O})] \rightarrow \mathrm{CO} + \mathrm{H_2} + \mathrm{N} + \mathrm{S}$$

with the same shift and ammonia synthesis reactions as above.

Historically, a number of hydrogen feedstocks have been used in China, including anthracite, coke, natural gas, naptha, and residual fuel oil (Ma, 2000). With rising crude oil prices in the early 2000s, many ammonia plants that were using petroleum-based feedstocks converted to natural gas, and anthracite and natural gas are now the two primary feedstocks for hydrogen used in ammonia synthesis (Li, 2003).

In addition to feedstock (feed) energy, ammonia production requires energy for running the gasifier or reformer, for removing sulfur and carbon dioxide, and for ammonia conversion. China again is relatively unique in terms of the composition of energy inputs to ammonia plants. China's small- and medium-sized plants use atmospheric (i.e., air rather than oxygen and steam) gasification and electric reciprocating compressors rather than centrifugal compressors driven by steam turbines (Li, 2004). Thus, while electricity use in ammonia production is typically low in other countries, in China it constitutes a significant share of the "fuel" energy used by ammonia plants.

Energy use for ammonia production is typically reported as an aggregate, rather than being separated into feed and fuel energy. According to Yu (2009), specific energy consumption (SEC) in ammonia production (total energy use per unit ammonia output) in China was 1 662 ktce tNH_3^{-1} (48.7 GJ tNH_3^{-1}) in 2006. Yu (2009) reports that, for the 49.4 million tons of ammonia produced in 2006, anthracite, natural gas, and electricity use were 42.3 Mtce, 11.0 billion m^3 (BCM), and 64.7 TWh, respectively. However, these three sources only account for 1 304 ktce (78%) of the total 1 662 ktce tNH_3^{-1} estimate, and do not include either "fuel coal" (燃料煤)[6] use or petroleum-based feedstocks. The above estimates by Yu (2009), though cited elsewhere as "industry statistics" (Wen, 2010), do not have a source. The total SEC estimate for 2005 (1 700 ktce tNH_3^{-1}) reported in Yu (2009) is consistent with the SEC estimate that Cao et al. (2008) report is from the China Nitrogen Fertilizer Industry Association (中国氮肥工业协会).

We assume that the official estimate for the total specific energy of ammonia (1 662 ktce tNH_3^{-1}) is accurate, and that the omitted energy use is accounted for by petroleum-based feedstocks and fuel coal. Based on Li (2004), we assume that petroleum products account for roughly 10% of feed energy (7.5% of total energy use), and that fuel coal ("Other Coal" in Table 30) accounts for the residual.

Table 30. Energy Use and Specific Energy Consumption in Ammonia Production in China, 2006

	Physical Use	**Total Energy Use (PJ, % Total in paren)**	**Specific Energy (ktce tNH_3^{-1} / GJ tNH_3^{-1})**
Anthracite	42.3 Mtce	1 241 (52%)	857 / 25.1
Other Coal	11.6 Mtce	324 (13%)	224 / 6.56
Natural Gas	11.0 BCM	427 (18%)	295 / 8.65
Petroleum Products	6.2 Mtce	180 (8%)	125 / 3.65
Electricity	64.7 TWh	233 (10%)	161 / 4.72
TOTAL		**2 423**	**1 662 / 48.7**

Source and Notes: All figures are based on Yu (2009). One tce is equivalent to 29.31 GJ. We use lower heating values (LHVs) of 27.2 GJ t^{-1} for anthracite, 22.2 GJ t^{-1} for fuel coal, 0.039 GJ m^{-3} for natural gas, and 43 GJ t^{-1} for petroleum products. The LHV estimate for anthracite is based on a commonly used value of 6 500 kCal kg^{-1} for Shanxi anthracite. Fuel coal and natural gas LHVs are based on heating values used to convert mass and volume to coal equivalent units in the China Energy Statistical Yearbook. *The LHV estimate for petroleum products is a middle of the road value that reflects an unknown mix of residual fuel oil and naphtha.*

The total specific energy estimate in Table 30 is misleading because electricity is an energy carrier rather than a primary energy source. In general, comparisons between the total energy intensity of ammonia production in China and in other countries should be treated with caution because electricity conversion and line losses are typically not accounted for in Chinese statistics on ammonia energy use. At a total, mid-range 31% conversion efficiency (33% aggregate thermal efficiency, 7% line losses) for electricity, the above estimate for aggregate energy intensity would rise to 59.4 GJ tNH_3^{-1}. By way of comparison, the IFA (2009) estimates

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[6] Fuel coal here refers to the run-of-the-mine coal used to provide additional process steam. Fuel coal use can be particularly high in smaller ammonia plants.

that global average energy use in ammonia production was 36.6 GJ tNH_3^{-1} (1,073 ktce tNH_3^{-1}) in 2008.

Electricity conversion losses may explain discrepancies in published estimates of specific energy use for ammonia production in China. For instance, Price et al. (2000) report that energy use by small- and medium-sized ammonia plants can be 20-25% higher than in larger plants, but cite a Liu et al. (1994) report that estimates much higher energy use in small- (65.9 GJ tNH_3^{-1}) and medium- (63.9 GJ tNH_3^{-1}) than in large-sized (39.3 GJ tNH_3^{-1}) plants in 1990. The former estimate may be from an NDRC (2004) report that states that energy use in small- and medium-sized ammonia plants was around 300 ktce tNH_3^{-1} higher than an estimated 1 372 ktce tNH_3^{-1} in larger plants (i.e., 1 672 ktce tNH_3^{-1} or 49.0 GJ tNH_3^{-1}) in 2000. Interestingly, though, this NDRC rule of thumb estimate for energy use in small- and medium-sized ammonia plants is lower than the official estimate of average specific energy use in ammonia production in 2005 (1 700 ktce tNH_3^{-1}, or 49.8 GJ tNH_3^{-1}) (Yu, 2009).

