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Potential Energy Savings and CO2 Emissions Reduction of China's Cement Industry

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Abstract

This study analyzes current energy and carbon dioxide (CO2) emission trends in China's cement industry as the basis for modeling different levels of cement production and rates of efficiency improvement and carbon reduction in 2011-2030. Three cement output projections are developed based on analyses of historical production and physical and macroeconomic drivers. For each of these three production projections, energy savings and CO2 emission reduction potentials are estimated in a best practice scenario and two continuous improvement scenarios relative to a frozen scenario. The results reveal the potential for cumulative final energy savings of 27.1 to 37.5 exajoules and energy-related direct emission reductions of 3.2 to 4.4 gigatonnes in 2011-2030 under the best practice scenarios. The continuous improvement scenarios produce cumulative final energy savings of 6.0 to 18.9 exajoules and reduce CO2 emissions by 1.0 to 2.4 gigatonnes. This analysis highlights that increasing energy efficiency is the most important policy measure for reducing the cement industry's energy and emissions intensity, given the current state of the industry and the unlikelihood of significant carbon capture and storage before 2030. In addition, policies to reduce total cement production offer the most direct way of reducing total energy consumption and CO2 emissions.

Keywords: Cement Industry, Energy Efficiency, Emissions Reduction

1. Introduction

Cement is produced worldwide in virtually all countries (Worrell et al., 2001) as an important building material. With the fast growth of China's economy, cement demand and production in that country grew rapidly over the past 30 years. Figure 1 illustrates China's cement output from 1985 to 2010. In 1985, China produced 145.95 million metric tons (Mt) of cement and became the world's largest cement manufacturer. In 2010, China's cement output was 1.87 billion metric tons (or gigatonnes, Gt), which accounted for 56% of world total cement production (CEMBUREAU, 2011; Digital Cement, 2011; Ma, 2011). The average annual growth rate of cement output was 10.7% from 1985 to 2010.

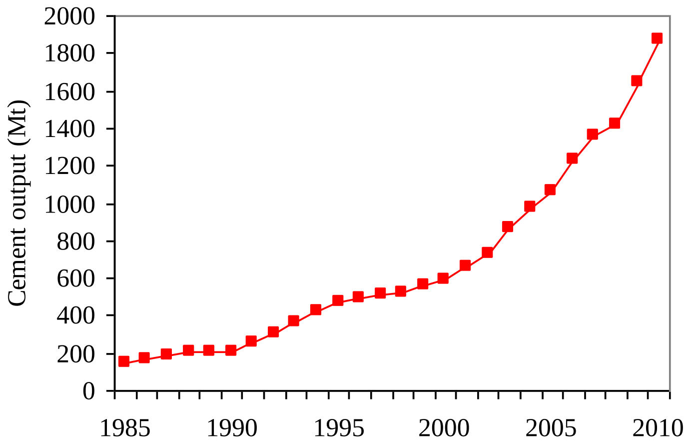

Figure 1. China's Cement Output in 1985-2010.

Source: CBMF, 2010; CCA, 2010; CEMBUREAU, 2011; Ma, 2011; NBS, 2010b.

Cement production is highly energy intensive and the cement industry is one of the largest industrial energy consumers in China (CCA, 2010, 2011; NBS, 2010a; Worrell et al., 2001). Because of the huge amount of cement output, China's cement industry accounts for about 10% of the country's industrial final energy consumption (CCA, 2010, 2011; NBS, 2010a).

Coal is the main fossil fuel used in China's cement industry, accounting for nearly 90% of the total final energy consumption of China's cement industry (CCA, 2008, 2009, 2010, 2011). Cement production is a major source of carbon dioxide (CO2) emissions from fossil fuel combustion, as well as the consumption of large amount of electricity, which is mainly produced by China's coal-dominated power industry[1] (Wang, 2011). Besides energy-related CO2 emissions, cement production also emits large amount of CO2 from the clinker calcining process (Gregg, 2008; PBL, 2008; Worrell et al., 2001).

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[1] Waste heat recovery (WHR) power generation technologies have been utilized by some Chinese cement facilities. WHR power generation can typically provide 25-33% of a cement facility's electricity demand for cement production (Zeng, 2009b).

In light of the cement industry's role as a main energy consumer and CO2 emitter in China, this industry deserves analysis and assessment of future production estimates as well as possible energy savings and CO2 emissions reduction policies and option.

There have been a number of projections of China's future cement production. In 2002, Soule et al. (2002) projected the future trends and opportunities in China's cement industry, but in retrospect, their projections were much lower than the actual situation. Cai et al. (2008) compared CO2 emission scenarios and mitigation opportunities in China's cement sector to 2020, but their projections also did not reflect the recent rapid development of China's cement industry.

A case study produced by Tsinghua University for the Center for Clean Air Policy (CCAP) projected that cement production would track economic development, or more specifically gross domestic product (GDP) growth (TUC, 2008). By assuming relatively high GDP growth rates and an elasticity of one between GDP growth and cement production growth, the CCAP projections of cement production in China were very high compared to other projections (TUC, 2008). Hayashi and Krey (2005) used regression of GDP growth and cement production for their projection. The pure economic-driver based projections usually did not take into consideration resource constraints and did not incorporate important non-linear effects, such as saturation effects. As a result, these projections were often quite high compared to other physical-driver based projections (Zhou et al., 2010).

