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Estimating Total Energy Consumption and Emissions of China's Commercial and Office Buildings

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Abstract

Buildings represent an increasingly important component of China's total energy consumption mix. However, accurately assessing the total volume of energy consumed in buildings is difficult owing to deficiencies in China's statistical collection system and a lack of national surveys. Official statistics suggest that buildings account for about 19% of China's total energy consumption, while others estimate the proportion at 23%, rising to 30% over the next few years. In addition to operational energy, buildings embody the energy used in the mining, extraction, harvesting, processing, manufacturing and transport of building materials as well as the energy used in the construction and decommissioning of buildings. This embodied energy, along with a building's operational energy, constitutes the building's life-cycle energy and emissions footprint. This report first provides a review of international studies on commercial building life-cycle energy use from which data are derived to develop an assessment of Chinese commercial building life-cycle energy use, then examines in detail two cases for the development of office building operational energy consumption to 2020. Finally, the energy and emissions implications of the two cases are presented.

Table of Contents

1	Background	1
2	Methodology and Assumptions	3
2.1	Embodied energy estimates	4
2.1.1	Overview of Methodology	4
2.1.2	Manufacturing of Building Materials	5
2.1.3	Transport Embodied Energy	6
2.1.4	Construction Embodied Energy	6
2.1.5	Demolition Embodied Energy	6
2.1.6	Water Consumption-Related Energy Use	6
2.1.7	Emissions Calculations for Embodied Energy	7
2.1.8	Fuel Mix Calculations	7
2.1.9	Energy Input Emission Factors	8
2.1.10	Lifetime Total Emission Calculations	9
2.2	Operations Energy Modeling	10
2.2.1	Reference and Alternative Case Assumptions	11
3	Results	18
3.1	Embodied Energy and Emissions	18
3.2	Operations Energy and Emissions	23
3.2.1	Commercial Buildings Sector: All Buildings	23
3.2.2	Commercial Building Sector: Office Buildings	28
3.3	Summary	37
3.4	Further Research	38
4	Major References	38

List of Tables and Figures

Table 1 End-Use Structure of the Commercial Sector.....	10
Table 2 Commercial Building Floor Space, All Cases.....	13
Table 3 Office Buildings: Penetration of Energy Services, All Cases	15
Table 4 Office Buildings: Equipment Penetration for Cooling	15
Table 5 Office Buildings: Equipment Penetration for Heating	15
Table 6 Office Buildings: Equipment Penetration for Water Heating.....	16
Table 7 Office Buildings: Penetration of Lighting and Other Equipment by Efficiency Level	16
Table 8 Office Buildings: Space Cooling Efficiency	16
Table 9 Office Buildings: Space Heating Efficiency.....	16
Table 10 Office Buildings: Water Heating Efficiency	17
Table 11 Office Building Embodied CO2 and Pollutant Emissions.....	22
Table 12 Projected Primary Energy Savings between Reference and Alternative Cases.	34
Table 13 Projected CO2, SO2 and PM Emission Savings between Reference and Alternative Cases	37
Figure 1 Life Cycle Building Energy Use Chain.....	3
Figure 2 Distribution of Floor Space, All Cases.....	12
Figure 3 Commercial Building Floor Space, All Cases.....	13
Figure 4 Office Buildings: Intensity of Energy Services, All Cases	14
Figure 5 Commercial Sector Embodied Energy (Primary Energy)	18
Figure 6 Primary Energy Consumption by End-Use in Commercial Buildings, Reference Case.....	24
Figure 7 Primary Energy Consumption by Fuel in Commercial Buildings, Reference Case	24
Figure 8 Final Energy Consumption by Fuel in Commercial Buildings, Reference Case	25
Figure 9 CO2 Emissions from Commercial Buildings (Primary Energy, Reference Case)	26
Figure 10 Commercial Building SO2 Emissions, Reference Case.....	26
Figure 11 Commercial Buildings PM Emissions, Reference Case.....	27
Figure 12 CO2 Emissions by Sector (Primary Energy, Reference Case).....	28
Figure 13 Office Building Primary Energy Use by Application, Reference Case	29
Figure 14 Office Building Final Energy Use by Fuel (Reference Case)	30
Figure 15 Office Building Primary Energy Use by Fuel, Reference Case	30
Figure 16 Office Building CO2 Emissions (Reference Case, Primary Energy).....	31
Figure 17 Office Building SO2 Emissions (Reference Case).....	32
Figure 18 Office Buildings PM Emissions (Reference Case)	32
Figure 19 Primary Energy Savings by Fuel, Alternative Case, Trillion BTUs	33
Figure 20 Primary Energy Savings by Fuel, MTCE.....	34
Figure 21 Projected CO2 Emissions Savings between Reference and Alternative Cases	35
Figure 22 Projected SO2 Emissions Savings between Reference and Alternative Cases	36
Figure 23 Projected PM Emissions Savings between Reference and Alternative Cases .	36

Estimating Total Energy Consumption of China's Commercial and Office Buildings

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1 Background

Buildings represent an increasingly important component of China's total energy consumption mix. However, accurately assessing the total volume of energy consumed in buildings is difficult owing to deficiencies in China's statistical collection system and a lack of national surveys. Officially, residential and commercial building energy use accounts for 19% of China's total energy consumption¹. This measure, though, omits many commercial and residential buildings that belong to units that are categorized under the industrial, agricultural, construction and other sectors of the economy. Chinese academics estimate that the buildings sector actually accounts for 23% of total energy use and will exceed 30% by 2010 (Liang, 2007). Beyond data uncertainties, current figures on building energy consumption exclude the energy used in the mining, extraction, harvesting, processing, manufacturing and transport of building materials as well as the energy used in the construction and decommissioning of buildings. These activities all contribute to a building's "embodied" energy; an analysis of the relative contribution of each process to a building's total energy consumption can point to additional policies that can help reduce the building's carbon and other emissions footprints.

The aim of this study was to investigate the availability of data on the life-cycle energy consumption of Chinese buildings as well as data from building life-cycle assessments that have been performed in other countries. Because the investigation turned up few China-specific studies (excluding Hong Kong), international assessments served as proxies in estimating the life-cycle consumption of Chinese buildings. Utilizing this data, carbon and other pollutant emissions were calculated based on China-specific emissions factors. In addition, the study assembled an end-use accounting model of the Chinese office building sector and calculated two forecasts of operational energy till 2020 based on differing assumptions of technology penetration and efficiency.

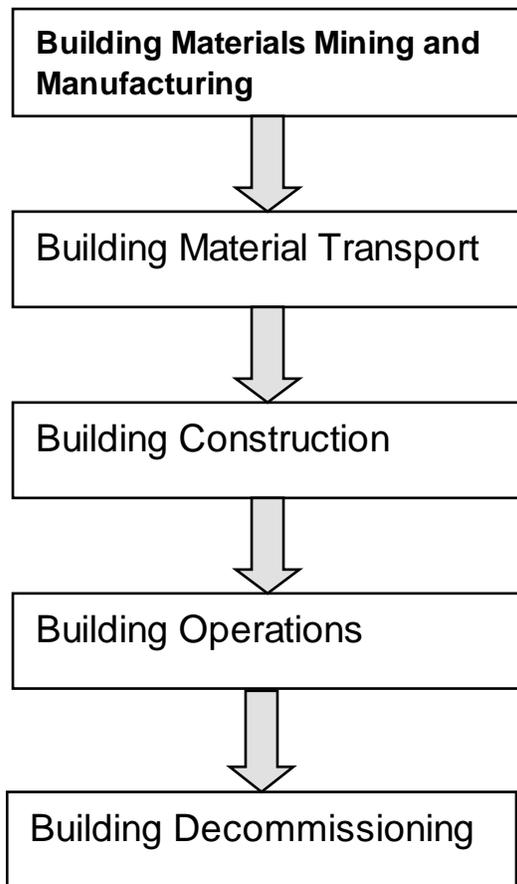
¹ *China Energy Statistical Yearbook 2006*. In China's statistical system, building energy use is subsumed in the energy consumption figures of the agriculture, industry, commerce, construction, transportation, residential and other (public) sectors. Assuming commerce, residential and other energy consumption is almost entirely buildings related, energy consumption in these subsectors equal 19% of the national total.

Section 2 of the report provides details on the methodology and calculations used to derive the China office-building life-cycle energy consumption estimate as well as details on the development of the end-use accounting model of the office building sector, and the assumptions used in developing the two operational energy forecasts to 2020. Section 3 presents the results of the life-cycle estimate and the energy and emissions consequences of China's office buildings operations to 2020.

2 Methodology and Assumptions

The purpose of this study is to assess the estimated energy use and emissions consequences of China's commercial buildings as a first step towards understanding the potential impact of policies aimed at reducing the emissions from this sector. In this effort, the scope of the study includes not only the energy consumption and emissions from building operations, but also the embodied energy and related emissions from the other phases of building construction and lifetime use, including the mining and manufacturing of a building's materials, the transport of material and personnel for building construction, construction of the building, and the decommissioning or demolition of the building at the end of its lifetime (Figure 1).

Figure 1 Life Cycle Building Energy Use Chain



In reviewing the body of available information about China's buildings, very little was found related to non-operations energy consumption. Basic data on material intensity, energy intensity of materials, building sector consumption of building materials, water consumption and many other variables are poorly characterized or unavailable altogether. As a result, it was necessary to rely on international studies to estimate such values for China. The most valuable sources were "Environmental impacts of building materials and building service components for commercial buildings in Hong Kong" (Chau 2007) and

“Analysis of embodied energy use in the residential building of Hong Kong,” (Chen 2001), which provided many of the details on materials intensity for different types of commercial buildings. Other studies provided supporting and sometimes contradictory material to the Hong Kong case, and these were referenced when the underlying assumptions and measurement boundaries were clear.

From the range of published materials, it was possible to assemble an initial estimate of the total energy use and carbon footprint of a Chinese office building. To improve the accuracy of the estimate, further research would be needed, including on-the-ground research in China in conjunction with qualified experts in the buildings and building materials sphere. Given China’s current interest in this area, it may be a promising topic for future US-China research cooperation.

2.1 EMBODIED ENERGY ESTIMATES

2.1.1 Overview of Methodology

To perform a life-cycle assessment (LCA) of the non-operational, embodied energy use of a commercial building in China, a preliminary comprehensive literature review of past and current LCA studies of commercial and office buildings was undertaken. The purpose of the literature review was to find data relevant and applicable to estimating the initial and end-use embodied energy use of a commercial building in China. As defined in many different life-cycle assessment studies of building energy and resource consumption, the initial embodied energy includes the one-time use of energy in the initial processes of erecting a commercial building. More specifically, this includes the initial energy used in manufacturing the main building materials, transporting the materials and workers to and from the construction site, and on-site installation of the building materials. In addition, an estimate is also included for the energy required for a commercial building’s end-use stage of demolition. Additionally, this study provides initial estimates of the energy consequences of water use in commercial buildings.

The studies reviewed include China-specific, U.S.-specific and other international studies of energy and resource consumption of different types of buildings. However, the literature search revealed a paucity of references and data on Chinese buildings and construction. In particular, the vast majority of reviewed studies focused on commercial buildings in the U.S., Canada, New Zealand, Europe and Japan. In contrast, there were only three papers on China and Hong Kong’s building sectors. The China-specific data used in this study is derived from these three papers, which include two studies of Hong Kong’s residential and commercial building sector respectively, and one on a China-based model for urban construction. Besides attempts to use regional data from Hong Kong to localize the LCA as much as possible, best available international data was also used as proxies for China’s commercial building industry. The specific sources and methodology for estimating Chinese commercial buildings’ total embodied energy use are detailed below.

2.1.2 Manufacturing of Building Materials

The first component of the initial embodied energy use of a building is the energy requirements for manufacturing building materials used in construction. While more comprehensive LCA studies include both raw material extraction and manufacturing in calculating the initial embodied energy, only the energy use directly in materials manufacturing is included in this study due to a lack of available and applicable data on extraction. To determine manufacturing energy use, both the material intensity of a typical commercial building (how many units of each material are used in construction) and each material type's manufacturing energy intensity (how much energy it takes to produce each unit of each material) are needed.

Since both the material and the manufacturing energy intensity of each type of building material are likely to vary significantly between countries, the data used for manufacturing energy use was primarily from China-specific sources. For the energy intensity of major building materials, values cited in the Chen, et. al. paper for Hong Kong's residential buildings were used. These values were within the range of energy intensities for common building materials used in previous studies, as compiled in the Cole & Kernan paper.

For material energy intensity, similarly, the important role of local factors on material used in constructing commercial buildings was estimated using Hong Kong data for five different types of commercial buildings. The data taken from the Chau, et. al. paper, however, was not calculated by the mass of material used per square meter. Rather, the paper focused on the environmental impacts of building materials as measured through single point impact values determined by human health, ecosystem quality, and resource depletion damages in the Eco-indicator 99 approach. In keeping with this approach, the paper provided data on the total life cycle impact values of major building materials for different building types as well as the single point impact values related to one kilogram of each type of building material. The relevant commercial building types include general commercial buildings, retail centers, hotels, and Class A office buildings. From these two sets of data—the single-point impact values and the life-cycle impact values—we were able to calculate the material intensity of each building material by the following formula: $\text{Material intensity} = (1/\text{single point impact}) * (\text{life-cycle impact point value})$, expressed as kg/m^2 .

From this, material intensity was calculated for the major building materials, including aggregate, virgin aluminum, plasterboard, reinforcing bar, and galvanized virgin and stainless steel, for each of the four applicable building types. Because the Chau, et. al. paper contained insufficient data for concrete and float glass, the material intensity of these two materials were taken from the Fernandez paper. These material intensities were then multiplied by their respective energy intensities to find the embodied energy in the manufacture of each type of material. As a result of different material intensities, the total manufacturing embodied energy range from 7.4 GJ per square meter for hotels to 10 GJ for retail centers, with 9.2 GJ for commercial buildings in general and 8.7 GJ for office buildings.

2.1.3 Transport Embodied Energy

Due to the lack of China-specific data on the transport of building materials and workers in existing studies, data from the Canadian construction industry was used as a proxy. The value of 50 MJ/ m² for transport energy from the Cole paper is used; this figure is based on the transport of building materials, equipment and workers for a round trip of 40 kilometers.