Using the energy use estimates in Table 30, we calculate ammonia (t NH_3^{-1}) emission factors for each energy source using IPCC (2006) CO_2 default emission factors for anthracite, sub-bituminous coal (for “Other Coal,”) natural gas, an average of naptha and residual fuel oil for petroleum products, and a 2005 electricity grid emission factor (i.e., accounting for line losses and generator own use) for China from the NDRC (Table 31). The total CO_2 emission factor for ammonia is the sum of these individual emission factors

$$AEF = \sum_i AE_i \times EF_i \qquad 1)$$

where

- AEF is the total emission factor for ammonia (tCO_2 tNH_3^{-1})
- AE_i is the average use of energy source i per unit ammonia produced (GJ or kWh tNH_3^{-1})
- EF_i is an emission factor for energy source i

Table 31. Ammonia Energy and Weighted Emission Factors

	Unit Energy Use	**Emission Factor**	**NH_3 Emission Factor (tCO_2 tNH_3^{-1})**
Anthracite	25.1 GJ tNH_3^{-1}	98.3 $kgCO_2$ GJ^{-1}	2.47
Other Coal	6.56 GJ tNH_3^{-1}	96.1 $kgCO_2$ GJ^{-1}	0.63
Natural Gas	8.65 GJ tNH_3^{-1}	56.1 $kgCO_2$ GJ^{-1}	0.49
Petroleum Products	3.65 GJ tNH_3^{-1}	75.4 $kgCO_2$ GJ^{-1}	0.28

Electricity	1 310 kWh tNH_3^{-1}	1.04 $kgCO_2$ kWh^{-1}	1.36
Total			**5.22**

Sources and Notes: Electricity emission factor is based on the NDRC's Public Notice on Regional Baseline Grid Emission Factors for 2009 *[关于公布2009年中国区域电网基准线排放因子的公告], online at http://qhs.ndrc.gov.cn/qjfzjz/t20090703_289357.htm. The NDRC's national estimate (1.03 $kgCO_2$ kWh^{-1}) does not include line losses; SERC (2010) reports that line losses were 7.2% in 2005, which raises the national grid emission factor to (1.04 $kgCO_2$ kWh^{-1}).*

The two most commonly used N fertilizers in China historically have been ammonium bicarbonate (NH_4HCO_3) and urea ($(NH_2)_2CO$), with urea production overtaking ammonium bicarbonate production in 2005 (Zhang et al., 2007). CO_2 is used as a feedstock in the production of both of these fertilizers, requiring 0.56 gCO_2 g^{-1} NH_4HCO_3 and 0.73 gCO_2 g^{-1} $(NH_2)_2CO$, respectively. In the former case, reactions with alkaline earth metals can convert some of the bicarbonate (HCO_3^-) to calcium carbonate ($CaCO_3$), which is effectively a form of CO_2 sequestration (Lee and Li, 2003). For simplicity we ignore this possibility here, and assume that all CO_2 feedstock in synthetic N fertilizers is released to the atmosphere after application.

Nitrogen Fertilizer Production and Embodied Ammonia

Urea and ammonium bicarbonate (ABC) accounted for roughly 75% of total synthetic N fertilizer (by nutrient) production in China in 2005 (Zhang et al., 2007), and we use weighted shares of these two fertilizers to represent N fertilizer more broadly in China. By focusing on these two fertilizers we neglect the growing use of compound fertilizers (NPK, MAP, DAP) and other ammonium-based fertilizers (ACL, AP, AN) in China since 2003. From an energy and emissions perspective, this approach commits us to the assumption that the average CO_2 emissions intensity for residual fertilizers is the weighted average of the emissions intensity of urea and ABC. Given the lack of energy use data for lesser used fertilizers, we argue that the uncertainty introduced by this approach is lower than the uncertainty from using energy use estimates for the production of non-urea and non-ABC fertilizers that are not specific to China.

Urea [$(NH_2)_2CO$] is produced by reacting ammonia with carbon dioxide

$$2\,\mathrm{NH_3} + \mathrm{CO_2} \rightarrow (\mathrm{NH_2})_2\mathrm{CO} + \mathrm{H_2O}$$

and under idealized conditions requires 0.57 kg NH_3 $kg(NH_2)_2CO^{-1}$. Some ammonia is lost during urea synthesis, and, as implied in Lu et al. (2008), we assume that fertilizer synthesis is on average 96% efficient in ammonia conversion. Incorporating ammonia losses raises the urea ammonia requirement to 0.59 kg NH_3 $kg(NH_2)_2CO^{-1}$.

Ammonium bicarbonate (NH_4HCO_3) is produced by reacting ammonia with carbon dioxide and water

$$\mathrm{NH_3 + CO_2 + H_2O \rightarrow NH_4HCO_3}$$

and under idealized conditions requires 0.22 kg NH_3 kg$NH_4HCO_3^{-1}$. We assume that ABC production in also, on average, 96% efficient in ammonia conversion, which increases the ABC ammonia requirement from 0.215 to 0.224 kg NH_3 kg$NH_4HCO_3^{-1}$.

Both urea and ABC require process steam to reach sufficiently high temperatures and pressures for synthesis, and electricity to power equipment. In China, urea is produced primarily using coal and natural gas to provide process steam, with smaller amounts of petroleum product use. ABC is produced exclusively using coal for process steam. Both urea and ABC production consume electricity to run equipment.

Because the two fertilizers require different amounts of energy and ammonia inputs, we calculate separate fertilizer CO_2 emission factors for each, and then calculate a total average CO_2 emission factor based on the shares of urea-N and ABC-N production in 2005. Official data on energy use in urea and ABC production in China are not publicly available. CMA and CCC (2006) provide what appears to be the only published estimate of energy used in urea and ABC synthesis in China, and this estimate is used elsewhere in the literature (e.g., Lu et al., 2008). The CMA and CCC (2006) estimate includes the energy embodied in ammonia production and is not entirely consistent with reported energy use in ammonia production from Yu (2009) and Cao (2008), and we make adjustments to the CMA and CCC (2006) estimate to maintain consistency, assuming that the estimates for ammonia energy use in Yu (2009) are accurate.

To adjust the CMA and CCC (2006) estimate, we assume that the coal, natural gas, and oil use totals used in that estimate and cited more succinctly in Lu et al. (2008) are correct, and subtract the ammonia embodied fuels from Yu (2009) to arrive at average, production-weighted specific energy values for coal, natural gas, and oil use in urea and ABC synthesis. Because the fuel use estimates in Yu (2009) are reported at an aggregate level (i.e., not classified by facility fuel type) and are for 2006 (whereas the CMA and CCC [2006] estimates are from 2005), to subtract out ammonia embodied energy we multiply the specific energy values in Table 30 (kg or m^3 $tNH3^{-1}$) by the total implied ammonia in the CMA and CCC (2006) urea-N and ABC-N production estimates, subtract ammonia embodied fuel from the CMA and CCC (2006) total fuel use estimates, and use the residual to calculate specific energy consumption for urea and ABC synthesis.