This research aims to assess the current status of energy consumption and CO2 emissions and quantitatively project future production trends and estimate the potential for energy savings and CO2 emissions reduction of China's cement industry, taking into consideration resource constraints which are likely to be significant for China in the long term. Important non-linear effects, especially saturation effects, are also incorporated in the analysis and projections.

2. Energy Consumption and CO_2 Emissions of China's Cement Industry

China's cement industry developed rapidly in the past 30 years due to fast economic growth and urbanization (CCA, 2008, 2009, 2010, 2011). China's cement output increased from 79.86 Mt in 1980 to 1.87 Gt in 2010 (CCA, 2011; Ma, 2011). China's annual cement consumption per capita increased from 81 kilograms (kg) in 1980 to 1,380 kg in 2010. In other words, China's cement output and annual cement consumption per capita increased by factors of 23 and 17 from 1980 to 2010, respectively.

In parallel to the rapid growth of cement production, the energy consumption of China's cement industry also increased significantly. The cement output and energy consumption of China's cement production in 2000-2009 are plotted in Figure 2. Final energy consumption of China's cement production more than doubled from 2.44 exajoules (EJ) in 2000 to 5.16 EJ in 2009. Primary energy consumption followed the same trend as final energy consumption, though it was higher than final energy consumption due to the incorporation of energy conversion losses for electricity production2.

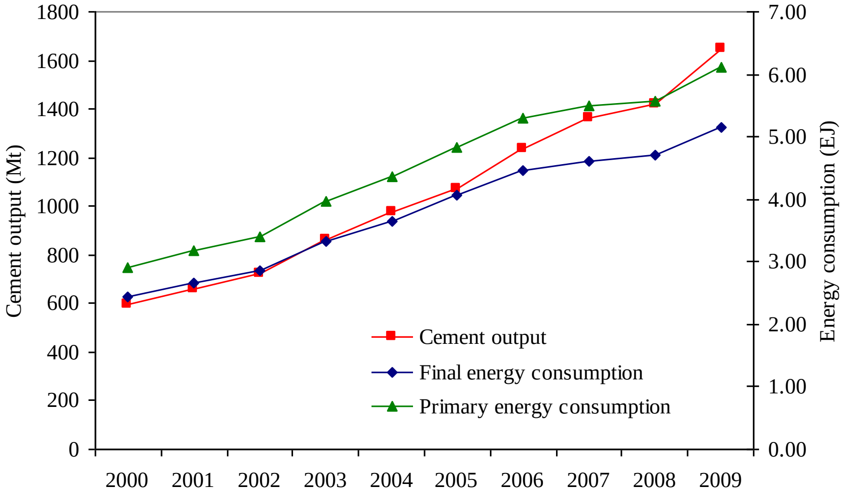

Figure 2. China's cement output and energy consumption in 2000-2009.

Source: Primary data from CCA, 2008, 2009, 2010, 2011; NBS, 2010a, 2010b, 2011; QEASCBM, 2011; SERC, 2009, 2010; Zeng, 2006, 2009a, 2009b, 2010; Zhou, 2007a, 2007b. Calculations by authors.

The average annual growth rate of final energy consumption was 8.7% from 2000 to 2009, lower than the average annual growth rate of cement output which was 12.0% during the same time period (CCA, 2008, 2009, 2010, 2011).

One main reason for the energy intensity reduction in recent years is the popularization of the more energy-efficient new dry process of cement manufacture in China, most of which are new suspension preheater (NSP) kilns. The rapid growth of new dry process cement manufacture was a key trend in the development of China's cement industry after 2000, which is shown in Table 1.

Another reason for the energy intensity reduction seen in the Chinese cement industry is the rising adoption and utilization of waste heat recovery (WHR) power generation technologies, which is also shown in Table 1. WHR power generation avoided 0.23 EJ of fuel consumption3 in 2009 (Ze, 2010; Zeng, 2009b). At the same time, WHR power generation contributes to lower reported energy intensity of cement facilities as a result of the use of different energy conversion factors for accounting for electricity consumption and deducting WHR power generation. More specifically, according to the Chinese energy standard for cement facilities (AQSIQ and SAC, 2008), the conversion factor is 3.6 megajoules (MJ) per kilowatt-hour (kWh) when accounting for electricity consumption (i.e., adding 3.6

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[2] China officially uses coal equivalent calculation for its energy statistics (NBS, 2010a, 2010b). In this study, primary energy conversion of electricity uses the annual Chinese national average energy input of thermal power generation.

[3] The avoided fuel consumption is calculated using Chinese national average energy input of thermal power generation in 2009 of 9.96 megajoules (MJ) per kWh of electricity.

MJ to final energy consumption for kWh of electricity consumption), while the conversion factor is 11.8 MJ per kWh when deducting WHR power generation (not including self-use of WHR power generation). This implies that for every kWh of electricity produced by WHR to offset purchased electricity (electricity from external power generation), there is a net deduction of 8.2 MJ from final energy consumption [4]. Because WHR power generation can typically provide 25-33% of a cement facility's electricity demand for cement production (Zeng, 2009b), concerns have been raised about the discrepancy in electricity conversion factors and the significant resulting underestimation of final energy intensity of cement facilities (Wu, 2008; Zuo and Yang, 2011).

Table 1. Development of New Dry Process and Waste Heat Recovery (WHR) Power Generation in Chinese Cement Industry from 2000 to 2009.