2.1.4 Construction Embodied Energy

Similar to the data concerning transport energy, Canadian data on embodied construction energy was used as a proxy for China's commercial buildings. As most buildings in China use a concrete structural frame, this study references the Cole paper's average value of the 20 to 120 MJ/m² range of construction energy for concrete structural buildings. The construction energy used for this study was 70 MJ/m² for all types of commercial buildings.

In this study, it is assumed that construction is a one-time event. No further embodied energy is added to the building during its 30 year lifetime through renovation or redecoration, although these often take place during a building's period of use.

2.1.5 Demolition Embodied Energy

As one of the more uncertain components of a building's embodied energy, the energy required for decommissioning a building depends on various factors such as the extent of material recycling and the method of disposing waste materials. As a rudimentary proxy for this study, the specific embodied energy use for demolition of 136 MJ/m² was taken from the Cole & Kernan paper. Although there are high uncertainties with this value, this value is applicable to this study because it is based on previous studies of initial and recurring embodied energy in office buildings.

2.1.6 Water Consumption-Related Energy Use

To calculate the embodied energy in providing water supply over a commercial building's lifetime, international data was used as proxies due to the lack of water energy data for China. An estimate of the water intensity was first found in a Japanese government study of the resource use of its central government buildings in which it said "water consumption per unit area was 1.1 m³/m², about 10% more than in a private sector office building."² Given that private sector office buildings consume 10% less water, we derived our proxy estimate of 1 m³ of water consumed per square meter per year of commercial building.

² Ministry of Land, Infrastructure , Transport and Tourism, 2006, "Results of Green Assessment of Central Government Buildings" http://www.mlit.go.jp/english/2006/p_g_b_department/07_green-office/01_results.html

Next, California data were used to estimate the total embodied energy intensity of water consumption. This specifically included the energy needed for the conveyance, treatment and distribution of water supply to the building for consumption and subsequent wastewater treatment and disposal. The three main studies consulted for this estimate include a Natural Resources Defense Council Report, a California Energy Commission (CEC) staff paper and a study by Navigant Consulting on behalf of the CEC. Using data from each study on the energy intensity of each process of preparing the water for consumption, a range of total energy intensity for water consumption was determined. This varied from a low end of 2700 kWh per million gallon of water to a high end of 5411 and 5485 kWh per million gallon of water supplied. Since two of the three studies had estimates in the 5400 kWh range, the energy intensity of 5400 kWh per million gallon of water was taken to be a proxy for China. This may overstate the energy use in China, a result of an insufficient understanding of the level of treatment of urban water.

To find the annual water-related energy consumption per square meter of a commercial building, the water and energy intensities were multiplied together, using the conversion factor of 264 gallons of water per cubic meter. Our water consumption embodied energy intensity was thus 1.43 kWh/ m² or 5.13 MJ/m².

2.1.7 Emissions Calculations for Embodied Energy

To find the CO₂, SO₂ and PM emissions resulting from a commercial building's embodied energy use, different approaches were taken for different processes due to fuel mix variations for each process. Since emissions vary greatly by fuel source, the first step was to calculate the composition of fuels for each process using Chinese national data.

2.1.8 Fuel Mix Calculations

For manufacturing, the different building materials were separated into the two main manufacturing processes depending on the type of the material. Based on the earlier building material assumptions, non-metallic mineral products included aggregate, concrete, float glass and plasterboard while ferrous/non-ferrous materials included reinforcing bar, the three types of steel and virgin aluminum. For each category, the individual materials' embodied manufacturing energy is then added together to find a total embodied energy for each manufacturing process in terms of MJ per m².

Next, the two fuel mixes for the different manufacturing processes of non-metallic and ferrous/non-ferrous materials were determined. For each manufacturing industry, the proportion of energy consumed from coal, coke, liquid fuels, natural gas, and electricity were determined using 2005 energy consumption by industrial subsector, data acquired from the 2006 China Energy Statistical Yearbook. This average composition percentage by fuel was then multiplied by the total embodied energy of the specific manufacturing process, and converted into mass of fuel using the energy content for Chinese fuels. This mass represents the amount of fuel used on average to manufacture the non-metallic and ferrous/non-ferrous building materials needed per square meter of floor area. The calculation for the proportion of electricity in the fuel mix involved an additional step of

converting electricity in kWh to kgce because the industry's total energy consumption was expressed in terms of coal equivalency.

2.1.8.1 TRANSPORT

Since transport primarily relies on the use of liquid fuels, it is assumed that all embodied energy of transport is derived from the use of petroleum fuels, specifically diesel.

2.1.8.2 CONSTRUCTION AND DECOMMISSION

Since the China Energy Statistical Yearbook does not have a separate industrial sector for demolition, it is assumed that the fuel mix for building decommissioning is the same as construction because both sectors likely use similar equipment. The fuel mix for both the construction and demolition processes was thus determined using the same methodology as the manufacturing processes.

2.1.8.3 WATER-RELATED ENERGY CONSUMPTION

For the embodied energy use for the building's water consumption, it was assumed that all energy requirements were in the form of electricity.

2.1.8.4 OPERATIONAL

To calculate operational energy consumption, two different analyses were performed using total primary energy demand and total final energy demand. For each analysis using data from the Long-Range Energy Alternatives Planning (LEAP) end-use accounting model, the total energy consumption by fuel type was divided by the total square footage of the building in the 2005 base year, and then multiplied by 30 years as the assumed lifetime of an average building in China in order to derive the total consumption of energy produced from that fuel source. Total operational energy is expressed in units of thousand BTU (kBTU).

2.1.9 Energy Input Emission Factors

2.1.9.1 ELECTRICITY EMISSION FACTORS

To find the emission factor per kWh of electricity, data on the total national thermal power output and total electricity output was taken from the 2006 China Energy Statistical Yearbook. For thermal power, the total national fuel inputs of coal, natural gas and petroleum were then each divided by the total national thermal power output to find the different fuel input per kWh of thermal power. Similarly, the total fuel inputs of coal, natural gas and petroleum were also divided by the total electricity output to find the weighted fuel input per kWh of total electricity. By doing this, we assume that the other two power sources, hydropower and nuclear power, had zero CO₂ emissions and thus only the fossil fuel inputs were responsible for CO₂ emissions. Because Chinese energy

statistics are expressed in weight or volume terms, each of the fuel types—cleaned coal, crude oil, diesel, and natural gas—used in thermal power generation was converted to a standard energy content (MJ) in order to apply the IPCC emissions factors, which are expressed on a per-MJ basis. These factors were taken from the 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual. The sum of the carbon emissions from coal, natural gas and petroleum inputs was then converted to the carbon emission factor in kg CO₂ emitted per kWh. Finally, this carbon emission factor was converted to units of kg per kBTU using the conversion factor of 3414 BTU per kWh.

For SO₂ and PM emission factors, data on the total SO₂ and PM emission released by the thermal power industry was collected from the China Environment Yearbook 2006. The total emissions divided by the total electricity output then yielded the SO₂ and PM emission factors in grams of pollutant per kWh, later converted to grams of pollutant per kBTU.

Current emissions factors for SO₂ and PM were kept frozen over the period used for the model calculations. CO₂ emissions per kWh, however, decline along with the expected improvement of the average heat rate of China's thermal power plant fleet over the model period.

2.1.9.2 PRIMARY FUEL EMISSION FACTORS

For the primary fuels of coal and liquid fuels, the 1996 IPCC Guidelines carbon emission factors were also used, with additional unit conversions into kg CO₂ emitted per kBTU of primary fuel. For the SO₂ and PM emission factors, a different methodology was used due to limited data. In particular, without a detailed breakdown of pollution data by fuel source within industries, the simplifying assumption that all SO₂ and PM emissions result from coal use was made. The national SO₂ and PM emissions, subtracting emissions from the thermal power industry that was already accounted for by electricity emission factors, can then be attributed directly to the balance (non-thermal power) consumption of coal. Due to the smaller magnitude of the emission factors, the final factors were expressed in units of grams of pollutants per kBTU.

2.1.10 Lifetime Total Emission Calculations

2.1.10.1 NON-OPERATIONAL TOTAL EMISSION CALCULATIONS

For each process, the embodied energy content of the different fuel inputs was multiplied by their respective carbon emission factors to calculate the total carbon emissions for that process. The carbon emissions from different fuel inputs to the process were then added together and converted to units of kg CO₂ emissions per square meter.

In contrast, because the emission factors for SO₂ and PM were in units of kg emission per kg fuel input, the total SO₂ and PM emissions for each process were calculated using the mass of each type of fuel input. Because it is assumed that these two pollutants only result from the use of coal, there are no calculations of emissions of these pollutants from processes that do not use coal, such as transportation.

2.1.10.2 OPERATIONAL ENERGY EMISSIONS

For recurring energy use associated with a building’s water consumption over its lifetime, all three types of emissions were calculated using a water-related electricity consumption per square meter figure multiplied by the previously determined emission factors for electricity. The three emissions were each multiplied by 30 years to calculate the total emissions from water consumption energy use over a building’s lifetime.

For all other operational energy use, the total emissions were calculated by multiplying the lifetime energy consumption of each fuel source in kBTU by that fuel source’s CO₂, SO₂ and PM emission factors. The CO₂, SO₂ and PM emissions from each individual fuel source were then summed together for the total operational CO₂, SO₂ and PM emissions.

2.2 OPERATIONS ENERGY MODELING

To calculate office building operations energy use to 2020 and to test an alternative scenario of technology deployment within this sector, a model encompassing the major energy end-uses in commercial buildings was developed using the Long-Range Energy Alternatives Planning (LEAP) model. In this model, the commercial building sector is composed of the major subsectors of office, retail, hotel, school, hospital, and other buildings. The key energy end uses by the subsectors include space heating, space conditioning, water heating, lighting, and other uses. The end-uses were further broken down by technologies, as shown in Table 1.

Table 1 End-Use Structure of the Commercial Sector

End use	Space heating	Space cooling	Lighting and other appliances	water heating
Technologies	Electric heater Gas boiler Coal Boiler Small cogen Stove District heating Heat pump	Central AC Room AC Geothermal Heat Pump Central AC by NG	Existing Efficient	Electric water heater Gas boiler Coal Boiler Small cogen Oil boiler

For each end-use there is an associated level of intensity in terms of energy/m² of delivered useful energy. In addition, the penetration rate of each end-use is described over the total floor space of the commercial building sector, in terms of the percent of floor space supplied with each end-use. For example, for services such as lighting, it is assumed 100% of the floor space is covered; for space heating, the percentage reflects the fact that space heating is not universal outside of the northern heating zone.

Each technology associated with each end-use listed in Table 1 has a related efficiency level, and each commands a certain percent of the installed base (i.e. penetration rate) for each end-use set of technologies. The year 2005 was chosen as the baseline year.

The interaction of these variables can be summed up in the following equation:

$$E_{CB} = \sum_k^{OPTION} \sum_n^{OPTION} \sum_q^{OPTION} \left[A_{CB,n} \times P_{q,n} \times \left(\sum_k Intensity_{q,n} \times Share_{k,q} / Efficiency_{k,q} \right) \right]$$

where, in addition to the variables listed above:

- k = fuel type (technology type)
- q = type of end use
- $A_{CB,n}$ = total commercial floor area in commercial building type n in m^2
- $P_{q,n}$ = penetration rate of end use q in building type n
- $Intensity_{q,n}$ = intensity of end use q in building type n
- $Share_{k,q}$ = type of technology k for end use type q
- $Efficiency_{k,q}$ = efficiency of technology k for end use type q

2.2.1 Reference and Alternative Case Assumptions

This study looks at the energy and emissions impacts of two scenarios of China's office sector development to 2020: the reference case and an alternative case. The reference case is based on the "best available" combination of assumptions about the rate of growth, rate of technology penetration and rate of intensity change, primarily based on Chinese surveys of the current state of technology in commercial buildings and published estimates of development trends and targets (RNECSPC 2005, Zhou 2003). Where China-specific forecasts were not available, reference was made to parameter values in other countries such as Japan or the UK, depending on climatic characteristics, development level measurements, or cultural similarities. For each technology, efficiency improvements over the period to 2020 are assumed.

The alternative case focuses on the role of technology in improving office building performance. In both the reference and alternative cases, the growth of floor space is assumed to be the same, and the trends in delivered energy (energy intensity) are assumed to be identical as well. For each technology, however, the alternative case describes the impact, for example, of a more stringent equipment standards program that accelerates efficiency improvements, such as increasing boiler efficiency from 68% average efficiency in 2020 (as expected in the reference case) to 76%, up from 59% today, or room air conditioners increasing from an average 2.65 COP in 2020 to 2.76, up from 2.57 in the 2005 base year. At the same time, the technology mix is altered in the alternative case. Either achieved through stricter building codes or through incentive programs, the alternative case looks at the impact of a more rapid adoption of more efficient technology choices, such as increasing the penetration of geothermal heat pumps from 6% in 2020 to 11%. Although the model does not include costs, the range of the

variation between the reference and alternative cases is technologically feasible, though constraints (such as limited natural gas supply) could ultimately limit the penetration rate of certain technologies such as natural gas central air conditioning.

The specific assumptions in the model are illustrated in the figures and tables below.

Office building floor space is assumed to grow by over 70% by 2020, to 6.06 billion m², yet falls as a proportion of total commercial building floor space because faster growth is expected in both the retail and school subsectors (Figure 2, Table 2, Figure 3).