A more general formalization of this approach is

$$FSF_{ij} = \frac{(TE_i - TAE_i) \times \alpha_{ij}}{Y_j \times \mu_j} \qquad 2)$$

where

- FSF_{ij} is the average consumption of fuel i needed to produce one unit of fertilizer j (t or m^3 t^{-1} fertilizer)
- TE_i is the total consumption of fuel i (embodied and direct) in the production of all fertilizers (t or m^3)
- TAE_i is the total consumption of fuel i embodied in ammonia (t or m^3)
- α_{ij} is fertilizer j's share of fuel i (%, as in urea production's share of the total coal used in producing fertilizer)
- Y_j is the total output of fertilizer j (tons fertilizer)
- μ_{ij} is the share of fuel i in producing fertilizer j (%, as in the percent of urea produced with coal)

and

$$TAE_i = \sum_j ASE_i \times \frac{FN_j \times \rho_j}{\omega_j} \qquad 3)$$

where

- TAE_i is the total consumption of fuel i embodied in ammonia (t or m^3)
- ASE_i is average consumption of fuel i needed to produce one unit of ammonia (t or m^3 tNH_3^{-1})
- FN_j is the total production of fertilizer j in nitrogen equivalent units (tN)
- ρ_j is the total NH_3 requirement, including NH_3 losses, for fertilizer j
- ω_j is the N content of fertilizer j (0.46 for urea, 0.17 for ABC)

CMA and CCC's (2006) estimate of the total electricity embodied in ammonia and used in urea and ABC synthesis is too low to be consistent with average electricity use in ammonia production reported by Yu (2009). Dividing the former's estimate of total electricity use (40.2 TWh) by the total implied urea and ABC ammonia requirement (36.9 $MtNH_3$) gives 1 089 kWh tNH_3^{-1}, which is significantly (16%) lower than the 1 310 kWh tNH_3^{-1} value implicit in Yu (2009). To correct for this discrepancy, we first assume that the 1 310 kWh tNH_3^{-1} value is accurate, and that shares of electricity use among different kinds of production facilities (urea coal, urea natural gas, urea oil, ABC coal) in CMA and CCC (2006) are accurate. These assumptions allow us to calculate the total electricity embodied in ammonia production for each kind of facility, which we then use to calculate electricity use in urea and ABC synthesis.

Smaller and larger urea facilities have different levels of electricity consumption and we use different assumptions when calculating their average electricity use per unit fertilizer. Based on CMA and CCC (2006), we assume that small- and medium-sized firms account for 40% of urea production from coal and natural gas (i.e., large firms account for 60% of production), and that the distinction in electricity use between large and small- and medium-sized firms is not important in oil-based urea production. We assume that the 60 kWh t^{-1} urea estimates for coal-, and gas-based urea production from CMA and CCC (2006) are accurate, but that this estimate applies to urea synthesis only and not to both ammonia and urea synthesis. Contrary to CMA and CCC(2006), who report total (embodied and direct) specific electricity consumption of 600 kWh t^{-1}urea for oil-based urea production, we assume that specific electricity consumption for urea synthesis for oil-based producers is also 60 kWh t^{-1}. These are conservative assumptions; net specific electricity consumption (before electricity exports) in urea synthesis in the U.S. for 1997 was 69.3 kWh t^{-1} urea (USDOE, 2000).

For both small- and medium-sized coal- and gas-based urea producers, we use the reported value from CMA and CCC (2006) and assume that urea synthesis requires, on average, 193 kWh t^{-1} urea. All ABC producers in China are small- and medium-sized. CMA and CCC (2006) report specific electricity consumption of 400 kWh t^{-1} for ABC manufacture, but do not separate direct and embodied ammonia consumption. To estimate specific electricity consumption for ABC synthesis, we assume that the urea (51%) and ABC (49%) shares of total (embodied and direct) electricity consumption in urea and ABC manufacture are the same for electricity used in urea and ABC synthesis as well. We then estimate specific electricity consumption in ABC synthesis as the total estimated electricity consumed in urea synthesis (from above), divided by urea's share of fertilizer electricity consumption (from CMA and CCC [2006]), divided by total ABC production (from CMA and CCC [2006])

$$ELCT_{ABC} = \frac{Y_{URE} \times \left(\sum_i \sum_s ELCT_{is,URE} \times \gamma_{is}\right)}{\varphi_{URE} \times Y_{ABC}} \qquad 4)$$

where

- $ELCT_{ABC}$ is specific electricity consumption in ABC synthesis (kWh t^{-1} ABC)
- Y_{URE} is the total production of urea (tons urea)
- $ELCT_{is,URE}$ is specific electricity consumption for fuel i based, facility size s production of urea (kWh t^{-1} urea)
- γ_{is} is the share of facility s in fuel i based urea production (%)
- φ_{URE} is urea's share of total fertilizer electricity consumption (%)
- Y_{ABC} is the total production of ABC (tons ABC)

The above assumptions lead to the fuel and electricity use estimates shown in Table 32, Table 33, and Table 34.

Table 32. Estimated Fuel Energy Use in Urea Manufacture

	Production Share (%)	Specific Energy (kg, m^3 t^{-1} urea)	Weighted Energy (GJ t^{-1} urea)
Coal	62%	509	7.0
Natural Gas	26%	280	2.8
Oil	12%	203	1.1
Total			**10.9**

Note: The LHV values used in this table are identical to those in Table 30.

Table 33. Estimated Electricity Use in Urea Manufacture

	Prod Share (%)	Size Share (%)		Electricity Use (kWh t^{-1} urea)		
		Large	**SM**	**Large**	**SM**	**Weighted**
Coal	62%	60%	40%	60	193	70.2
Natural Gas	26%	60%	40%	60	193	29.4
Oil	12%	100%		60		7.2
Total						**106.8**

Note: SM is small- and medium-sized firms.

Table 34. Estimated Fuel Energy and Electricity Use in Ammonium Bicarbonate Manufacture

	Specific Energy (kg, kWh t^{-1} ABC)	Energy (GJ t^{-1} ABC)
Coal	164	3.6
Electricity	244	

Note: The LHV values used in this table are identical to those in *Table 30.*

From the above tables and using a 0.31 conversion factor for electricity, total (fuel and electricity) estimated energy use in urea and ABC manufacture is 12.2 GJ t^{-1} urea (26.4 GJ tN^{-1}) and 6.5 GJ t^{-1} ABC (38.0 GJ tN^{-1}). Facility-level energy use data are needed to improve these estimates.