Technology	Item	Year 2000	Year 2009	Average annual growth rate from 2000 to 2009
New dry process	Number of operational production lines	135	1113	26%
	Total clinker production capacity	70 Mt [a]	959 Mt	34%
	Share of Chinese clinker production capacity	10% [a]	77%	25%
WHR power generation	Installed capacity	6 MW [b]	3318 MW	100%
	Estimated electricity produced by WHR	0.05 TWh [b]	23.23 TWh [c]	100%

Source: CCA, 2008, 2009, 2010, 2011; Kong, 2009; Ze, 2010; Zeng, 2009b; Zhou, 2010. Calculations by authors.
[a] Approximation (Zhou, 2010).
[b] Estimated by authors according to Kong (2009) and Zeng (2009b).
[c] Estimated by Zeng (2009b).

According to Chinese statistics, the clinker-to-cement ratio has been decreasing in recent years, dropping from 72.9% in 2005 to 65.8% in 2009 (CCA, 2008, 2009, 2010, 2011; Digital Cement, 2011; Ze, 2010), which also reduces the energy intensity of cement industry. Because clinker making accounts for about 90% of the final energy consumption in cement production, reducing the clinker-to-cement ratio by mixing clinker with additives can greatly reduce the energy consumption for cement manufacture (Worrell et al., 2008). In other words, a lower clinker-to-cement ratio generally results in less energy consumption per unit of cement produced.

Table 2 lists the clinker and cement output and energy consumption and intensity of China's cement production in 2005-2009. Table 3 lists the final energy shares of China's cement production in 2005-2009. As seen in Table 2, from 2005 to 2009, the heat intensity for burning clinker decreased from 4.22 to 3.57 gigajoules (GJ) per metric ton (t) clinker produced, the final energy intensity of cement production decreased from 3.80 to 3.13 GJ per t cement produced, and the primary energy intensity of cement production decreased from 4.51 to 3.71 GJ per t cement produced. These results show the energy efficiency improvement in China's cement industry.

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[4] The net deduction of 8.2 MJ per kWh is the difference of 11.8 MJ deducted for kWh of electricity produced by WHR and 3.6 MJ added for kWh of electricity consumption (AQSIQ and SAC, 2008).

Table 2. Energy Consumption and Intensity of China’s Cement Production in 2005-2009.

Year	Clinker production		Cement Production							
	Output (Mt)	Heat intensity for burning clinker (GJ/t clinker)	Output (Mt)	Clinker to cement ratio (%)	Total fuel use (EJ)	Total electricity consumption (TWh)	Total final energy consumption (EJ) [a]	Total primary energy consumption (EJ) [b]	Final energy intensity (GJ/t cement)	Primary energy intensity (GJ/t cement)
2005	779.0	4.22	1068.9	72.9	3.68	105.50	4.06	4.82	3.80	4.51
2006	873.3	4.10	1236.1	70.6	4.03	118.30	4.46	5.30	3.61	4.29
2007	956.7	3.90	1361.2	70.3	4.16	127.68	4.62	5.49	3.39	4.03
2008	977.0	3.78	1420.1	68.8	4.22	133.35	4.70	5.57	3.31	3.92
2009	1084.0	3.57	1648.6	65.8	4.62	150.19	5.16	6.12	3.13	3.71

Source: Primary data from CCA, 2008, 2009, 2010, 2011; NBS, 2010a, 2010b, 2011; QEASCBM, 2011; SERC, 2009, 2010; Zeng, 2009a, 2009b, 2010; Zhou, 2007a, 2007b. Calculations by authors.

[a] Total final energy consumption is calculated using cement output and final energy intensity of cement production. Electricity produced by waste heat recovery (WHR) is not deducted to reflect the actual energy consumption for *cement production* without considering the sources of energy (i.e., from energy consumer’s view). When calculating the energy balance of cement facilities or the cement industry, electricity produced by WHR needs to be deducted from the total energy consumption to avoid double-counting.

[b] Primary energy conversion of electricity uses the annual Chinese national average energy input of thermal power generation: 10.84 MJ/kWh of electricity in 2005, 10.76 MJ/kWh of electricity in 2006, 10.43 MJ/kWh of electricity in 2007, 10.11 MJ/kWh of electricity in 2008, and 9.96 MJ/kWh of electricity in 2009.

Table 3. Final Energy Shares of China’s Cement Production in 2005-2009

Energy type	2005	2006	2007	2008	2009
Coal (%)	89.2	89.1	87.9	87.5	86.7
Electricity (%)	9.4	9.6	10.0	10.2	10.5
Diesel (%)	0.4	0.4	0.5	0.4	0.4
Other fuels (%) [a]	1.1	1.0	1.6	1.9	2.4

Source: Primary data from CCA, 2008, 2009, 2010, 2011; IFC, 2007; QEASCBM, 2011; Zhou, 2007a, 2007b. Calculations by authors.

[a] Other fuels mainly include coke, coal gangue, heat, industrial and municipal wastes.

Cement process and fossil fuel combustion emissions are defined as direct emissions from cement industry and emissions from external production of electricity consumed by cement production are referred as indirect emissions (CSI, 2005). The cement process emissions are estimated according to the Cement Sustainability Initiative (CSI) clinker-based methodology and default emission factors and adjustments (CSI, 2005). The CO2 emissions from external production of electricity consumed by cement production are estimated using the annual national average emission factor for China’s power sector (NBS, 2010a, 2011; SERC, 2009, 2010). Electricity transmission and distribution (T&D) losses are not taken into account (CSI, 2005).