Figure 2 Distribution of Floor Space, All Cases

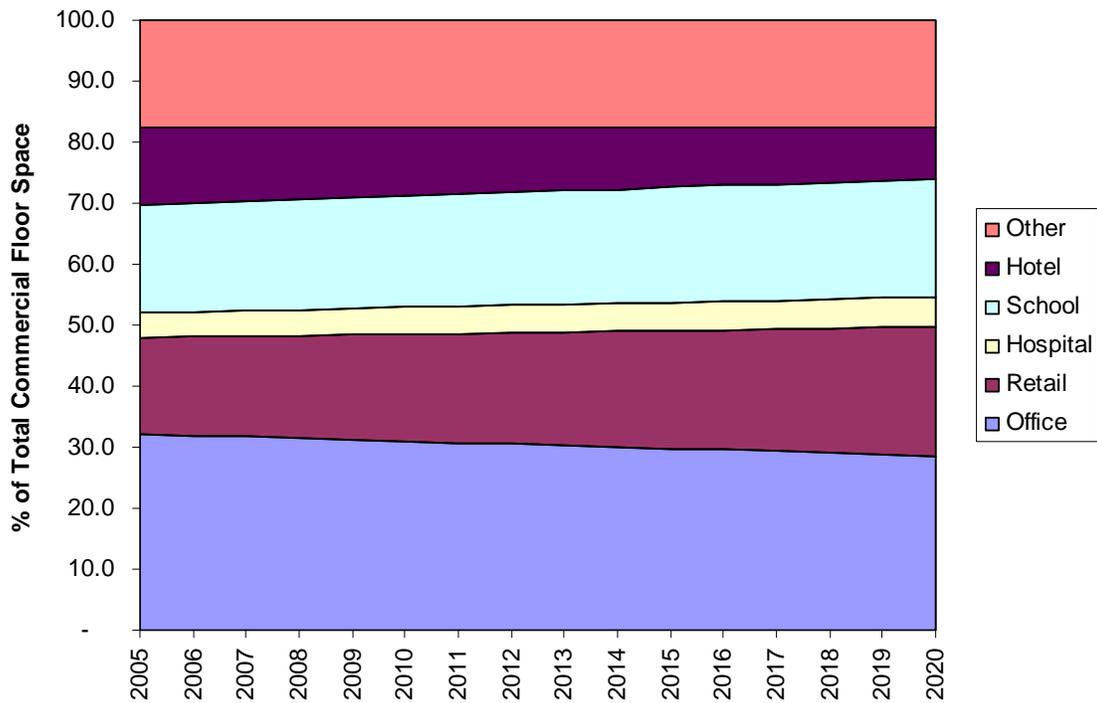
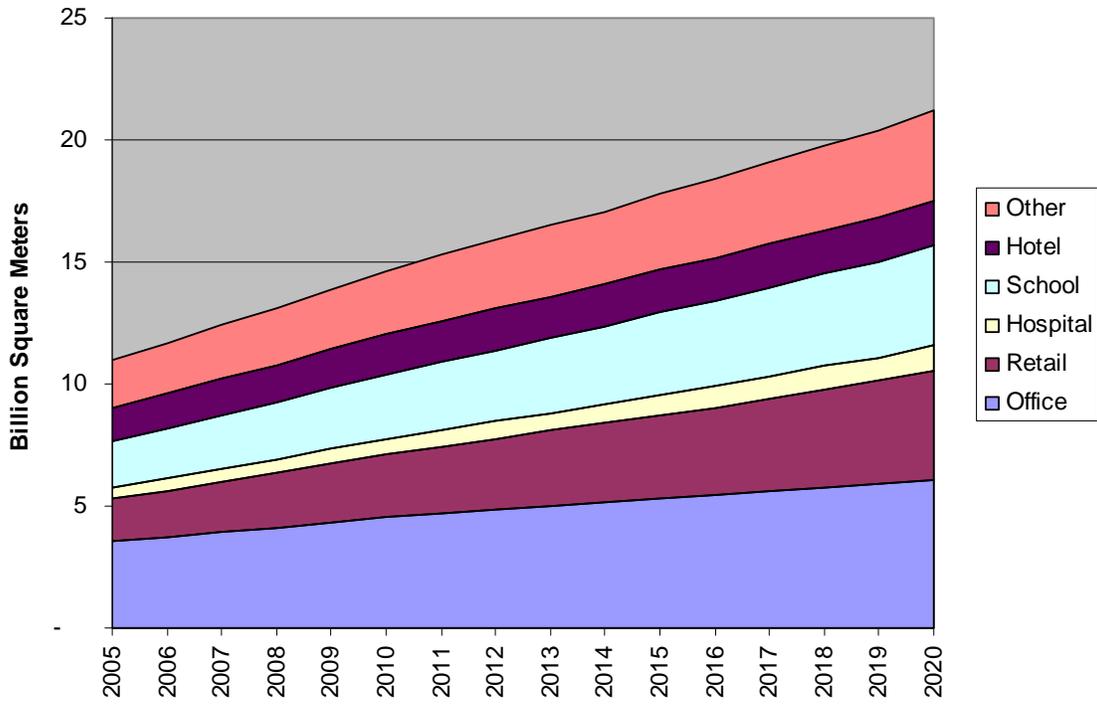


Table 2 Commercial Building Floor Space, All Cases

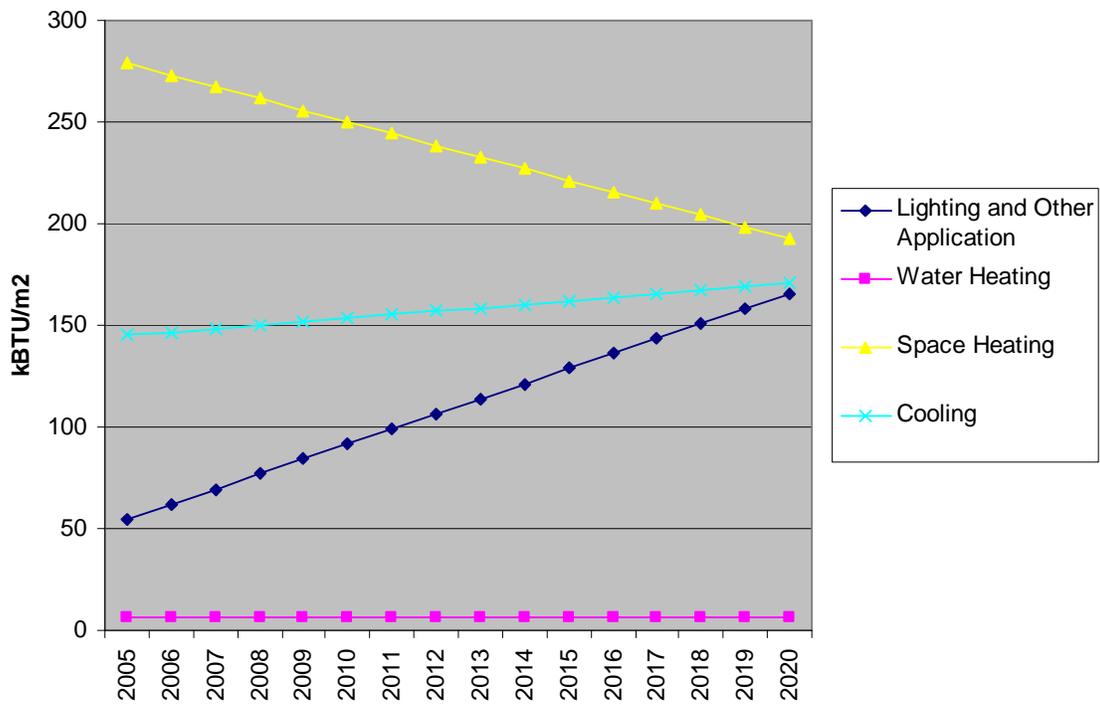
<i>Billion square meters</i>	2005	2010	2015	2020
Office	3.53	4.53	5.30	6.06
Retail	1.74	2.57	3.44	4.45
Hospital	0.45	0.63	0.82	1.04
School	1.94	2.66	3.36	4.13
Hotel	1.40	1.65	1.74	1.78
Other	1.95	2.57	3.13	3.73
Total	11.00	14.60	17.80	21.20

Figure 3 Commercial Building Floor Space, All Cases



In the office building subsector, end-use intensity is expected to decrease for space heating, cooling, and lighting and other applications. Currently, heating intensity in Chinese commercial buildings tends to be fairly high because of inefficient practices in heat delivery (district heating), heat management (poor controls), historic low heat pricing and poor building performance. As a result, Chinese experts expect heating intensity to decline as these factors are ameliorated, and this trend is reflected in Figure 4. On the contrary, cooling intensity is expected to rise, as air conditioning use becomes more prevalent and the expected level of comfort increases. For lighting and other applications, such as office equipment and miscellaneous building equipment, intensity is expected to increase with increased lighting levels and increased density of office and other equipment.

Figure 4 Office Buildings: Intensity of Energy Services, All Cases



Finally, it is assumed that 100% of office floor space is covered by lighting and other applications and with water heating. Space heating, however, will increase from 40% of floor space to 55%, while cooling will jump from 29% of floor space to 55% (Table 3).

Table 3 Office Buildings: Penetration of Energy Services, All Cases

(% of Floorspace)

	2005	2010	2015	2020
Lighting and Other Application	100	100	100	100
Water Heating	100	100	100	100
Space Heating	40	45	50	55
Cooling	29	38	46	55

Tables 4-10 detail the assumptions of technology change for each end use between the reference and alternative cases. In the alternative case, space cooling sees a shift from traditional central and room AC to geothermal heat pumps and natural gas central AC, while heating assumes a strong shift to natural gas boilers and the final retirement of coal boilers by 2020. Similarly, water heating is increasingly natural-gas based, and the use of oil (LPG, propane) for water heating is phased out.

Table 4 Office Buildings: Equipment Penetration for Cooling

(% Total Installed Capacity)

	Reference Case				Alternative Case			
	2005	2010	2015	2020	2005	2010	2015	2020
Centralized AC	62	59	59	58	60	55	53	50
Room AC	33	34	31	28	32	32	28	24
Geothermal Heat Pump	2	3	5	6	3	5	8	11
Centralized AC by NG	4	4	6	8	6	8	12	15
Total	100	100	100	100	100	100	100	100

Table 5 Office Buildings: Equipment Penetration for Heating

(% Total Installed Capacity)

	Reference Case				Alternative Case			
	2005	2010	2015	2020	2005	2010	2015	2020
District Heating	28	27	27	26	25	22	22	22
Boiler	47	35	22	8	47	35	18	0
Gas Boiler	11	20	30	40	14	25	38	50
Small Cogen	11	12	13	14	11	12	14	15
Electric Heater	1	2	3	4	0	0	0	0
Heat Pump	2	4	6	8	3	6	10	13
Total	100	100	100	100	100	100	100	100

Table 6 Office Buildings: Equipment Penetration for Water Heating*(% Total Installed Capacity)*

	Reference Case				Alternative Case			
	2005	2010	2015	2020	2005	2010	2015	2020
Boiler	62	51	46	40	62	51	38	25
Gas Boiler	11	20	23	27	14	25	38	50
Small Cogen	11	12	13	14	11	12	14	15
Electric Water Heater	1	2	3	4	3	5	8	10
Oil	15	15	15	15	11	8	4	0
Total	100	100	100	100	100	100	100	100

Table 7 Office Buildings: Penetration of Lighting and Other Equipment by Efficiency Level*(% Total Installed Capacity)*

	Reference Case				Alternative Case			
	2005	2010	2015	2020	2005	2010	2015	2020
Existing	26	22	18	14	23	15	13	10
Efficient	74	78	82	87	77	85	88	90
Total	100	100	100	100	100	100	100	100

Table 8 Office Buildings: Space Cooling Efficiency*(COP)*

	Reference Case				Alternative Case			
	2005	2010	2015	2020	2005	2010	2015	2020
Centralized AC	185	191	196	200	191	202	212	222
Room AC	257	263	264	265	259	268	272	276
Geothermal Heat Pump	308	315	317	318	311	321	326	331
Centralized AC by NG	123	126	127	127	124	128	130	132

Table 9 Office Buildings: Space Heating Efficiency*(%)*

	Reference Case				Alternative Case			
	2005	2010	2015	2020	2005	2010	2015	2020
District Heating	70	75	78	81	70	75	82	89
Boiler	59	63	66	68	59	63	70	76
Gas Boiler	76	81	84	87	76	81	87	92
Small Cogen	65	69	72	75	65	69	76	83
Electric Heater	92	94	96	98	92	94	96	98
Heat Pump*	224	269	313	357	233	287	340	393

*COP

Table 10 Office Buildings: Water Heating Efficiency*(%)*

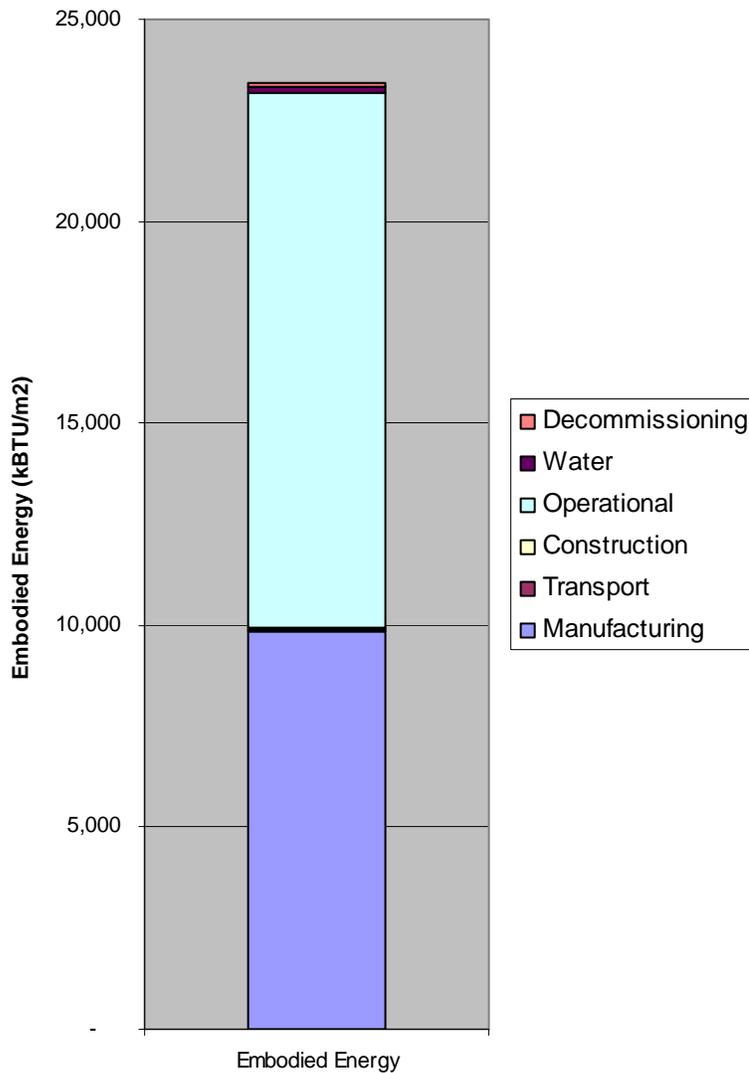
	Reference Case				Alternative Case			
	2005	2010	2015	2020	2005	2010	2015	2020
Boiler	59	63	66	68	59	63	70	76
Gas Boiler	76	81	84	87	76	81	87	92
Small Cogen	65	69	72	75	65	69	76	83
Electric Water Heater	92	94	96	98	92	94	96	98
Oil	76	81	84	87	76	81	84	87