Using the above tables, we calculate a weighted average CO_2 emission factor ($tCO_2\ tN^{-1}$) for fertilizer synthesis

$$FSEF = \sum_j \sum_i \frac{(FSE_{ij} \times EF_i) \times \beta_j}{\omega_j} \qquad 5)$$

where

- FSEF is the fertilizer synthesis emission factor
- FSE_{ij} is the specific energy for energy source i used to produce fertilizer j (GJ or kWh t^{-1} fertilizer)
- EF_i is an emission factor for energy source i ($tCO_2\ GJ^{-1}$ or kWh^{-1})
- β_j is the share of fertilizer j in total N production (74% urea, 26% ABC)
- ω_j is the N content of fertilizer j (0.46 for urea, 0.17 for ABC)

Table 35. Fertilizer Synthesis Weighted Emission Factors

Fertilizer	Fertilizer Share of Production	Energy Source	Weighted Specific Energy (GJ or kWh t^{-1} fertilizer)	Weighted Emission Factor ($tCO_2\ tN^{-1}$)
Urea	74%	Coal	6.9	1.08
		Natural Gas	2.9	0.26
		Oil	1.1	0.13
		Electricity	107	0.18
ABC	26%	Coal	3.6	0.53
		Electricity	243	0.39
TOTAL				**2.57**

Given that our energy use estimates for ammonia are aggregate rather than fuel- and fertilizer-specific averages, we calculate an embodied ammonia emission factor as a weighted average across fertilizers

$$EAEF = AEF \left(\sum_j \frac{\beta_j \times \rho_j}{\omega_j} \right) \qquad 6)$$

where

- EAEF is an embodied emission factor for ammonia
- AEF is the total emission factor for ammonia ($tCO_2\ tNH_3^{-1}$)
- β_j is the share of fertilizer j in total N production (74% urea, 26% ABC)
- ρ_j is the total NH_3 requirement, including NH_3 losses, for fertilizer j
- ω_j is the N content of fertilizer j (0.46 for urea, 0.17 for ABC)

The total fertilizer emission factor ($tCO_2\ tN^{-1}$) is the sum of FSEF and EAEF. Final emission factors for embodied ammonia and fertilizer synthesis for China are shown in Table 36.

Table 36. Total Fertilizer Emission Factor

	Emission Factor (tCO_2 tN^{-1})
Embodied Ammonia	6.7
Fertilizer Synthesis	2.6
TOTAL	**9.3**

Nitrification-Denitrification

N_2O emissions from agricultural soils result from nitrification (aerobic oxidation of NH_4^+ to NO_2^- and NO_2^- to NO_3^-) and denitrification (anaerobic reduction of NO_3^-), and are highly dependent on local conditions. There is a significant body of research in China focused on measuring N_2O fluxes from cropland in coastal China, but isolating N_2O that results from mineral fertilizer use in these estimates is relatively difficult. Based on field-based estimates, Xing (1998), for instance, calculates that the total N_2O flux from cropland in China was 398 Gg N_2O-N in 1995, but this estimate presumably includes N_2O resulting from manure and biological fixation in addition to synthetic N additions. To overcome this ambiguity, we use IPCC (2006) N_2O emission factors as an initial reference point, which are specific to N inputs but have the disadvantage of being both relatively uncertain and not adapted to Chinese agro-ecosystems.

N_2O emissions from human-induced N soil additions occur through three pathways: A direct pathway (direct emissions from denitrification) and two indirect pathways (volatilization to NH_3 and NO_x and leaching and runoff, primarily as NO_3^-). Direct emission factors for N_2O per applied N are from IPCC (2006). Based on Xing's (1998) estimate of 398 Mt N_2O-N and reported value of synthetic N fertilizer use of 22.2 Mt for 1995, the total direct N_2O flux normalized by applied synthetic N fertilizer would be 0.02 kg N_2O-N (kg N)$^{-1}$, which, when organic fertilizer inputs and biological fixation are accounted for, is likely close to the IPCC (2006) default value.

Indirect emission factors per applied N are typically calculated by multiplying the fraction of N that volatilizes ($FRAC_{GASF}$ in IPCC nomenclature) or leaches/runs off ($FRAC_{LEACH-(H)}$) by an emission factor (e.g., kg N volatilized per kg N applied). For $FRAC_{GASF}$ we use IPCC (2006) estimates. Xing and Zhu (2000) estimate that 11% of applied synthetic N is volatilized as NH_3 in China, which, though omitting NO_x volatilization, is close to the IPCC default value. For $FRAC_{LEACH-(H)}$ we use the limited estimates from Xing and Zhu (2000) to create a range of 0-0.1, with a default value (in this case, a mean) of 0.05. For volatilization and leaching/runoff emission factors we use IPCC (2006) estimates EF_4 and EF_5. These inputs give a direct emission factor of 0.016 (0.003-0.079) $kgN_2O\ kg^{-1}$ (uncertainty range in parenthesis), an indirect emission factor of 0.002 (0.000-0.028) $kgN_2O\ kg^{-1}$, and a total range of 0.018 (0.003-0.106) $kgN_2O\ kg^{-1}$.

The low end of the IPCC uncertainty range for N_2O emission factors is close to zero, which on average over a large geographical area is not realistic. Based on atmospheric N balances, Crutzen et al. (2007) suggest an upper bound of 0.078 $kgN_20\text{-}N\ kgN^{-1}$ (4.6% N_2O-N of applied N), which is lower than our high estimate using primarily IPCC coefficients (6.8% N_2O-N of applied N). In Table 37, we use IPCC default emission factors (“Default”) and Crutzen et al.’s upper bound (“High”) to create an N_2O emission factor range. Weighting the values in this range by the N_2O GWP value (298) from Forster et al. (2007) gives a final, GWP-weighted emission factor for N_2O. Much of the range in this estimate is driven by uncertainties in indirect N_2O emissions, but both direct and indirect N_2O emissions factors both have a significant degree of uncertainty.

Table 37. Total N_2O Emission Factors

	Emission Factor ($kgN_2O\ kgN^{-1}$)	GWP-weighted Emission Factor ($kgCO_2e\ kgN^{-1}$)
Default	0.018	5.3
High	0.072	21.5

Adding emission factors from Table 37 and Table 36 gives the following total GHG emission factor estimates for N fertilizer (Table 38).

Table 38. Final CO_2e Emission Factors for Synthetic N Fertilizer Use (in $tCO_2e\ tN^{-1}$)

Default N_2O EF	High N_2O EF
15	31

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Chapter 7

Conclusions: 从扬汤止沸到釜底抽薪[1]

监管部门只当裁判员，不当运动员，也不当教练员 — 周小川
Regulators should only referee; they should neither play nor coach — Zhou Xiaochuan[2]

Global energy and climate in the 21st century hinge on China. The Chinese economy will drive world energy markets and the development and deployment of future energy technologies.[3] Climate stabilization, however defined, will require China's greenhouse gas (GHG) emissions to peak and then begin to decline sometime before, and likely much earlier than, 2050.[4] China's energy and emissions future, however, is highly uncertain and depends critically on a complex and extensive range of nearer-term policy decisions, many of which are only indirectly related to energy or GHG emissions.

Although most of the discourse on energy and climate policy in China has focused on energy technologies — carbon capture and storage, renewables, green buildings, electric vehicles — the chapters in this study paint a different picture, in which energy technologies are one factor among many, and indeed one that depends on other, factors that will influence China's energy and GHG emissions trajectories. Other factors described in the preceding chapters include: China's economic growth model (Chapter 2, 3); electricity planning, pricing, and operations (Chapter 4, 5); and energy pricing and agricultural extension (Chapter 6). All of these factors are outcomes of more fundamental political and institutional processes that are embedded in the political economy of China's multiple transitions, from a planned to a post-planned economy and from an agrarian to a post-industrial society. This "embeddedness" implies that the politics of institutional reform are the central determinant of China's energy and emissions future.