Table 4 lists the estimated direct and indirect CO2 emissions from China's cement production in 2005-2009. This shows that the total CO2 emissions from China's cement production increased from 2005 to 2009 due to the rapid growth of cement output, even though the CO2 emission intensity significantly decreased during the same time period.

Table 4. Estimation of CO$_2$ Emissions from China's Cement Production in 2005-2009

Year	2005	2006	2007	2008	2009
Clinker output (Mt)	779.0	873.3	956.7	977.0	1084.0
Process emission factor (t CO$_2$/t clinker) [a]	0.547	0.547	0.547	0.547	0.547
Cement process CO$_2$ emissions (Mt CO$_2$) [a]	426.0	477.6	523.2	534.3	592.9
Cement output (Mt)	1068.9	1236.1	1361.2	1420.1	1648.6
Emissions from fossil fuel combustion (Mt CO$_2$) [b]	347.8	381.2	393.3	399.1	437.6
Implied emission factor of fossil fuel combustion (t CO$_2$/t cement)	0.325	0.308	0.289	0.281	0.265
Direct emissions (Mt CO$_2$) [c]	773.8	858.8	916.5	933.5	1030.5
Implied direct emission factor (t CO$_2$/t cement) [c]	0.724	0.695	0.673	0.657	0.625
Total electricity consumption (TWh)	105.50	118.30	127.68	133.35	150.19
Electricity produced by waste heat recovery (TWh) [d]	0.44	1.56	4.28	11.29	23.23
Electricity from external power generation (TWh) [e]	105.05	116.73	123.40	122.06	126.96
National average grid emission factor (kg CO$_2$/kWh) [f]	0.834	0.836	0.813	0.763	0.755
Emissions from external electricity production (Mt CO$_2$) [g]	87.6	97.5	100.3	93.2	95.9
Clinker-to-cement ratio (%)	72.9	70.6	70.3	68.8	65.8
Total emissions (Mt CO$_2$) [h]	861.4	956.3	1016.8	1026.6	1126.4
Implied total emission factor (t CO$_2$/t cement) [h]	0.806	0.774	0.747	0.723	0.683

Source: Primary data from CCA, 2008, 2009, 2010, 2011; CSI, 2005; IPCC, 2006; NBS, 2010a, 2010b, 2011; QEASCBM, 2011; Zeng, 2009b; Zhou, 2007a, 2007b. Calculations by authors.

[a] Cement process emissions are estimated according to the Cement Sustainability Initiative (CSI) clinker-based methodology and default emission factors and adjustments (CSI, 2005).

[b] According to the final energy consumption and fuel mix for cement production, the CO$_2$ emissions from fossil fuel combustion are estimated by adopting the Intergovernmental Panel on Climate Change (IPCC) default CO$_2$ emission factors for fossil fuels combustion (IPCC, 2006).

[c] Direct emissions include cement process and fossil fuel combustion emissions.

[d] Estimated by Zeng (2009b).

[e] Calculated by subtracting the electricity produced by waste heat recovery from the total electricity consumption.

[f] Electricity transmission and distribution losses are excluded (CSI, 2005).

[g] The emissions from external generation of electricity consumed by cement production are regarded as indirect emissions for cement industry (CSI, 2005) and are estimated using the annual national average grid emission factor.

[h] Total emissions include direct emissions and emissions from external electricity production (indirect emissions). IEA (2007) estimated that the total CO$_2$ emissions per t of cement from calcination and energy (including electricity) in 2003-2004 were about 0.65 t CO$_2$ /t of cement in Brazil, Italy and Spain, 0.84 CO$_2$ /t of cement in China, and 0.93 t CO$_2$ /t of cement in the United States (in 2003-2004, the average clinker-to-cement ratio was about 81% in Brazil, 78% in Italy, 80% in Spain, 74% in China, and 91% in the United

States). IEA (2007) noted that care should be taken when making direct inter-country comparisons because of uncertainties in system boundaries and methodological issues.

It should be noted that because the Chinese government has already decided to phase out most of the outdated cement production capacity by 2012 (MIIT, 2009), the energy and CO2 emission intensities of cement production are expected to further decrease. However, total energy consumption and CO2 emissions will still increase if China's cement industry continues its fast development.

3. Projections of China's Cement Output to 2030

Projections of cement output are needed to reasonably estimate the potential energy savings and CO2 emissions reduction from the cement industry in the future. While the future cannot be predicted accurately, it is possible to build scenarios of the future that may reflect the consequences of different economic, technological or policy conditions (Sathaye and Meyers, 1995). We make three projections of China's cement output: a Building and Infrastructure Construction-based (BIC) projection, a Peak Consumption Per Capita-based (PCPC) projection, and a Fixed Assets Investment-based (FAI) projection. We note that the BIC projection relies more on physical drivers than the other two projections.

Recent research indicates that China's total primary energy consumption will rise continuously until it approaches a plateau around 2030 because of saturation effects, slowdown of urbanization, low population growth, and change in exports to high value-added products (Zhou et al., 2010). This indicates China's economic development will enter a relatively steady phase around 2030. For this reason, our projection of China's cement industry production, energy use, and CO2 emissions is focused on the time period of 2011 to 2030.

A number of variables need to be defined in order to estimate future cement production. Specifically, it is important to define the drivers of the growth of cement output. Historical data show China's cement output is closely related to fixed assets investment 5 (CCA, 2010, 2011). We analyzed the relationship between cement output and many economic and physical factors, such as GDP, fixed assets investment, population and income per capita, and verified the close relationship between cement output and fixed assets investment.