3 Results

3.1 EMBODIED ENERGY AND EMISSIONS

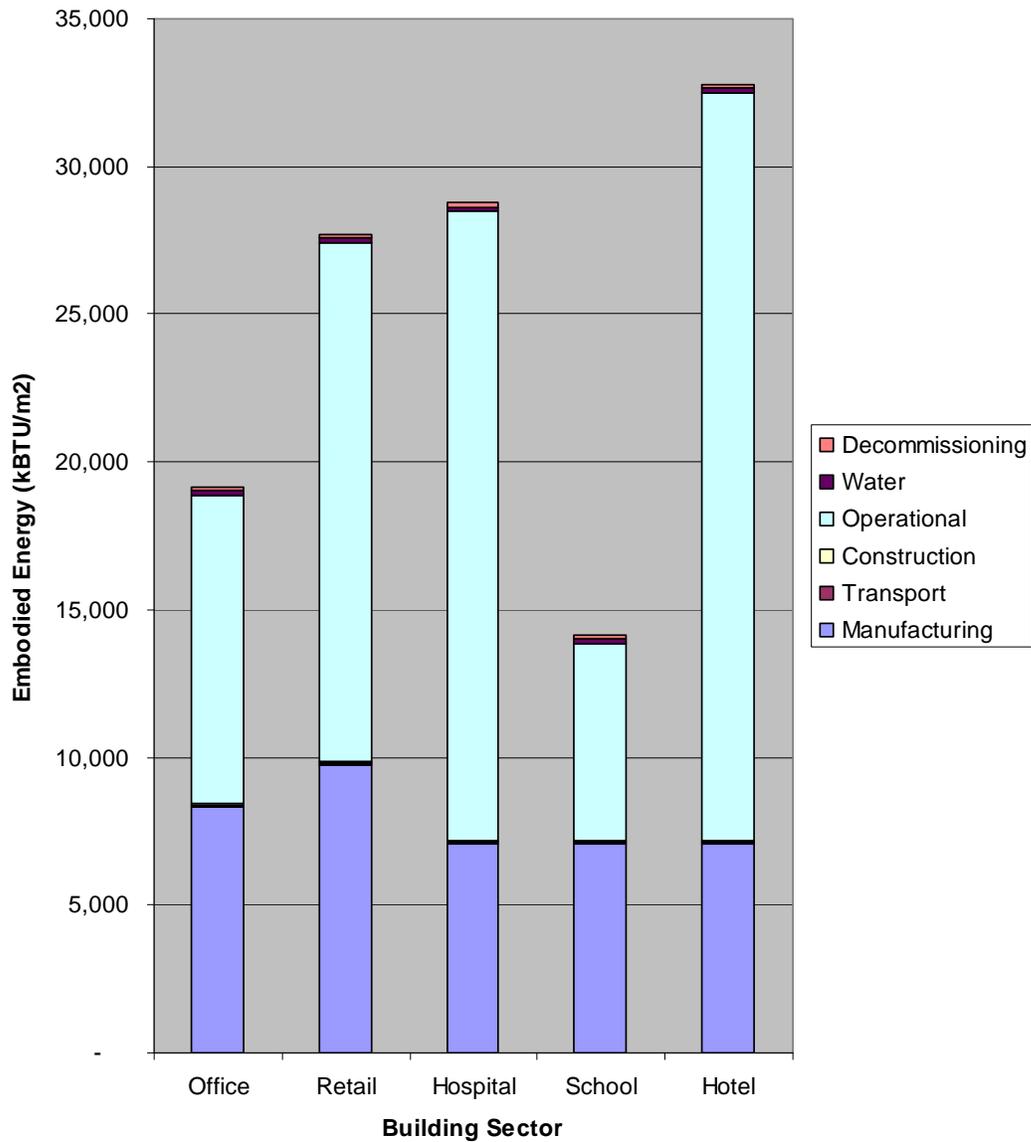
For the entire commercial building sector, estimated embodied energy per square meter of floor space totaled 23.4 kBTU, of which 42% was manufacturing energy and 56% was operational energy (Figure 5). Transport, construction, water use, and decommissioning together accounted for just 2% of the estimated total. For operational energy, the calculation was based on total primary energy consumption (source energy), instead of final energy (site energy) as is used in some studies. For a coal-based system such as China, primary energy consumption provides a more comprehensive idea of the energy and emissions impact of buildings.

Figure 5 Commercial Sector Embodied Energy (Primary Energy)



Because most of the data sources focused on office, retail buildings and hotels, little information was available on schools and hospitals. As a result, the estimated non-operational embodied energy for the hospital and school subsectors is assumed to be the same as hotels (Figure 6, Table 12). Total embodied energy was highest for the hotel subsector, mainly because of the higher operational energy stemming from long hours of use and higher use of water heating and other services. Embodied energy was lowest for schools, where limited hours of operation and lower levels of energy services such as lighting and cooling keeps operational energy low.

Figure 6 Embodied Energy by Building Sector (Primary Energy)



The total non-operational embodied energy of 8,554 kBTU/m², or approximately 8.77 GJ/m² for the office sector, is consistent with previous international studies of the non-operational embodied energy of office buildings. In the Cole and Kernan paper, a summary of five studies in U.S., U.K., Japan, Australia and New Zealand revealed a broad range of 4 to 12 GM/ m² for concrete, wood and steel office buildings with very different floor spaces. Compared to results from other studies of concrete office buildings, this study’s estimate of 8.77 GJ/m² is comparable to 8.23 GJ/ m² for a 15-story office building in Australia and lower than estimates of 10 – 12 GJ/ m² for several concrete buildings in Japan. It is, however, higher than previous results for concrete office buildings in New Zealand and Canada.

Table 11 Embodied Energy by Building Sector (Primary Energy)

(kBTU/m²)

	Office	Retail	Hospital	School	Hotel
Manufacturing	8,316	9,731	7,054	7,054	7,054
Transport	47	47	47	47	47
Construction	65	65	65	65	65
Operational	10,437	17,578	21,325	6,701	25,333
Water	146	146	146	146	146
Decommissioning	126	126	126	126	126
Total	19,137	27,693	28,763	14,139	32,771

Interestingly, the 8.77 GJ/m² result is very similar to the results of a recent study of two U.S. office buildings that was included as an international proxy for this study. In a 2005 life-cycle analysis by Guggemos and Horvath, they found the non-operational embodied energy for a concrete-frame office building to be 8.3 GJ/m². Within the specific stages of embodied energy consumption, this study’s total estimate of 118 MJ/m² for construction and transportation also falls within the range of 20 – 120 MJ/ m² found for 12 buildings with concrete structural assemblies in the Cole paper. The result of this study is therefore comparable to previous life cycle studies of commercial buildings, in spite of differences in life cycle analysis system boundaries, assumptions and geographic factors.

For embodied CO₂, SO₂, and PM emissions, China-specific factors were used to calculate the energy mix in manufacturing, construction, and decommissioning and to develop CO₂, SO₂ and PM emission coefficients for electric power and direct-use coal. Standard IPCC CO₂ coefficients were used to calculate CO₂ emissions from primary coal, oil and natural gas. The results of these calculations are shown in Figure 7, Figure 8, and Table 11. Total embodied CO₂ emissions in office buildings are slightly above 2500 kg/m², while SO₂ and PM emissions came in at 9.7 and 7.7 kg/m² respectively.

Figure 7 Office Sector Embodied Energy CO₂ Emissions (Primary Energy)

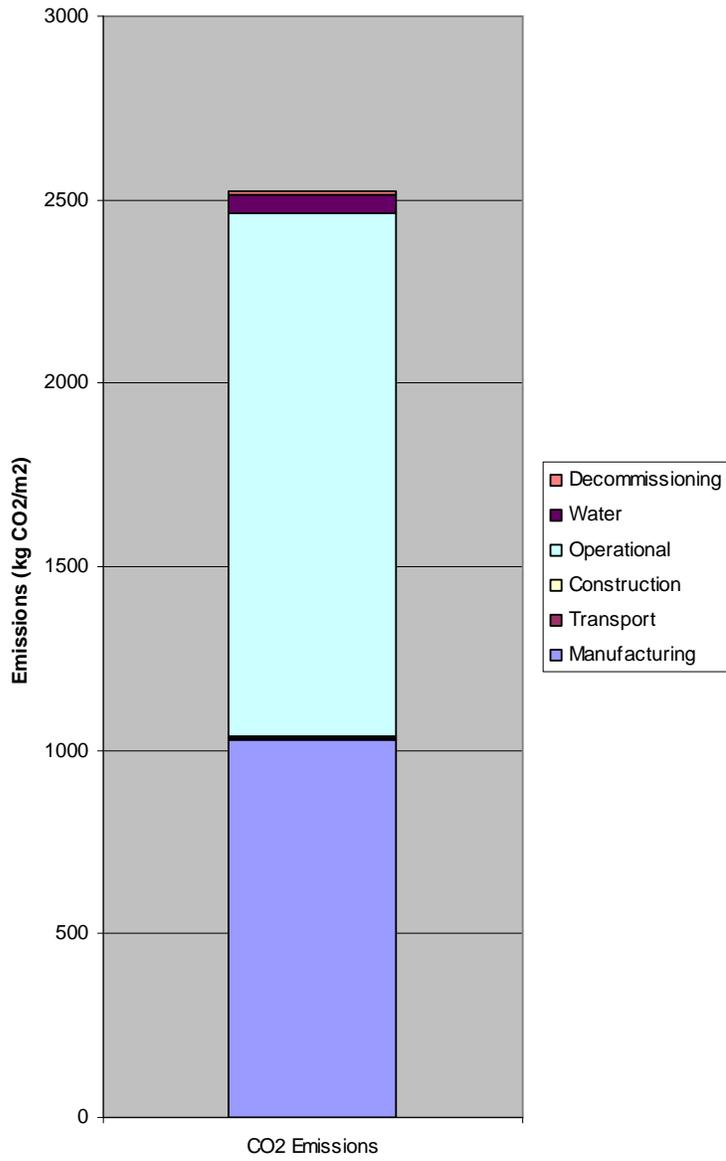


Figure 8 Office Sector Embodied Energy Pollutant Emissions (Primary Energy)

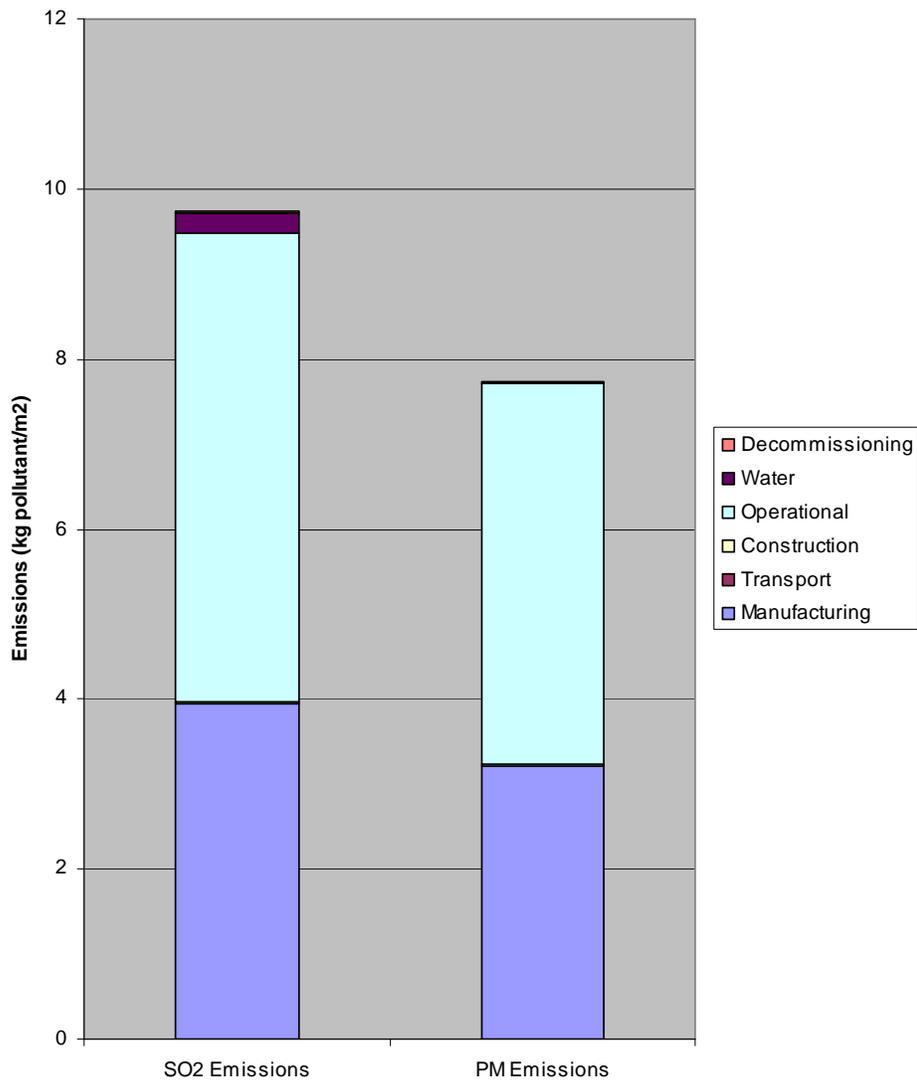


Table 11 Office Building Embodied CO2 and Pollutant Emissions

kg/m²

	CO ₂ Emissions	SO ₂ Emissions	PM Emissions
Manufacturing	1028.1	4.0	3.2
Transport	3.7	-	-
Construction	5.4	0.0	0.0
Operational	1426.4	5.5	4.5
Water	49.0	0.2	0.0
Decommissioning	10.58	0.0	0.0
Total	2,523.1	9.7	7.7

The relatively high proportion of embodied energy in building material manufacturing in China suggests that programs directed at energy efficiency improvements in those sectors may be effective as well in reducing the emissions impact of office buildings, and may thus compliment a continued focus on reducing operational energy use.