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[1] 从扬汤止沸到釜底抽薪 (cong yang tang zhi fei dao fu di chou xin) is a combination of two idioms that translates loosely to "from 'stirring the water to stop it from boiling' to 'stopping the fire by removing the wood.'"

[2] Zhou Xiaochuan is governor of the People's Bank of China, China's central bank.

[3] In its Reference Scenario, the IEA (2009) forecasts that China will account for more than 40% of the world's growth in demand for oil and nuclear power, and 65% of its demand for coal, from 2007 to 2030. Current plans would make China the largest market for wind, solar, and nuclear power over the next decade, and likely beyond. For instance, China's unofficial capacity targets for wind (150 GW) and solar (50 GW) for 2020 would require 105 GW of new wind and 49 GW of new solar, or roughly half of current global wind installed capacity (200 GW) and more than current global installed solar PV capacity (40 GW). Data are from BP (2011). For more on China's alternative energy targets see Kahrl et al. (2011). China's new 50 GW target for solar, a 30 GW increase over its previous target, was announced in early 2011.

[4] Multiple stabilization pathways and a range of emissions allocations among countries are possible to reach a climate stabilization target. In the IEA's (2009) 450 ppm stabilization scenario, for instance, China's energy-related CO_2 emissions peak in 2020.

Drawing on material from the chapters, this concluding chapter presents a broader case for how China's energy and GHG emissions trajectory is rooted in economic, social, and institutional transition, and why the political economy of institutional reform is such a central force in China's energy and climate policy. The final section assesses the prospects for institutional reform, and what these imply for international efforts to engage with China on energy and climate issues.

The Roots of China's Energy and GHG Emissions Trajectory in Transition

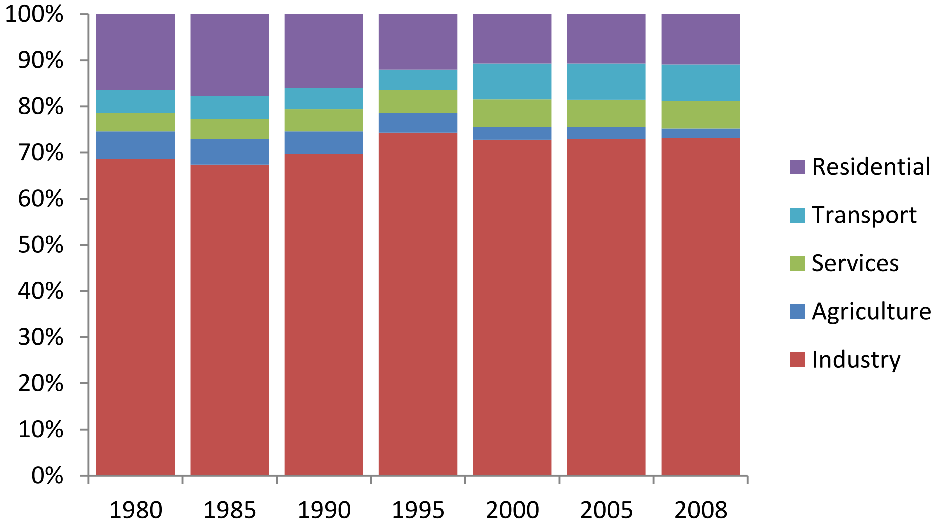
Economic growth, both its pace but more importantly its composition, will be the principal driver of China's energy demand and GHG emissions trajectory over the next two decades. Growth sets a baseline against which energy policies and GHG mitigation measures can reduce energy demand and GHG emissions. As the chapters describe, both the magnitude and composition of growth and the ability to implement energy policy and GHG mitigation measures in China are shaped by economic, social, and institutional transition.

Growth and Structural Change

Even as the size of its economy grew 19-fold over the last three decades (NBS, 2010), China's present energy economy retains a strong connection to its past. Industry, and particularly heavy industry, has continued to dominate energy use since the beginning of economic reforms in the early 1980s, with little change in the sectoral structure of energy use (Figure 47).

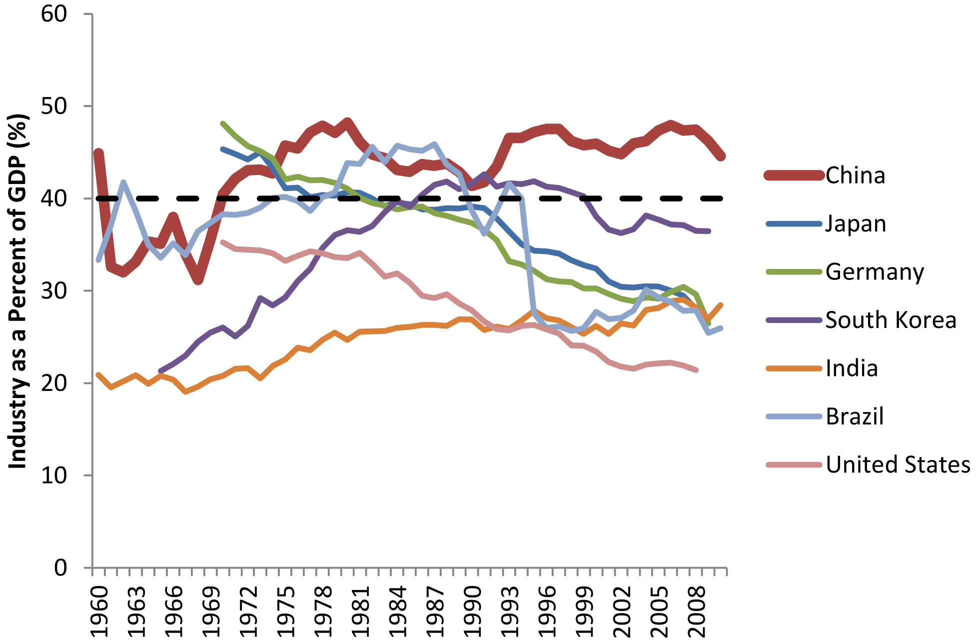
The economic companion of a high and sustained share of industry in energy consumption is a high and sustained share of industry in GDP. As Figure 48 shows, beginning in the early 1980s, gradual declines in the share of industry in China's GDP were reversed and brought back up to the levels of previous years during the economic downturns of the late 1980s and 1990s, so that the share of industry in GDP never fell below 40%. Such a sustained, high level of industrial value added in GDP is unusual. Though several countries have momentarily had levels of industrial value added that exceeded 40% of GDP, none has done so for nearly as long as China.