China's fixed assets investment in Chinese yuan (CNY) 2005 constant value6 and cement output in 1990-2010 are plotted in Figure 3. As Figures 3 shows, the growth of cement production generally follows the trend of fixed assets investment as construction and buildings together accounted for about 60% of China's fixed assets investment (NBS, 2010b). The growth of China's cement industry in 2009 was

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[5] National Bureau of Statistics (NBS) defines China's fixed assets investment as the volume of activities in construction and purchases of fixed assets and related fees, expressed in monetary terms during the reference period (NBS, 2010b).

[6] The average exchange rate of the Chinese yuan (CNY) for the U.S. dollar in 2005 is 8.19 yuan per dollar (NBS, 2010b).

accelerated by the Chinese government's 4 trillion CNY economic stimulus plan for 2009-2011. Because China's GDP growth relied heavily on investment after 2000, especially in 2009 when investment contributed 95.2% to the total GDP growth (NBS, 2010b), fixed assets investment played an important role in the economic stimulus plan. The growth rate of fixed assets investment was 30% in 2009 and 24% in 2010 (NBS, 2010b, 2011).

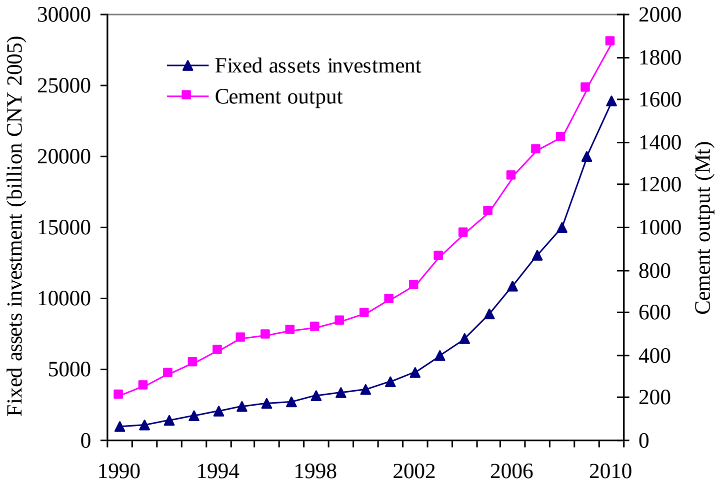

Figure 3. China's Fixed Assets Investment and Cement Output in 1990-2010

Source: Primary data from CCA, 2008, 2009, 2010, 2011; Ma, 2011; NBS, 2010b, 2011. Calculations by authors.

We used historical cement output data and fixed assets investment between 1990 and 2009 to build a statistical prediction model in SPSS (IBM, 2010) and used 2010 data to verify the model. The fitted and projected results are shown in Figure 4. As Figure 4 shows, the prediction of the model for 2010 is close to the actual output. This again verifies the close relationship between cement output and fixed assets investment. As a reference, the projections from the model for 2011-2015 are also plotted in Figure 4. The cement output projections for 2011-2015 are based on the projection of the growth rate and price index of the fixed assets investment in 2011-2015 in a number of referenced projections (Cheng and Yue, 2010; Sinolink Securities, 2010; Xu, 2011). Specifically, the nominal growth rate of fixed assets investment has been projected to be 20% for 2011, 15% for 2012, 10% for 2013-2015. We also assume that the price index for fixed assets investment will be 104 (preceding year = 100) for 2011-2015.

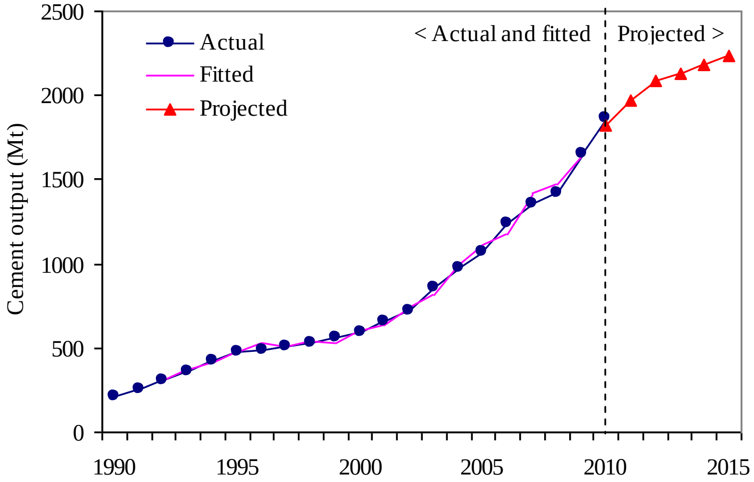

Figure 4. China's Actual Cement Output and FAI Model Output to 2015

Source: Primary data from CCA, 2008, 2009, 2010, 2011; Cheng and Yue, 2010; NBS, 2010b, 2011; Sinolink Securities, 2010; Xu, 2011. Calculations by authors.

According to this FAI prediction model, cement output in 2015 will be about 2.24 Gt, 20% higher than the 2010 level.