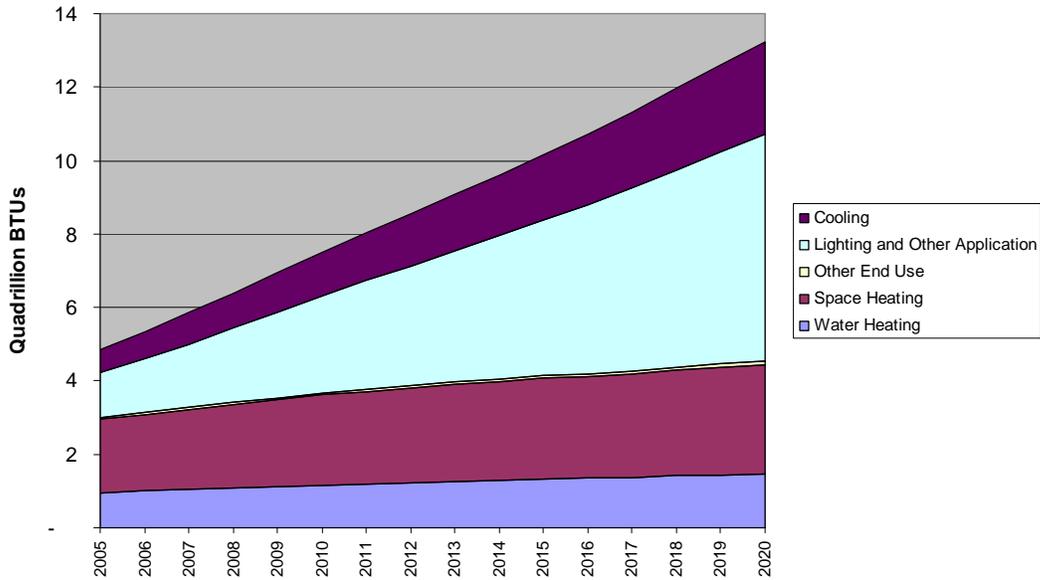
3.2 OPERATIONS ENERGY AND EMISSIONS

The major portion of a building's energy consumption and emissions occurs during its operational lifetime. In China, the construction (and deconstruction) boom since the 1980s has made it more difficult to estimate an "average" building lifetime; in this study, it is assumed that buildings will operate for 30 years. Based on the assumptions about floor space, energy intensity, equipment penetration, and equipment efficiency laid out earlier, we have calculated the energy consumption and emissions consequences for the entire commercial building sector (baseline case) and for office buildings in particular (baseline and alternative cases).

3.2.1 Commercial Buildings Sector: All Buildings

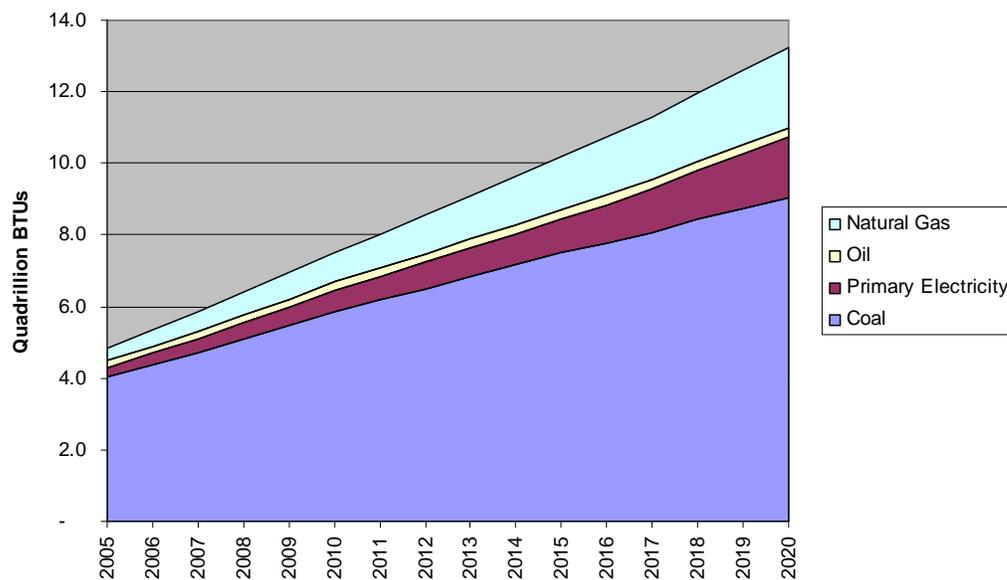
Under baseline case assumptions, total primary energy consumption in commercial buildings grows from 4.8 quads in 2005 to 13.2 quads in 2020, at an average annual rate of 6.9% (Figure 6). The largest growth occurs in the demand for lighting and other applications, such as office equipment, elevators, and other electric-powered equipment. Between 2005, energy consumption for these applications alone is expected to grow from 25% of total primary energy use to 47% of the total, both because of the expected higher unit intensity of lighting and other applications, and also because it is assumed that all these applications are electricity powered, which increases primary energy demand.

Figure 6 Primary Energy Consumption by End-Use in Commercial Buildings, Reference Case



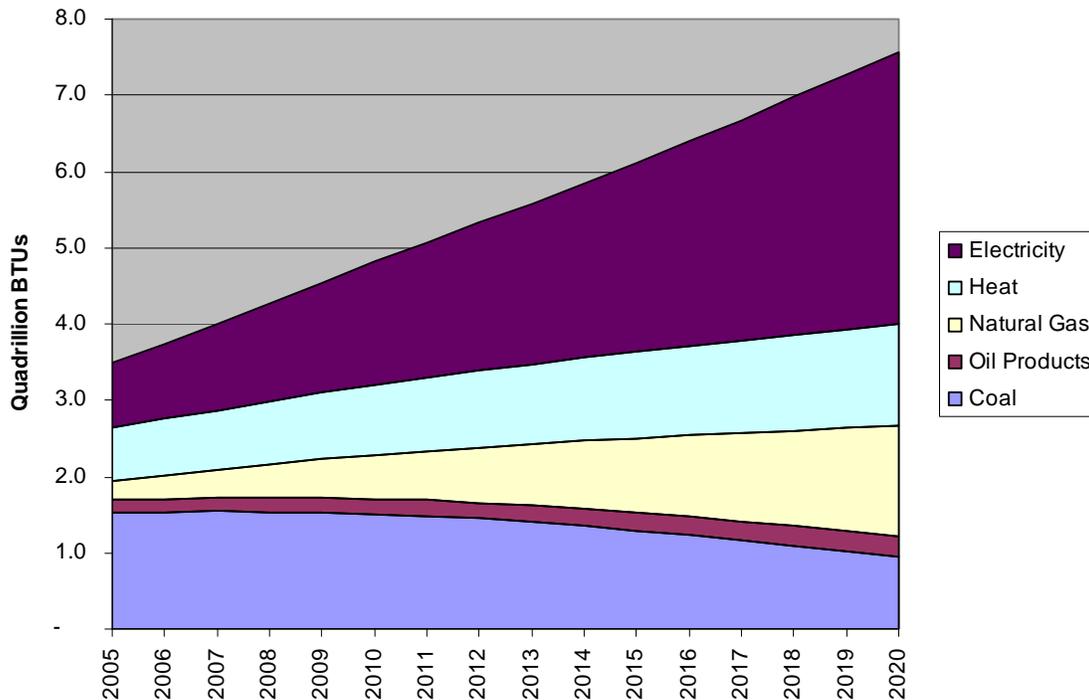
The high Chinese reliance on coal-powered electricity generation is evident in Figure 7, which displays primary energy consumption by fuel type. Natural gas, oil and some coal are used directly in buildings for space heating, water heating, and cooling purposes, while the balance is used for electricity generation, supplemented by China’s primary electricity sources of hydropower and nuclear power. It is assumed that China’s commercial building electricity supply is proportional to the generation mix in the entire country.

Figure 7 Primary Energy Consumption by Fuel in Commercial Buildings, Reference Case



Final energy use in buildings is largely determined by equipment choice. As noted, much of the expected growth in installed equipment is electricity-based, and it is expected that electricity will grow from 25% of total final energy use in 2005 to nearly half in 2020 (Figure 8). Purchased heat is primarily a final energy form in office buildings in the north, where district heating schemes are often used to provide winter heating in preference to onsite use of boilers.

Figure 8 Final Energy Consumption by Fuel in Commercial Buildings, Reference Case



Coal is the largest source of primary energy to buildings, and it is also the largest source of CO₂ emissions (Figure 9). With expectations that oil will remain a minor energy source for buildings, related emissions will correspondingly remain small. Natural gas represents the only other fast-growing primary energy source, and although unit emissions are lower than for coal, total emissions grow over the period as natural gas displaces both oil and coal, primarily for boiler use.

With the decline in direct coal use and its substitution with electricity, the composition of SO₂ emissions over this period is expected to change significantly. Without widespread adoption of sulfur removal technology at coal-fired power plants, total SO₂ emissions attributable to electricity consumption will rise to over 6 million tonnes, up from over 2 million tonnes in 2005 (Figure 10). Given the emphasis on reducing SO₂ emissions in the current 5 Year-Plan, actual emissions attributable to power production in 2020 are likely to be lower, but no power-sector-specific forecasts are available.

Figure 9 CO2 Emissions from Commercial Buildings (Primary Energy, Reference Case)

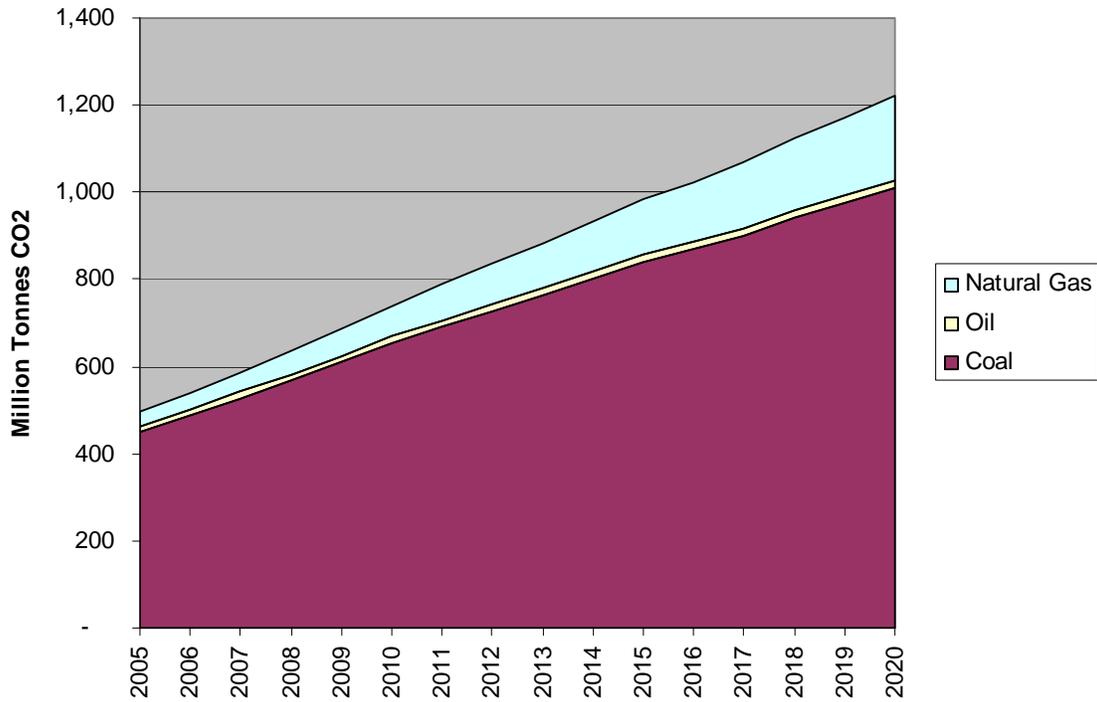
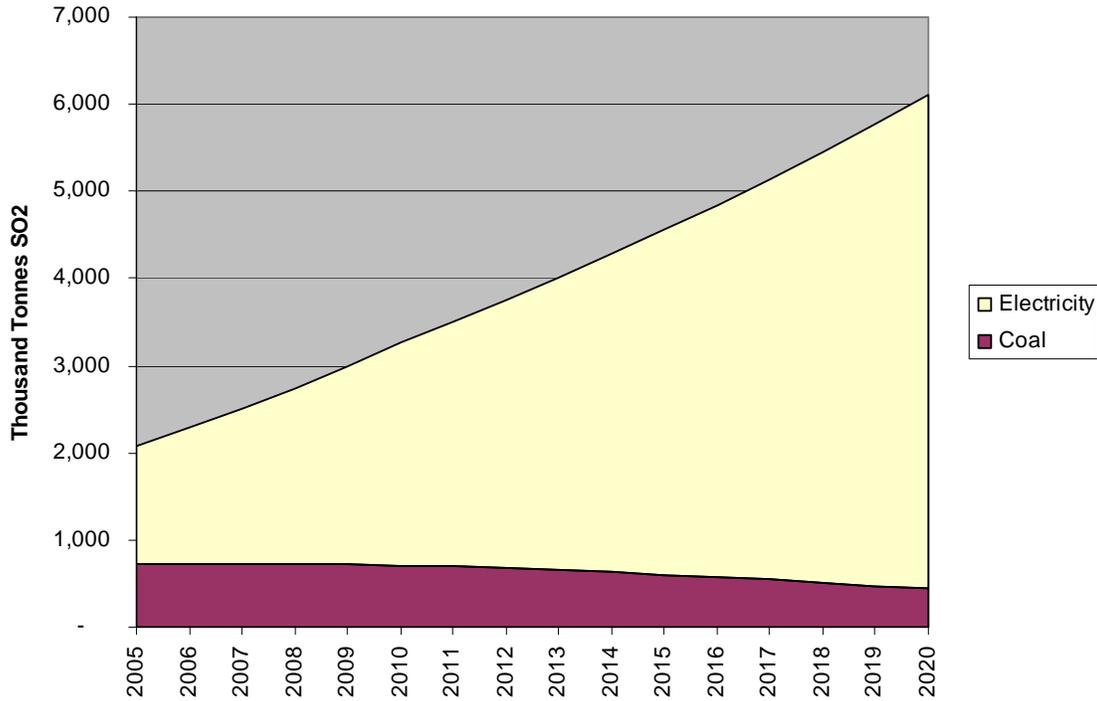
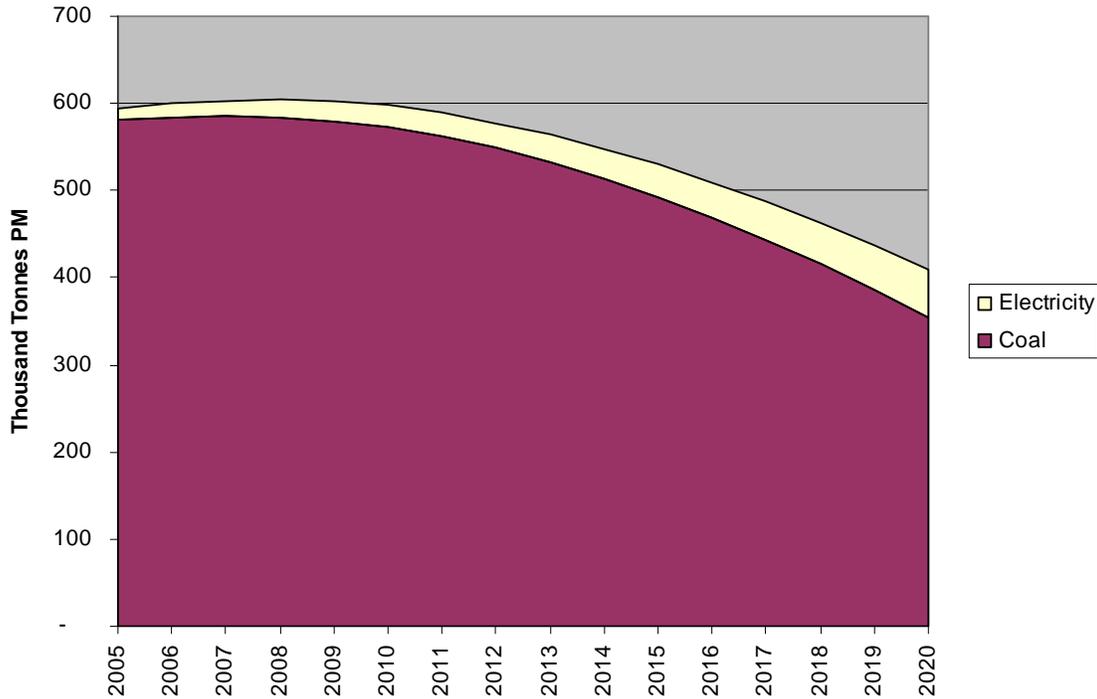