Figure 47. Industry, Agriculture, Services, Transport, and Residential Shares of Energy Use in China, 1980-2008



Notes and Sources: Transportation here includes residential transportation. Data for 1980 and 1985 are from CEG (2007). Data for 1990 to 2008 are from NBS (2010).

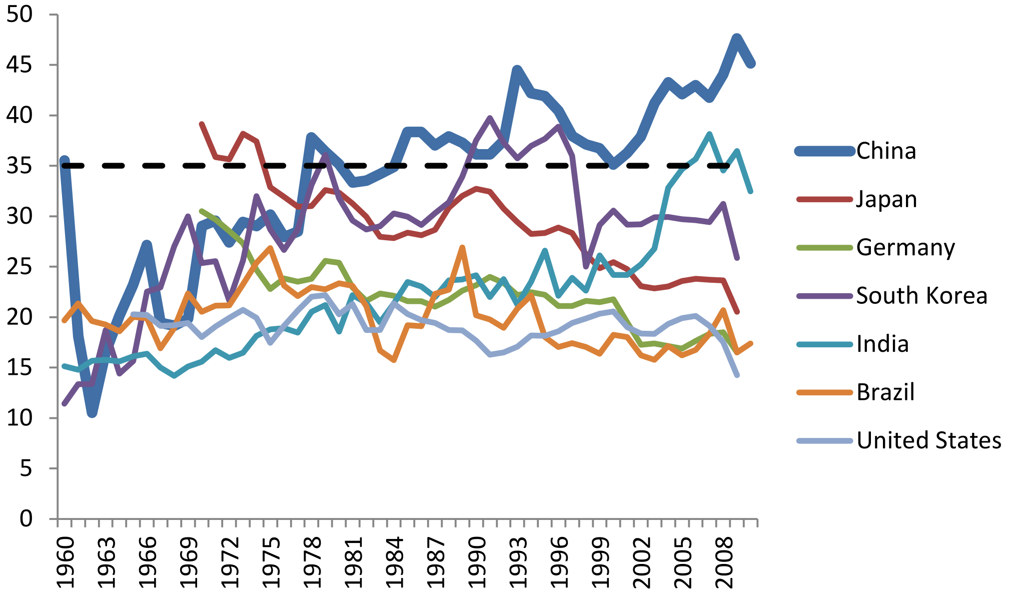
Figure 48. Industrial Value Added as a Share of GDP, China, Japan, Germany, South Korea, India, Brazil, and United States, 1960-2009



Source: Data are from World Bank (2011).

As Chapters 2 and 3 describe, energy use and the high share of industry in China were driven primarily by investment and exports. Investment has exceeded 35% of China's GDP since the early 1980s. Again, although several countries have reached this level of investment, none have sustained it for multiple decades (Figure 49). The share of trade (imports and exports) in the Chinese economy is, among open economies, not unique (Figure 50), nor is the share of net exports.[5]

Figure 49. Investment as a Share of GDP (Nominal), China, Japan, Germany, South Korea, India, Brazil, and United States, 1960-2009



Source: Data are from World Bank (2011).

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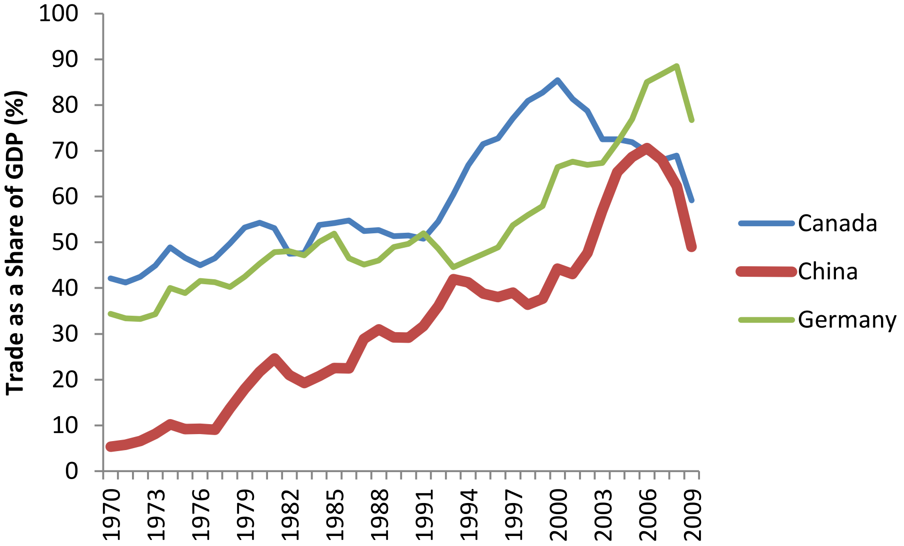
[5] From 1990 to 2009, Canada and Germany both had a higher share of net exports in GDP than China in all years except 2002-2004 and 2009. Data are from World Bank (2011).

Figure 50. Trade as a Share of GDP (Nominal), China, Canada, and Germany, 1960-2009



Source: Data are from World Bank (2011).

What is more unique about China's net exports is that they were driven, in part, by a large increase in net exports of metals, a sector in which China has no obvious comparative advantage.[6] The forces that drove net metal exports were the same forces that have driven high levels of investment and, by extension, GDP in China over its reform period (Chapter 3). Many of these forces were tied to distortions in the financial sector that kept the cost of capital low and concentrated investment in energy-intensive industries. However, as Huang and Wang (2010) argue, financial sector distortions in China are part of a larger problem of artificially low and administratively determined prices for factors of production — labor, capital, and land.

Energy, another factor, is also underpriced. As Chapter 6 illustrates, administratively set, subsidized energy prices have had a significant influence on the evolution of technology in different industries. In the nitrogen fertilizer industry, subsidized electricity and natural gas prices have left the industry without a dominant technology, with an energy and CO_2 intensity that are significantly higher than international levels, and have allowed the industry to continue "walking on two legs," where small-scale plants with less efficient technology operate alongside larger plants with more efficient technology.

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[6] Most importantly, the metals industries are all capital-intensive and, as noted in Chapter 1, China has a high opportunity cost of capital. China additionally does not have resource or technology advantages in metal production. In the steel sector, for instance, China is the world's largest importer of iron ore, accounting for two-thirds of world imports in 2009 (Jorgenson, 2011). For structural reasons, steel production in China is still more energy intensive than in OECD countries, such as the U.S. (Hasanbeigi et al., 2011). Resource and energy costs account for a substantial portion of the variable costs of steel production.