Zuo (2010) analyzed the historical trend of cement consumption per capita of three countries and regions in Asia and concluded that none of them could sustain their annual cement consumption per capita at their peak for more than five years. Annual cement consumption per capita of South Korea reached its peak in 1997, which was 1,343 kg cement per capita (Zuo, 2010). China's annual cement consumption per capita was already 1,380 kg in 2010. Researches show that China's annual cement consumption per capita is unlikely to substantially exceed this level (Hong, 2008; Zeng, 2009c; Zuo, 2010).

Given the above analysis, the three projections (i.e., BIC, PCPC and FAI) are explained as follows:

(1) BIC projection: this projection is based on Lawrence Berkeley National Laboratory (LBNL)'s China building and infrastructure construction forecast (Zhou et al., 2010). Physically, cement demand is closely linked to construction demand from urbanization and infrastructure development. In modeling China's cement industry, the future cement output Pc is calculated using the following formula:

$$P_c = F_b \times I_b + A_p \times I_p + A_h \times I_h + L_r \times I_r + X$$

where
Fb is the three-year rolling average total floor area of residential and commercial buildings and
Ib is building cement material intensity;
Ap is three-year rolling average urban paved area and
Ip is paved area cement material intensity;

Ah is three-year rolling average area of highways and
Ih is highway cement material intensity;
Lr is three-year rolling average railroad track length and
Ir is railroad track cement material intensity;
X is net export of cement.

Cement material intensities were derived by the authors based on relevant construction codes and standards (CABR, 2001; CCCC, 2003; MOHURD, 2010; MOT, 2004) and LBNL's China End-Use Energy Model (Zhou et al., 2010). Since the construction forecast is intended to be a long-term projection, only the mid- to long-term forecast (i.e., after 2020) is used and projected cement production is interpolated between 2010 and 2020. After 2022, the projected cement production enters a relatively steady state mainly due to the saturation effects.

(2) PCPC projection: this projection is based on the assumption that China's annual cement consumption per capita will increase steadily to 1,544 kg (15% more than the South Korea's peak value in 1997) by 2015[7] and then decrease steadily to 1,366 kg cement per capita (slightly lower than 2010 level of 1,380 kg) by 2020. We further assume the decreasing trend will continue until the annual cement consumption per capita reaches the 1,000 kg level[8] in 2025 at which point it remains frozen at this level. This will result in about 1.45 Gt of annual cement output for 2025-2030 [9].

(3) FAI projection: cement output is projected using the FAI prediction model in the short-term and the cement production and consumption trend observed in other countries over the long-term (Hong, 2008; Zeng, 2009c; Zuo, 2010). More specifically, cement output in 2011-2015 is projected using the FAI statistical prediction model, with the total cement output assumed to peak at 2.24 Gt in 2015 (with corresponding annual cement consumption per capita of 1,594 kg). After 2015, annual cement consumption per capita is assumed to gradually decrease to 750 kg by 2030, based on the trend seen in Japan and Taiwan[10] (Hong, 2008; Zeng, 2009c; Zuo, 2010). This assumption is reasonable because LBNL's China building and infrastructure construction forecast results in a similar level of cement consumption per capita in 2030 (Zhou et al., 2010). Cement output after 2015 is calculated using population projections and annual cement consumption per capita.

The three projections and their mean trend are plotted in Figure 5. Table 5 lists the projected cement output in 2020 and 2030 and cumulative projected cement output from 2011 to 2030.

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[7] The peak assumption of total cement output around 2015 by Gao (2010) and Tong et al. (2010) is adopted in this study.

[8] South Korea's average annual cement consumption per capita after its 1997 peak is used as a reference (Zuo, 2010).

[9] The population data were retrieved from the United Nations' *World Population Prospects*: *The 2008 Revision Population Database* (UN, 2009).

[10] Taiwan's annual cement consumption per capita peaked at 1,350 kg in 1993, and then decreased to 745 kg in 2001 (Zeng, 2009c).

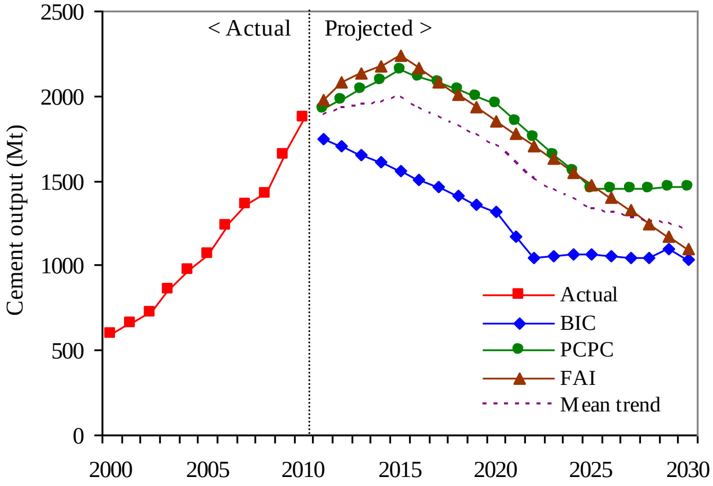

Figure 5. Projections of China's Cement Output to 2030

Note: BIC (Building and Infrastructure Construction-based), PCPC (Peak Consumption Per Capita-based) and FAI (Fixed Assets Investment-based) represent different projections of cement production levels.

As a reference, Table 5 also shows a comparison of some recent mid- to long-term projections by other researchers and LBNL projections of China's cement output. In 2020, LBNL BIC projection falls within the range of other studies while PCPC and FAI are slightly higher. In 2030, LBNL BIC and FAI projections are very similar to ERI high-demand and ISTIC projections, while PCPC projection is close to CEACER's projection.