Figure 10 Commercial Building SO2 Emissions, Reference Case



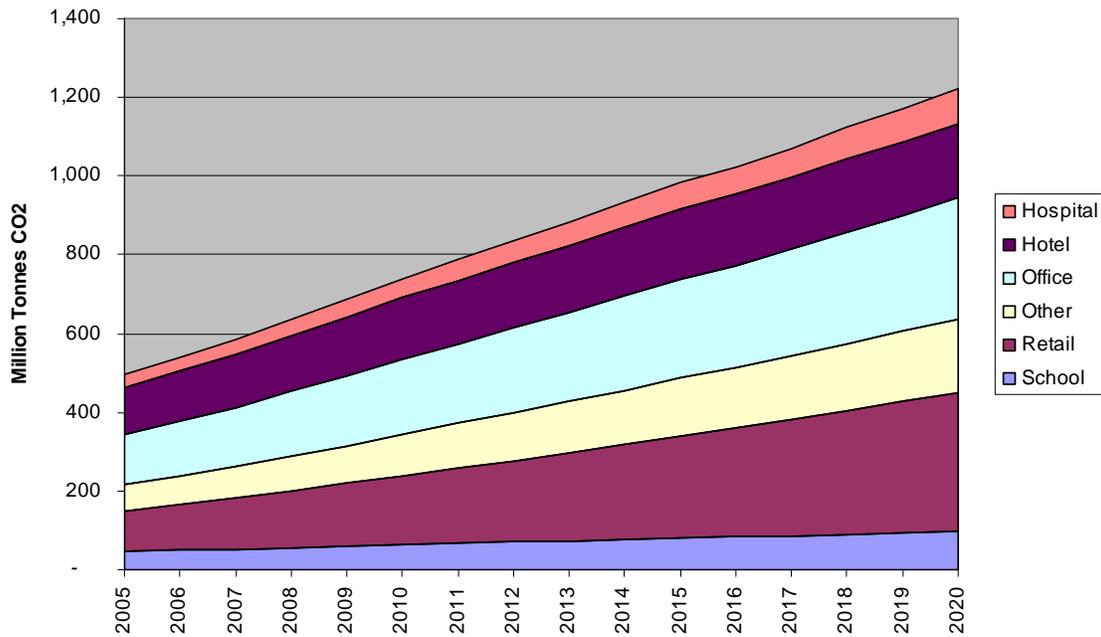
Total particulate matter emissions are expected to fall as well by 2020, mainly from the reduction in the direct combustion of coal. With PM management well established at power plants, rising electricity consumption is not expected to offset the decline in coal-based emissions (Figure 11).

Figure 11 Commercial Buildings PM Emissions, Reference Case



CO₂ emissions by building subsector are illustrated in Figure 12. Currently, office buildings account for about one-fourth of total commercial building sector CO₂ emissions, and it is expected that offices will maintain that share up to 2020. In contrast, emissions from the retail, hospital, and “other” (public buildings, etc) subsectors are expected to grow relatively faster than office buildings, with growth in emissions from hotels and schools relatively slower. Total emissions from commercial buildings is expected to reach 1.22 billion tonnes CO₂ in 2020.

Figure 12 CO2 Emissions by Sector (Primary Energy, Reference Case)



3.2.2 Commercial Building Sector: Office Buildings

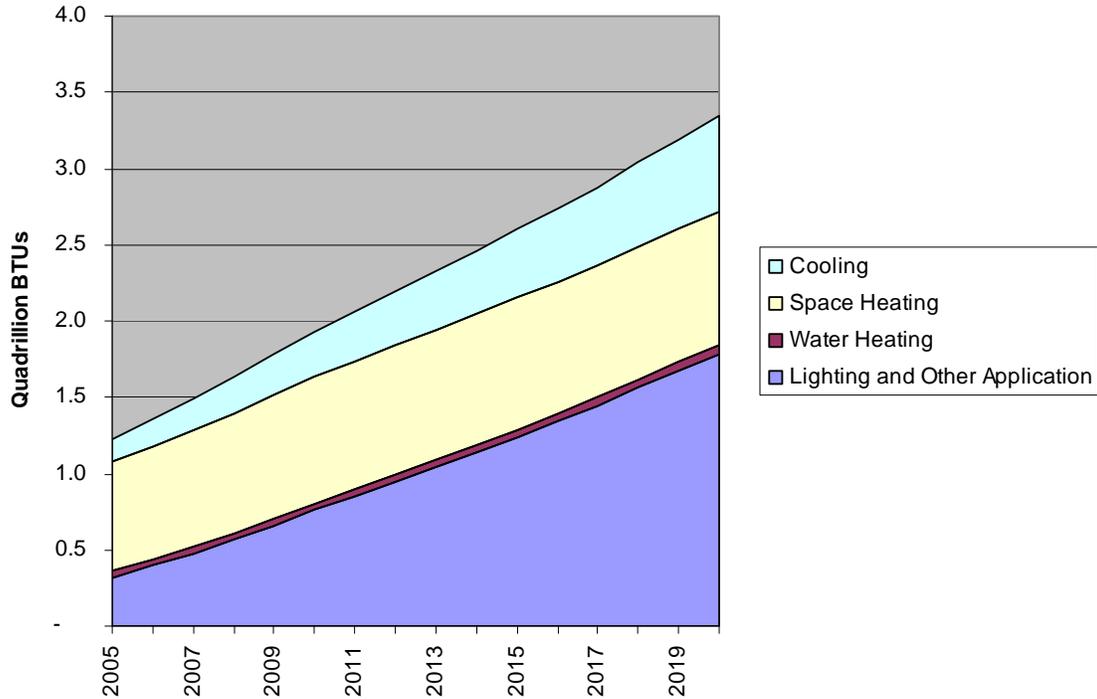
Office buildings currently account for about one-third of China’s commercial building stock, and this proportion is expected to decline only slightly by 2020 to 29% of the total as the floor space of retail and schools grows relatively faster over this period. Nonetheless, from a current 3.5 billion m² floor space, offices are expected to add over 2.5 billion m² by 2020.

In terms of energy and emissions, however, office buildings account for a smaller share of the commercial sector’s total, mainly because their operating hours and energy intensities are lower than other types of buildings such as hotels or many retail centers. In 2005, offices accounted for about 25% of total energy consumption, and this is expected to stay relatively stable through to 2020.

Using the energy intensity trends and equipment penetration trends detailed in section 2.2.1 as the reference case for office building development to 2020, energy consumption is expected to grow from 1.2 quads in 2005 to 3.3 quads by 2020, at an average annual rate of 6.9% (Figure 13). Although the amount of floor space to be heated expands significantly over the period, the expected decreased intensity of heating as building heat management improves and wasteful practices are reduced (especially in northern heating zone areas), combined with great efficiency of heat production in buildings, will keep total energy requirements for heat supply fairly stable, growing at just 1.3% per year. In contrast, the expected increase in cooling demand over a larger proportion of office building floor space will send cooling energy consumption up by 12% per year on average, from 0.3 to 1.8 quads. Similarly, consumption of other services—lighting, office

equipment, and miscellaneous electricity uses, is expected to grow by 9.7% per year, from 0.2 quads in 2005 to 0.6 quads in 2020.

Figure 13 Office Building Primary Energy Use by Application, Reference Case



The shift from the direct use of fuels such as coal, oil, and natural gas to electricity in end-use applications means that the growth of the electricity-consuming components within office buildings will have the greatest impact on primary energy use. Figure 14 illustrates this expected shift in the office building sector, with electricity growing from 26% of end-use energy to 56% by 2020. In contrast, direct use of coal, primarily for water heating and space heating, is expected to fall from 40% to 6% over this same period.

In contrast, total primary energy consumption will continue to be dominated by coal, the foundation of China's power system (Figure 15). As direct use of coal declines, however, and coal is increasingly supplanted by natural gas (and primary electricity), coal's share of the total will decline, from about 85% of the total today to 69% by 2020. This trend in turn contributes to slower growth in total CO₂ emissions as "cleaner" fuels supplant coal.

Figure 14 Office Building Final Energy Use by Fuel (Reference Case)

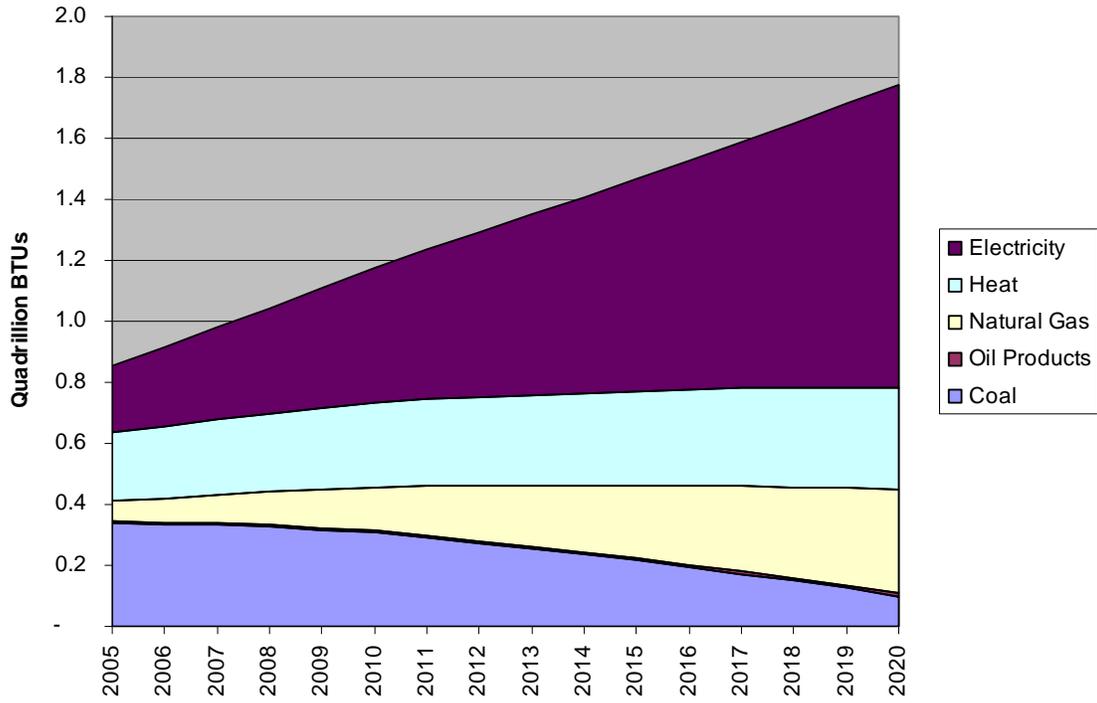
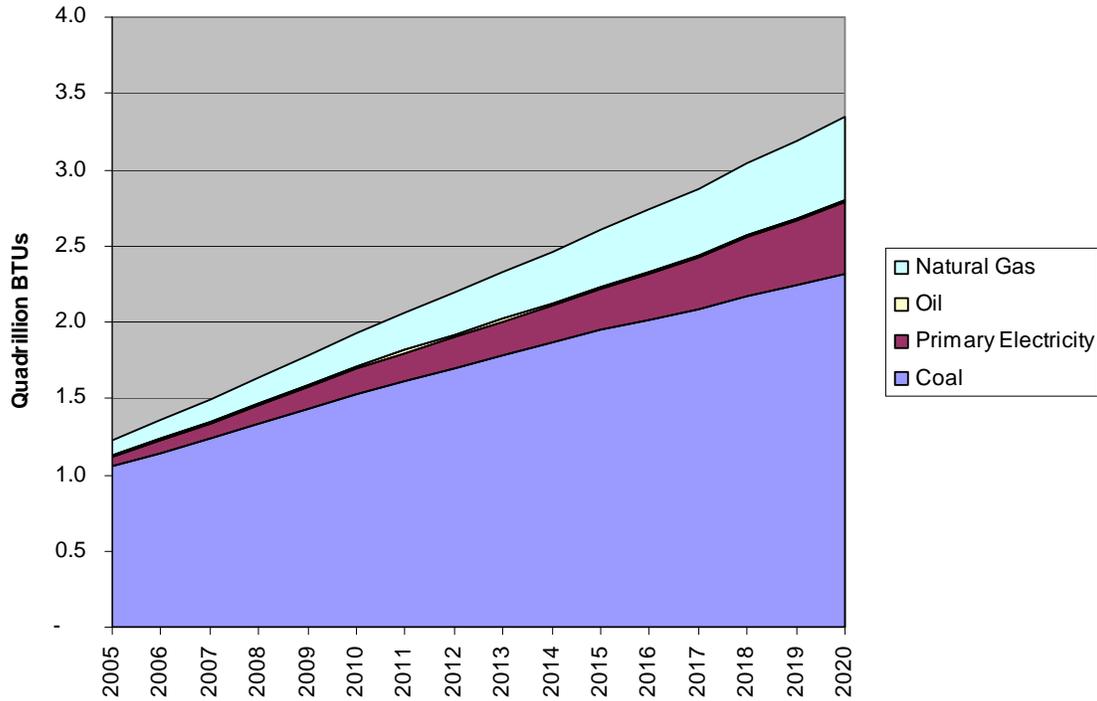
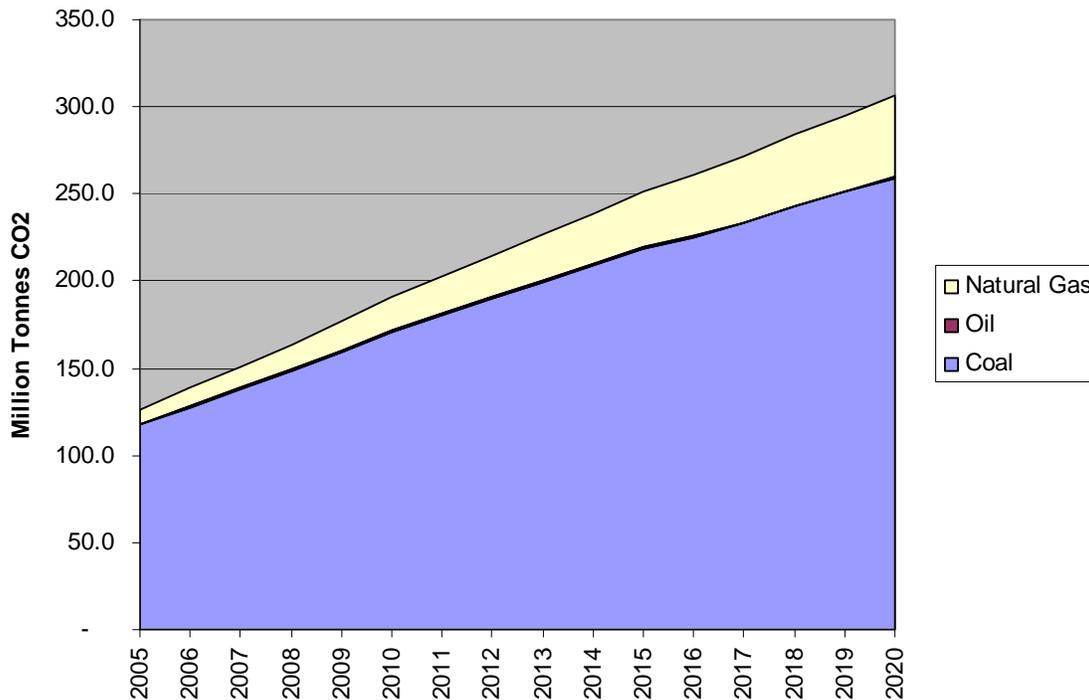