Although labor-intensive, export-led growth is in line with its factor endowments, China's investment-led domestic growth is driven by factor price distortions that have important parallels with the planned economy. In both the planned and transition economies, high levels of investment and industrial output were maintained through implicit taxes on households. In the transition economy, these taxes have become more subtle, such as administrative controls on interest rates, low dividend payments from state-owned enterprises to the state, and local government intervention in local bank lending decisions. As a result, China's current economic growth model, as it was in the planned economy, is geared toward high rates of output growth rather than high levels of employment or personal income.

As construction investment, in particular, is significantly more energy intensive on a lifecycle basis than household consumption (Chapter 2), rebalancing the Chinese economy toward lower GDP growth and a greater focus on income generation and higher levels of consumption could dramatically reduce China's energy demands over the coming decades (Chapter 3). Removing energy subsidies and rationalizing energy prices would increase energy and GHG emissions efficiency, both directly through technology adoption and conservation, and indirectly through outcomes as varied as optimized electricity dispatch (Chapter 5) and fertilizer use efficiency improvements (Chapters 6). A shift from administratively determined to more market-based interest rates and factor pricing is likely to be China's most important energy policy and GHG mitigation measure.

At the same time that it reduces industrial energy demand, rebalancing the Chinese economy toward consumption and removing barriers to urbanization would increase residential demand for energy, infrastructure, and higher input agricultural goods, though it is unclear by how much. As Chapter 2 describes, residential per capita demand for energy in China is currently considerably lower than in OECD countries. Per capita residential energy use in China will likely never reach OECD levels because of China's higher population density, but the large discrepancy between the two suggests that residential energy use in China has significant room to grow. More urban infrastructure will be needed to support growth in urban population, though how much is uncertain; there is no established link between urbanization and investment levels in China over the past three decades (Chapter 3). A larger urban population would also continue the trend toward more nitrogen-intensive, and thus energy- and GHG-intensive, diets (Chapter 6).

The deindustrialization of China's economy has other important consequences for energy use and GHG emissions. For the electricity sector, for example, higher growth in residential and commercial demand relative to industrial demand will make load shapes "peakier," requiring either coal-fired generating units to be run less efficiently, price reforms that support more load following and peaking generation with natural gas units, or cost-effective energy storage (Chapters 4 and 5).

From a macro perspective, China's future energy and GHG trajectory will be a balance between higher economic, energy, and emissions efficiency from more rational factor pricing on the one hand, and higher levels of energy consumption and more resource intensive diets that result from rebalancing the economy toward consumption on the other. Although most of the chapters focus on the energy dimension of this balance, Chapter 6 highlights the importance of agricultural systems, both in their links to urbanization and changing diets and as a source of GHG emissions (embodied CO_2, N_2O, and CH_4). Comparison with OECD countries, such as South Korea (Chapter 3), suggests that the efficiency gains from economic restructuring would outweigh the effects of higher consumption.

Energy Policy and GHG Mitigation

Perhaps in no other sector do China's energy policy and GHG mitigation measures depend more on the path of transition than in the electricity sector. Support for alternative electricity generation technologies exists at the highest levels of China's leadership, as evidenced by its support for the renewable energy industry and the massive targets China's central government agencies have laid out for wind and solar generation capacity. However, China's electricity system, which still retains much of the operational and institutional rigidity that defined it during the planned economy era, lacks the physical flexibility, pricing mechanisms, and planning capacity to integrate intermittent renewables on such a large scale (Chapter 4).

Rising electricity costs, both baseline costs and the higher cost of renewables, improve the economic basis for end use efficiency, but China does not currently have mechanisms in place to rationalize energy efficiency investment and tie it to the cost of supplying electricity. A recent rule that requires grid companies to obtain 0.3% of their kW and kWh sales from energy efficiency provides a foundation for scaling up energy efficiency investment, but because China's electricity sector has never been regulated under a cost-of-service framework there is no clear avoided cost basis on which to assess investments (Chapter 4).

A similar institutional challenge extends to electricity dispatch. Following the international model of deregulation, the Chinese government separated the monopoly State Power Corporation into generating companies and grid companies in 2002, but never reformed wholesale generation and transmission and distribution (T&D) prices to reflect organizational changes. As a result, reforming China's inefficient "equal shares" dispatch system is significantly more complicated than it would be with a vertically integrated utility, because the generation business is more fragmented and does not have a mechanism for price discovery. Proposed administrative fixes to revenue imbalances created by dispatch reform solve an immediate problem, but do not provide longer-term incentives for least cost investment, a downside that will become more acute as load shapes become steeper and the economic case for natural gas-fired load following and peaking generation becomes stronger (Chapter 5).

Outside of the electricity sector, improving the efficiency of nitrogen fertilizer use is a high potential GHG mitigation strategy in China because its nitrogen fertilizer industry, a prime example of a "two legs" industry, is significantly more energy and CO_2 intensive than international norms. Although a growing number of studies have demonstrated the potential to reduce nitrogen fertilizer use in China while increasing or maintaining yields, how to achieve fertilizer use efficiency improvements on a larger scale remains an open question. Removing or scaling back electricity and natural gas subsidies for fertilizer producers is an important strategy, as it would encourage a rationalization of energy use in the fertilizer industry. On the farm side, however, China does not currently have the physical infrastructure or agricultural extension necessary to support adjustment to higher and more volatile fertilizer prices, which makes government agencies hesitant to adjust energy subsidies.

The Political Economy of China's Energy and Climate Policy

The gradualist, "reform without losers" approach to reform explains the Chinese government's approach to energy and climate policy, which has thus far focused more on industrial policy and target setting, and less on actual implementation to achieve those targets. Actual implementation would force decision-makers, at some level, to make political decisions that reallocate resources between and among stakeholder groups. Chapters 2 through 6 describe the intersections between political economy and energy and climate policy in three main contexts — the macroeconomy, natural monopoly industries, and public services — summarized below.

Though China's investment-export driven growth model has not resulted in clear losers, some groups have clearly benefitted more than others (Chapters 2, 3). For instance, the lack of dividend obligations for state-owned companies is at the expense of the private sector, which is put at a competitive disadvantage, and households, for which this policy is an implicit income transfer. Interest rate controls have benefitted large state-owned companies through their access to cheap credit, but have also benefitted exporters, many of which are private firms, by facilitating an undervalued exchange rate. Interest rate controls are at the expense of savers, and particularly savers who do not borrow. In these instances and others, the largest beneficiaries of the factor price distortions that cause China's macroeconomic imbalances are state-owned companies, whereas the smallest beneficiaries are rural households.

In the electricity sector, an industry with natural monopoly characteristics, distributional issues exist primarily between generators and grid companies, between producers and ratepayers, and among ratepayers (Chapters 4, 5). With the existing electricity price system, for instance, most of the fuel cost risk is absorbed by generating companies, whereas in a more efficient pricing system more of this risk would be transferred to grid companies and ratepayers. The cost of integrating intermittent renewables is also currently borne by generators, in many cases by default, as cost allocation mechanisms have yet to be set up. Neither is there a mechanism for transparently allocating the costs of interregional transmission among provinces, which has led to high profile cases of wind overcapacity and waste of resources.