Table 5. Comparison of Mid- to-long-term Projections of China's Cement Output

Projection	Year 2020	Year 2030	Cumulative output from 2011 to 2030
BIC (Gt)	1.32	1.04	26.0
PCPC (Gt)	1.96	1.46	35.9
FAI (Gt)	1.86	1.10	35.0
ERI baseline scenario (Gt)	1.00	0.90	- [a]
ERI high-demand scenario (Gt)	1.10	1.10	- [a]
CEACER low-carbon scenario (Gt)	1.60	1.60	- [a]
ISTIC (Gt)	1.50 [b]	1.13	29 [b]

Source: CEACER (2009); ERI (Jiang and Hu, 2006); ISTIC (Tong et al., 2010).
Note: BIC (Building and Infrastructure Construction-based), PCPC (Peak Consumption Per Capita-based) and FAI (Fixed Assets Investment-based) represent different projections of cement production levels.
[a] Not available due to insufficient data.
[b] Approximation.

Because cement production is actually limited by domestic limestone resources11, the physical feasibility of LBNL's three projection is also verified. China has discovered 7000 to 8000 limestone mines that can be used for cement production and the total extractable reserve12 of the limestone resource is 54.2 Gt (Wang, 2007; Zeng, 2003; Zhang, 2005). Approximately 1 t limestone resources are consumed to produce 1 t of cement, based on an average clinker-to-cement ratio of about 65% for China's cement production13. Given the limestone resource constraint, China's maximum cumulative cement output from 2008 to 2030 should be about 54.2 Gt, if there is no significant change or improvement in cement production that reduces the limestone input per t of cement produced. Because China already produced about 4.9 Gt of cement from 2008 to 2010, the maximum cumulative cement output would be 49.3 Gt from 2011 to 2030. This illustrates that the three projections of cement production in this study are physically feasible as the cumulative projected cement output by 2030 of each projection (i.e., 26.0 Gt for BIC, 35.9 Gt for PCPC and 35.0 Gt for FAI) is less than the limit (i.e., 49.3 Gt) due to the resources constraint.

4. Potential Energy Savings and CO_2 Emissions Reduction from China's Cement Industry

We estimate two types of potential energy savings and CO2 emission reductions for China's cement industry: best practice savings potential and continuous improvement potential. The best practice savings potential is estimated using scenario analysis based on the assumption of a one-time improvement of China's cement industry to the current world best practice energy intensity14 and one-time implementation of currently available aggressive energy efficiency and carbon reduction measures, while the continuous improvement potential is based on continuous energy efficiency improvement and carbon reduction.

4.1. Scenario Assumptions

The Long-range Energy Alternatives Planning system (LEAP)15 modeling tool is used for the scenario-based modeling and analysis of potential energy savings and CO2 emissions reduction. To analyze the impact of different energy efficiency and carbon reduction measures and policies, four scenarios are constructed: a frozen scenario, a best practice scenario, a reference scenario and an efficiency scenario.

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[11] Cement production is a low value-added industry. It is unlikely that China will import limestone for its cement production due to the high cost of transportation.

[12] The definition of extractable reserve in China is equal to the definition of *reserve* of U.S. Geological Survey, i.e., "that part of the reserve base which could be economically extracted or produced at the time of determination" (USGS, 2011).

[13] Approximately 1.5 t limestone resources are consumed to produce 1 t of clinker (Zeng, 2011).

[14] "World best practice energy intensity values represent the most energy-efficient processes that are in commercial use in at least one location worldwide" (Worrell et al., 2008). Because best practice energy intensities may depend strongly on the material inputs, the potential energy savings and energy-related CO2 emission reductions estimated in this paper should be considered as indicative.

[15] LEAP is a scenario-based energy-environment modeling tool, of which scenarios are based on "comprehensive accounting of how energy is consumed, converted and produced" (SEI, 2010).

The frozen scenario is constructed based on 2009 production and energy data of China's cement industry and reflects a future path at the current energy efficiency and emission level of China's cement industry without further efficiency improvement.

The best practice scenario evaluates the theoretical upper bound savings potential of China's cement industry by assuming that the cement production instantly reaches the current world best practice energy intensity and implements currently available aggressive energy efficiency and carbon reduction measures by 2011 and stays at that level from then on. Specifically, we assume that in 2011, all outdated cement production is phased out and the average final energy intensity of China's cement production would reach current world best practice for 425 fly ash cement (2.07 GJ per t of cement produced), which has an assumed clinker-to-cement ratio of 65% that is similar to the cement produced in China after 2009 (Worrell et al., 2008). We further assume that: (1) alternative fuels would replace coal as the main fuels for cement production and coal share would be reduced to 40%; (2) the penetration of WHR power generation would be 100% and average of 36 kWh of electricity can be produced per t clinker through WHR power generation (Zeng, 2009b).

In contrast to the one-time achievement in the best practice scenario, the reference and efficiency scenarios are constructed as continuous improvement scenarios, taking into account current production trends and assuming different implementation levels of efficiency measures, technologies, fuel switching policy choices. Compared to the reference scenario, the efficiency scenario reflects faster efficiency improvement due to more aggressive policy choices.

Table 6 shows the assumed final energy intensity and cement output shares by technology for different scenarios, Tables 7 shows the assumed energy shares for different scenarios, and Table 8 shows the assumed penetration of WHR power generation and national average grid emission factor for different scenarios.