Figure 15 Office Building Primary Energy Use by Fuel, Reference Case



Total CO₂ emissions are expected to rise from 127 million tonnes in 2005 to 306 million tonnes by 2020. Similar to the trend in the overall commercial building sector, these emissions will be dominated by coal, with a rising share of natural gas, and the near-disappearance of oil use and related emissions (Figure 16).

Figure 16 Office Building CO₂ Emissions (Reference Case, Primary Energy)



Similarly, without improvements in sulfur capture at power plants, SO₂ emissions attributed to office building energy use will rise from 511,000 tonnes in 2005 to 1.6 million tonnes in 2020. Emissions from the direct burning of coal are expected to drop by over 70% (Figure 17).

Particulate emissions sources, however, remain dominated by the direct combustion of coal, although total emissions fall by about 60% by 2020 to 53,000 tonnes (Figure 18).

Figure 17 Office Building SO2 Emissions (Reference Case)

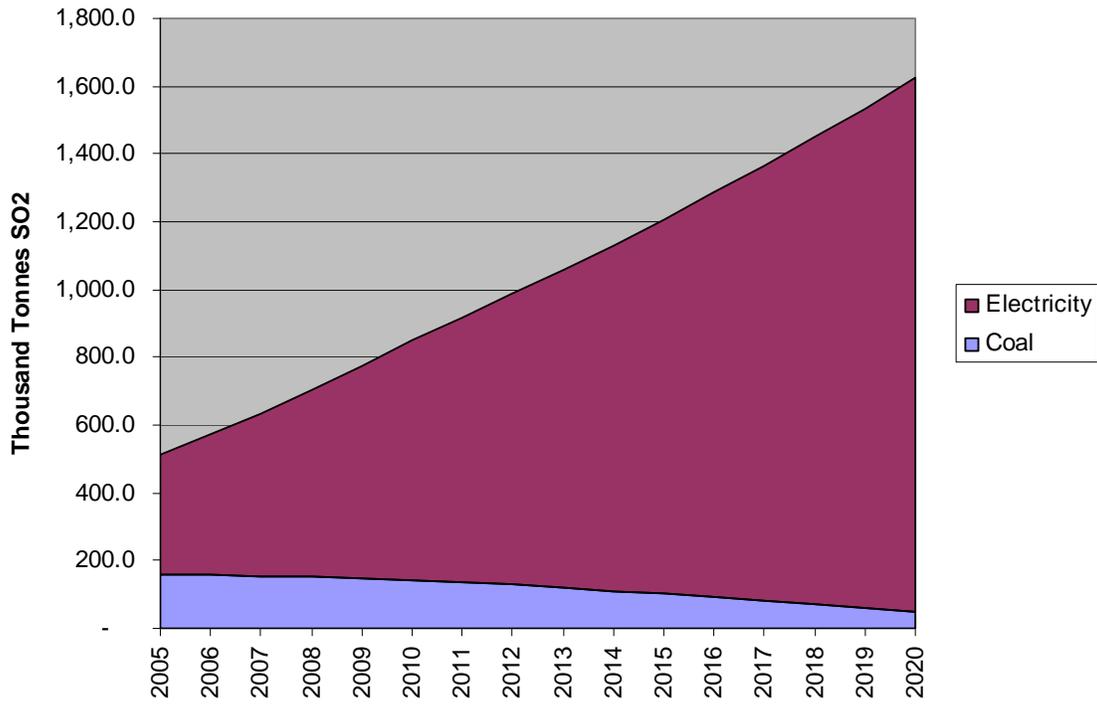
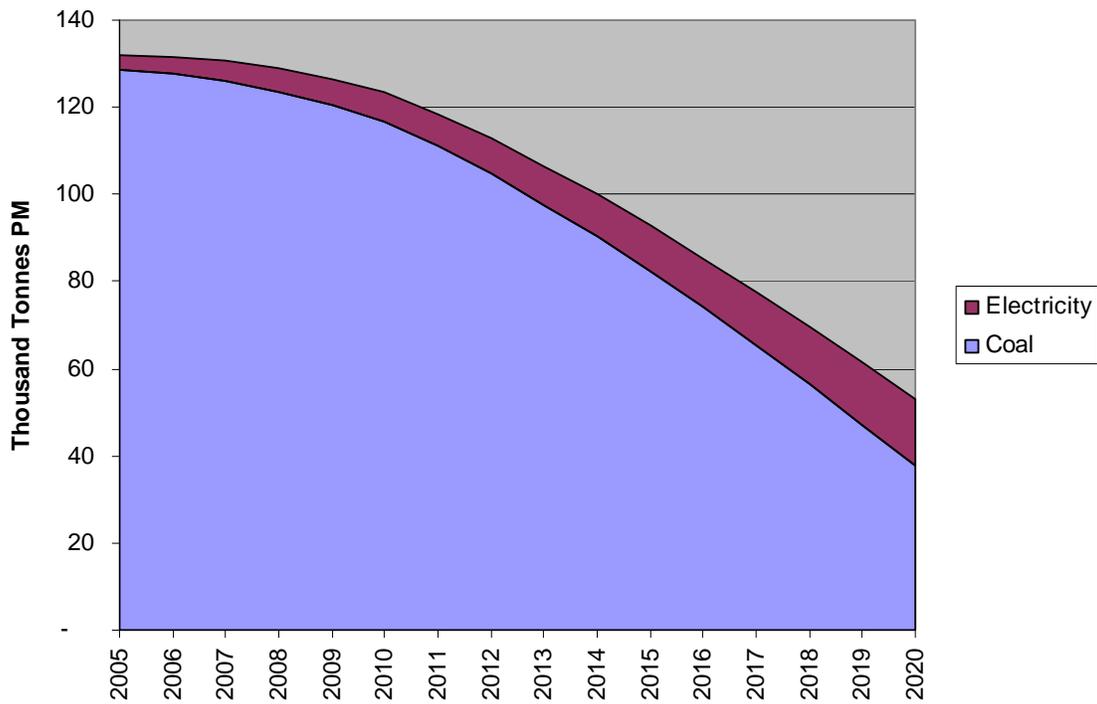


Figure 18 Office Buildings PM Emissions (Reference Case)



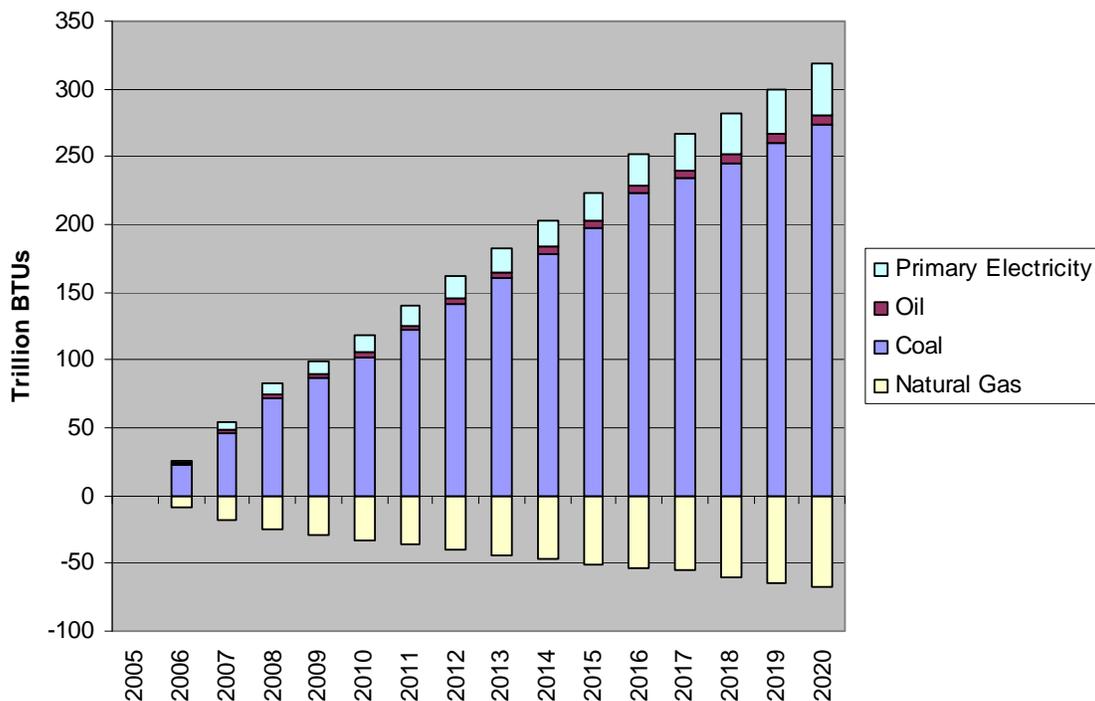
3.2.2.1 ALTERNATIVE CASE SAVINGS

Section 2.2.1 laid out the technology-shift assumptions underlying the alternative case for office subsector energy development. Generally speaking, this study assumed a more rapid introduction of more efficient technologies for heating, cooling, water heating and lighting, including technologies that use lower-emitting fuels such as natural gas. In addition, the technologies in use progress more rapidly to higher levels of operational efficiency, particularly for heating and cooling end uses.

This combination of assumptions provides tangible energy savings over the 15 year outlook. By 2020, the net amount of savings reaches 250 trillion BTUs (0.25 quads), including a gross savings of 318 trillion BTUs in primary electricity, oil and coal consumption, offset by increased consumption of 68 trillion BTUs of natural gas (Figure 19, Table 12). In 2020, the savings in the alternative case amounts to 7.5% of the reference case consumption, up from 4.4% in 2010. Cumulatively, between 2005 and 2020, savings total over 2 quads.

In terms of final energy, savings of electricity alone in 2020 reach 19.6 TWh. Gross consumer savings, then, assuming ¥0.60/kWh and, without discounting for additional costs of higher efficiency equipment, total over ¥11.7 billion (US\$1.7 billion). On an average generation basis, this would avoid 3.7 GW of generation capacity, or about 7 average new Chinese power plants.

Figure 19 Primary Energy Savings by Fuel, Alternative Case, Trillion BTUs



In terms of coal equivalent—China’s basic energy unit—primary energy savings reach 9 million tonnes of coal equivalent in 2020, including 11.4 million tonnes saved in electricity, oil and gas consumption, offset by 2.4 million tonnes coal equivalent in higher natural gas consumption (Figure 20, Table 12).