Until more recently, agriculture, one of the most unregulated and decentralized parts of the Chinese economy, received short shrift in both public spending and investment.[7] From an energy and climate policy perspective, particularly important is the underfunding of China's agricultural extension system (Chapter 6), a symptom of the larger withdrawal of the public sector from public service provision during the reform period (Chapter 1). The resulting pressure on public agencies to raise their own revenue has created perverse incentives. For instance, extension agents, who should be providing guidance to farmers on optimal fertilizer use, instead often sell fertilizer to farmers. As extension services have at least some public goods characteristics and should thus be funded at public expense, the root cause of underfunding of extension and other agricultural services lies in China's fiscal system, which does not adequately fund public goods and services.

Throughout China's reform process, government agencies have shied away from making explicit trade-offs, preferring instead to grow out of them. As a result, the development of legal and regulatory institutions to efficiently and fairly allocate costs and benefits relative to the kinds of distributional issues described above has not kept pace with the need for these institutions. However, in a range of priority energy and climate policies — rebalancing the economy, more efficient dispatch, increasing the share of renewables, energy efficiency, fertilizer use efficiency — the need to make politically acceptable trade-offs is becoming increasingly unavoidable.

Prospects for Institutional Reform, and Implications for International Climate Policy

It is facile, though common practice,[8] to argue that China must deal with the mounting challenges of rapid growth through building and strengthening its legal and regulatory institutions. Institutional reform in China is a monumental task, requiring either significant political will or a protracted process of incremental change. Indeed, the emergence of strong institutions would amount to no less than a redefining of the role of government and a rewriting of China's social contract, a process that required more than a century, and is still ongoing, in many OECD countries.

Legal and regulatory institutions, additionally, often function in highly contested economic spaces, where genuine institutional improvements are outcomes of political processes that pit private against public interest. This is particularly true for the institutions that govern interest

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[7] Agriculture accounted for a high of 13.4% of the national (central and local) budget in 1978, falling to a low of 7.1% in 2003 before recovering somewhat to 8.8% in 2009. Data are from the 2007 and 2010 China Statistical Yearbooks. Although data on public investment in agriculture are not available, increasing what was perceived to be disproportionately low levels of investment in agriculture was a priority of the Hu Jintao-Wen Jiabao administration.

[8] The most egregious example of this practice is by multilateral institutions, which often turn "China" into an actor with agency. For instance, in the OECD's 2005 report on governance in China, one finds statements like, "China improved the regulatory framework" (OECD, 2005). When discussing reform, in particular, this practice is not helpful because it masks the fact that reform is a process undertaken by specific organizations with overlapping, and sometimes conflicting, incentives and authorities.

rates and factor prices (e.g., energy prices, land prices, wages), which have direct relevance for China's energy demand and GHG emissions trajectories. The political economy of China's gradualist approach to transition, as described in the previous section, does not naturally favor the public interest.

The most obvious, but potentially the most difficult, area of institutional reforms is to actually empower independent regulatory bodies to oversee and manage the parts of the economy that they have been granted nominal authority over. For instance, the People's Bank of China, China's central bank, does not have control over monetary policy, which is the primary tool of central banks in most other countries. The State Electricity Regulatory Commission (SERC), the independent regulator for China's electricity sector, does not have authority over project approval or electricity prices, and its de facto authority over the two national grid companies that it has legal authority to regulate is ambiguous.

Beyond the need to empower regulatory agencies, there are a number of challenges to creating effective and efficient public interest regulators — "referees," to borrow from the quote at the beginning of this chapter — in China. The electricity sector is emblematic of many of these challenges. First, SERC has a mandate to protect investor, operator, ratepayer, and the public interest but has neither the authority nor the tools to do so.[9] The Price Department of the National Development and Reform Commission (NDRC), China's chief planning agency, has jurisdiction over ratemaking, and its decisions are driven by a mandate to maintain economic and social stability rather than welfare or efficiency considerations. In part as a result, costs and prices, particularly for grid companies, are only weakly linked in China's electricity sector (Chapter 4, 5).[10]

SERC is also a national regulator, in a sector that, particularly in China, physically operates primarily at a local (provincial) level. This mismatch reflects the reticence of China's central government to cede authority for an "economic lifeline" (经济命脉) industry to provincial governments, because China's central government and provincial governments have such different interests, incentives, and accountabilities. While this arrangement may help the central government achieve policy goals, national regulation of the day-to-day operations of a localized industry is unlikely to be efficient (Chapter 4).

Because the electricity sector was never regulated under a cost-of-service model, neither SERC nor the NDRC developed basic electricity sector planning and ratemaking tools that are used in other countries to transparently allocate benefits and costs across stakeholders. As a result, none of the administrative organizations with jurisdiction over China's electricity sector is

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[9] This mandate was made explicit in the State Council's Law on Electricity Regulation《电力监管条例》, which formally empowered SERC to regulate the electricity sector.

[10] The State Grid Corporation bought seven distribution businesses for nearly $1 billion in late 2010. John Duce, "China State Grid Completes Purchase of Brazil Electricity Assets," http://www.bloomberg.com/news/2010-12-22/china-state-grid-completes-purchase-of-brazil-electricity-assets.html. Since late 2007, the State Grid has, with a national partner, operated the Philippines' National Transmission Corporation (Transco).

equipped to handle incipient changes in demand, rising costs, and increased environmental requirements, let alone the challenges of decarbonizing the sector (Chapter 4).

In the electricity sector and in the economy more broadly, what are the prospects for institutional change? Given that organizations change institutions within their existing incentive structures (North, 1991), and that significant change in regulatory frameworks is unlikely when the costs and benefits of regulatory change are not equally shared (MacAvoy, 1974), there is no reason to think that major institutional change will occur in China in the near term. Line agencies have no obvious interest in conceding authority to independent regulators, for instance, and SOEs have no interest in being regulated. Only a champion among China's senior leadership would break this impasse.

Without institutional reform, however, there are limits on what China's energy and climate policy can achieve over the coming decades. This reality raises an important dilemma for OECD countries as they engage China on climate policy: Is the question of whether China develops stronger public interest institutions, from an international perspective, a descriptive or a normative one? If the former, then the current approach to engagement, emphasizing formal technology-focused partnerships and projects, and without strategically chosen partners, is a reasonable course of action. If the latter, the current approach must shift toward more politically active engagement, with strategically chosen partners and a greater emphasis on increasing the political space and strengthening the regulatory capacity of those partners.

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