Figure 20 Primary Energy Savings by Fuel, MTCE

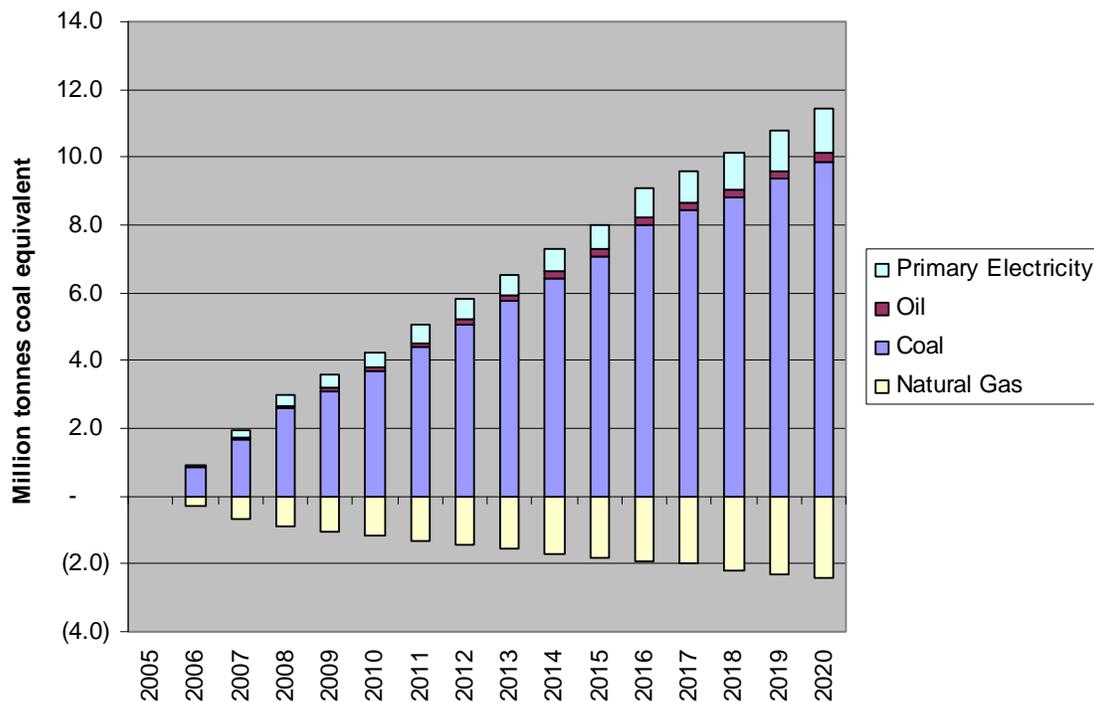
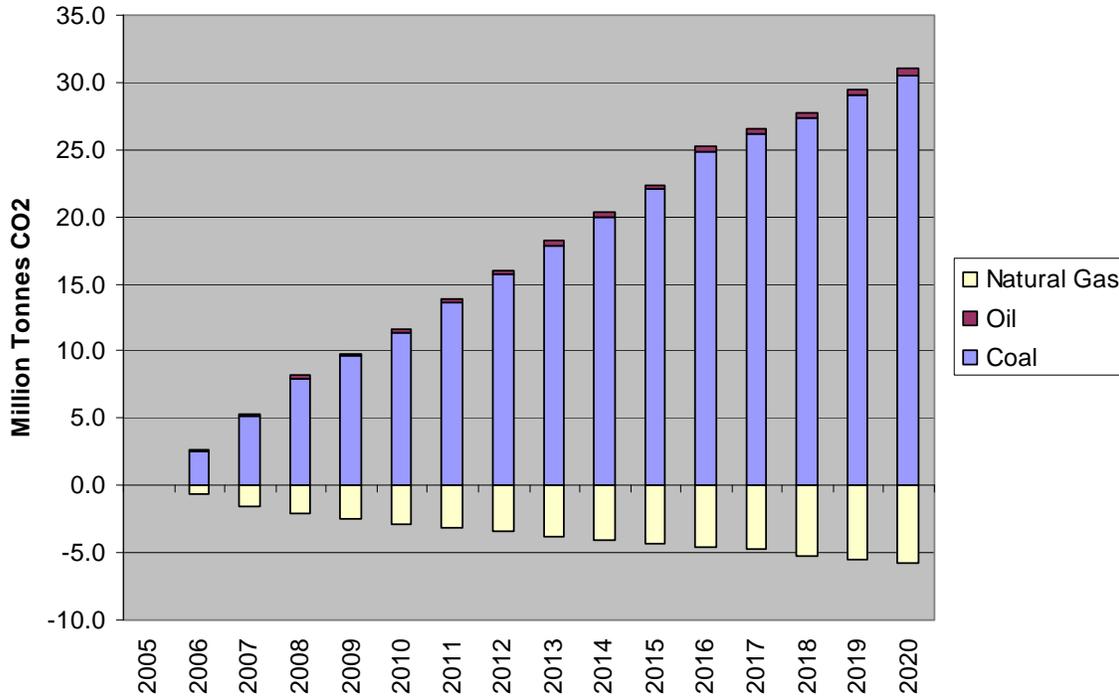


Table 12 Projected Primary Energy Savings between Reference and Alternative Cases

	2005	2010	2015	2020
<i>Trillion BTUs</i>				
Coal	-	101.9	197.0	273.7
Oil	-	3.6	5.4	7.3
Primary Electricity	-	12.8	20.4	37.2
Natural Gas	-	(32.9)	(50.6)	(67.7)
Total	-	85.5	172.2	250.5
<i>Million Tonnes Coal Equivalent</i>				
Coal	-	3.7	7.1	9.8
Oil	-	0.1	0.2	0.3
Primary Electricity	-	0.5	0.7	1.3
Natural Gas	-	(1.2)	(1.8)	(2.4)
Total	-	3.1	6.2	9.0

In the years before 2010, as faster coal boiler retirement is not assumed in the alternative case until after 2010, most of the emissions savings come from reduced consumption of electricity. In CO₂ terms, then, savings show a steady increase to a net 25.2 million tonnes of savings in 2020 (Figure 21, Table 13).

Figure 21 Projected CO₂ Emissions Savings between Reference and Alternative Cases



SO₂ and particulate matter emissions reductions clearly demonstrate the phased approach to coal boiler replacement, with coal-derived SO₂ and PM savings rising only after 2010. As has been seen in the overall trend of emissions from the office sector, SO₂ emissions reductions are driven mostly by reduced electricity use, while PM emissions reductions are driven largely by reduced direct coal use (Figure 22, Figure 23, Table 13).

Figure 22 Projected SO2 Emissions Savings between Reference and Alternative Cases

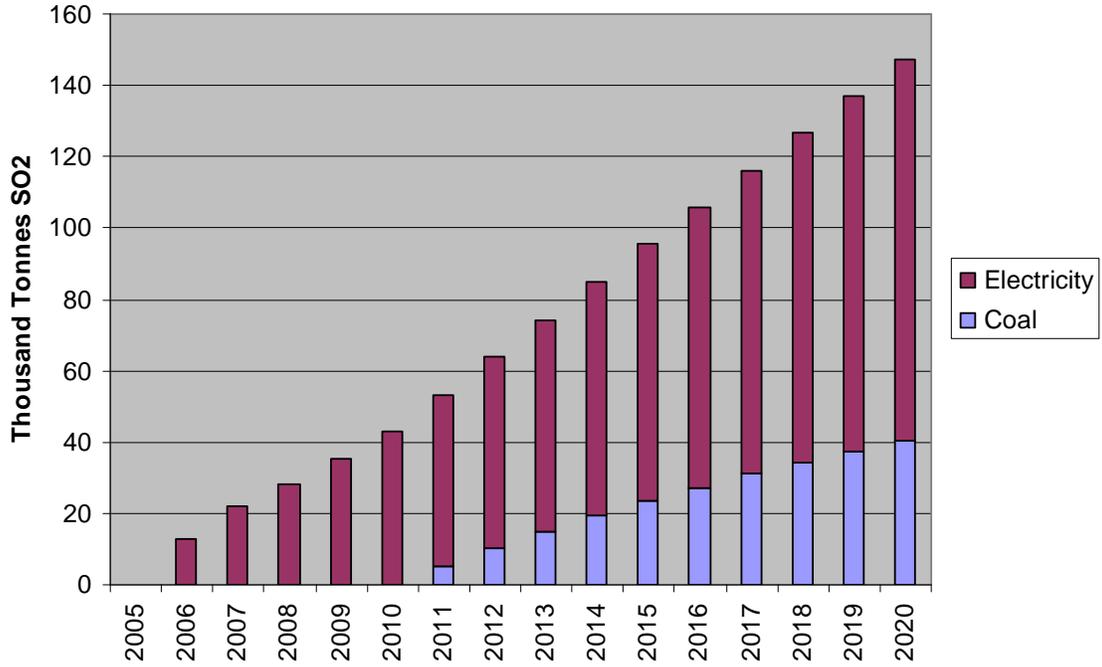


Figure 23 Projected PM Emissions Savings between Reference and Alternative Cases

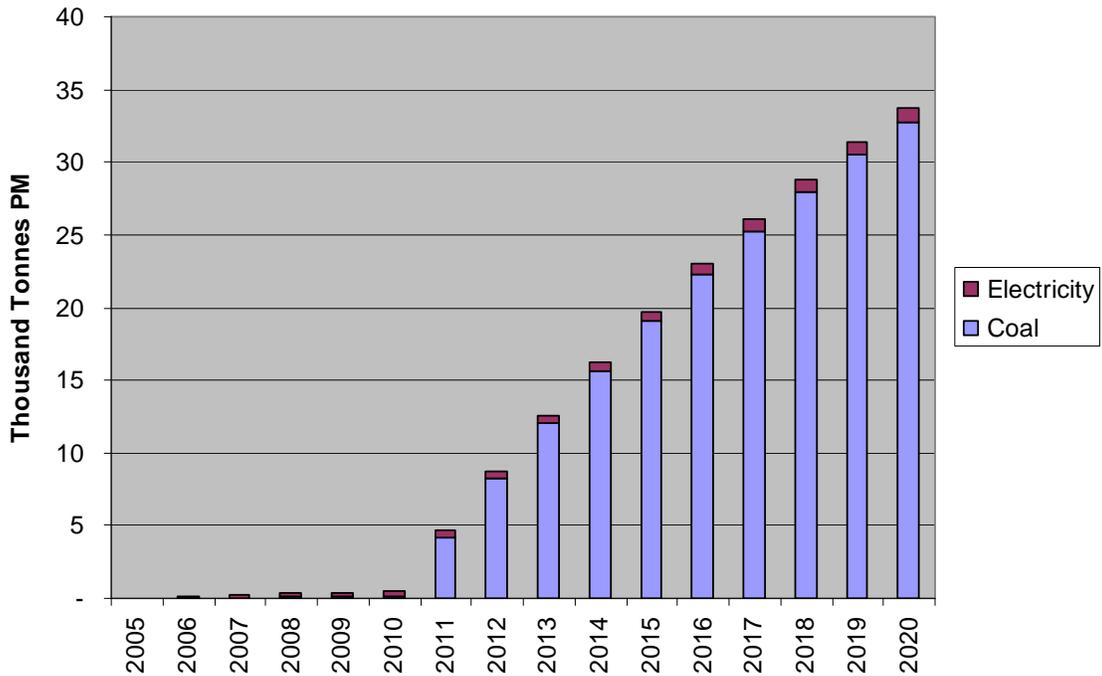


Table 13 Projected CO₂, SO₂ and PM Emission Savings between Reference and Alternative Cases

	2005	2010	2015	2020
<i>CO₂ Emissions (Million Tonnes)</i>				
Coal	-	11.4	22.0	30.6
Oil	-	0.2	0.4	0.5
Natural Gas	-	(2.8)	(4.3)	(5.8)
Total		8.8	18.0	25.2
<i>SO₂ Emissions (Thousand Tonnes)</i>				
Coal	-	0.1	23.4	40.2
Electricity	-	42.9	72.0	107.1
Total	-	43.0	95.3	147.3
<i>PM Emissions (Thousand Tonnes)</i>				
Coal	-	0.09	19.05	32.75
Electricity	-	0.41	0.69	1.02
Total	-	0.50	19.74	33.77

3.3 SUMMARY

The estimation of the embodied energy in Chinese commercial buildings suffers from a lack of China-specific building life-cycle studies, but the body of international literature on the subject provides benchmarks and a range of details from which it is possible to make an initial estimate of scale. In this initial estimate, as expected, operational energy accounted for the largest proportion of total embodied energy (over 50%, assuming a 30-year lifetime), but in contrast to many international findings, manufacturing energy for building materials accounted for over 40% of the total. This is understandable because of the relatively low level of operational energy consumption in Chinese buildings compared to those in developed economies, but it could also reflect the potential for impacting the total emissions footprint of a commercial building through improvements in the efficiency of production of the building materials themselves. Further study would be needed, however, to verify this initial estimate and to draw more concrete conclusions.

In terms of operations energy alone, the approach to improving operational efficiency through prudent selection of technology and accelerating the efficiency of deployed technologies demonstrates that significant savings can be achieved within a 15 year time frame. By retiring the least efficient (and highest-emissions) technologies such as coal boilers, introducing more efficient (and lower-emissions) technologies fueled by natural gas, and improving efficiency by 5-10 percentage points above the current level, 9 million tonnes of coal equivalent energy could be saved by 2020, reducing CO₂ emissions by over 25 million tonnes. In addition, cuts can be made to the growth of both SO₂ and PM emissions.

3.4 FURTHER RESEARCH

This preliminary assessment of the estimated energy and carbon footprint of Chinese commercial and office buildings could be significantly improved by further research in areas in which China-specific data are lacking, and by more detailed review of trends in building operational energy. Such research could involve working with building materials experts in China to determine the characteristics of Chinese building materials production, such as major mining areas, extraction processes, average raw material transportation distances, and energy intensity of production. Similarly, work with construction experts could better determine the amount of energy consumed in the construction of an average commercial building, or differences among the construction of different building types that distinguish hotels, for example, from schools. Average lifetime is also an issue. Better understanding the expected operational lifetime of existing and new buildings—and any differences between the two—would permit a better assessment of the split between operational and non-operational energy of these buildings. Similarly, as this analysis assumed no retrofits or renovations over the life of the building, it would be useful to develop better assumptions of the additional energy and material inputs into typical commercial building over its lifetime. Decommissioning is also a question: the energy consumed this during final stage of a building's life needs to be offset by the degree of recycling undertaken on the recovered materials.

Although much greater detail and more information is available about the operational energy consumption in Chinese commercial buildings, the rapid pace of growth in China's economy in recent years suggests that certain details—such as the degree of deployment of various technologies, or the use of certain technologies such as diesel-fired boilers—be reviewed for modification or inclusion into the model. Similarly, current expectations of floor space expansion by building type may need to be updated as well. In addition, further research is needed to determine SO₂ and PM emission coefficients from other fuels used during the total lifecycle of a building such as petroleum and natural gas

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