Table 6. Assumed Final Energy Intensity and Cement Output Shares by Technology for Different Scenarios in 2010-2030

Scenario	**Technology**	**Final energy intensity by technology (GJ/t cement)**					**Mass shares of cement output by technology (%)**				
		2010	2011	2015	2020	2030	2010	2011	2015	2020	2030
Frozen	Rotary kilns	3.01	3.01	3.01	3.01	3.01	79.1	79.1	79.1	79.1	79.1
	Shaft kilns	3.52	3.52	3.52	3.52	3.52	20.9	20.9	20.9	20.9	20.9
Reference	Rotary kilns	3.01	3.00	2.97	2.93	2.49	79.1	81.2	89.5	100.0	100.0
	Shaft kilns [a]	3.52	3.52	3.52	-	-	20.9	18.8	10.5	0.0	0.0
Efficiency	Rotary kilns	3.01	3.00	2.93	2.49	2.07	79.1	83.3	100.0	100.0	100.0
	Shaft kilns [a]	3.52	3.52	-	-	-	20.9	16.7	0.0	0.0	0.0
Best practice	Rotary kilns	3.01	2.07	2.07	2.07	2.07	79.1	100.0	100.0	100.0	100.0
	Shaft kilns [a]	3.52	-	-	-	-	20.9	0.0	0.0	0.0	0.0

[a] Phasing out all shaft kilns by 2020 for the reference scenario, 2015 for the efficiency scenario, and 2011 for the best practice scenario.

Table 7. Assumed Final Energy Shares for Different Scenarios in 2010-2030

Scenario	Energy type	Final energy shares (%)				
		2010	2011	2015	2020	2030
Frozen	Coal	86.7	86.7	86.7	86.7	86.7
	Electricity	10.5	10.5	10.5	10.5	10.5
	Diesel	0.4	0.4	0.4	0.4	0.4
	Biomass [a]	0.2	0.2	0.2	0.2	0.2
	Alternative fuels [b]	2.2	2.2	2.2	2.2	2.2
Reference	Coal	86.7	85.4	80.0	73.4	60.0
	Electricity	10.5	10.5	10.5	10.5	10.6
	Diesel	0.4	0.4	0.4	0.4	0.4
	Biomass [a]	0.2	0.2	0.2	0.2	0.2
	Alternative fuels [b]	2.2	3.5	8.9	15.5	28.8
Efficiency	Coal	86.7	84.4	75.0	63.4	40.0
	Electricity	10.5	10.5	10.5	10.5	10.6
	Diesel	0.4	0.4	0.4	0.4	0.4
	Biomass [a]	0.2	0.2	0.2	0.2	0.2
	Alternative fuels [b]	2.2	4.5	13.9	25.5	48.8
Best practice	Coal	86.7	40.0	40.0	40.0	40.0
	Electricity	10.5	10.6	10.6	10.6	10.6
	Diesel	0.4	0.4	0.4	0.4	0.4
	Biomass [a]	0.2	0.2	0.2	0.2	0.2
	Alternative fuels [b]	2.2	48.8	48.8	48.8	48.8

Source: Primary data from CCA, 2008, 2009, 2010, 2011; QEASCBM, 2011. Calculations by authors.

[a] Biomass is also a common alternative fuel. Biomass is assumed to be carbon neutral.

[b] Assume an average emission factor of 73.3 t CO2 per TJ for alternative fuels in this study.

Table 8. Assumed Penetration of Waste Heat Recovery (WHR) Power Generation and National Average Grid Emission Factor for Different Scenarios in 2010-2030

Scenario	Penetration of WHR power generation (% of clinker production) [a]					National average grid emission factor (kg CO_2/kWh) [b]				
	2010	2011	2015	2020	2030	2010	2011	2015	2020	2030
Frozen	0	0	0	0	0	0.755	0.742	0.655	0.584	0.451
Reference	60	63	75	80	90	0.755	0.742	0.655	0.584	0.451
Efficiency	60	64	80	90	100	0.755	0.742	0.655	0.584	0.451
Best practice	60	100	100	100	100	0.755	0.742	0.655	0.584	0.451

[a] Assume that WHR power generation can produce 36 kWh of electricity per t clinker produced (Zeng, 2009b).

[b] The annual national average grid CO_2 emission factor is derived from LBNL's China 2050 modeling research (Zhou et al., 2010). Electricity transmission and distribution losses are excluded (CSI, 2005).

The frozen scenario is taken as the basis to estimate the continuous improvement potential and best practice savings potential. More specifically, the potential energy savings and CO2 emission reductions are estimated according to the differences of energy consumption and CO2 emissions between a given scenario (e.g., reference or efficiency or best practice) and the frozen scenario.

By combining the three energy efficiency and emission reduction scenarios (reference, efficiency and best practice) with the three cement output projections (BIC, PCPC and FAI) from Section 3, the energy savings and emissions reduction potential can be estimated for nine cases: BIC reference, BIC efficiency, BIC best practice, PCPC reference, PCPC efficiency, PCPC best practice, FAI reference, FAI efficiency and FAI best practice.

It should also be noted that only energy-related CO2 emission reductions are taken into account in this analysis due to three primary reasons. First, due to the rapid growth of the new dry process cement manufacture and policy of phasing out outdated production capacity policy in China's cement industry, the cement process-related emissions reduction potential is rapidly declining. Second, carbon capture and storage (CCS) for control of CO2 in the cement industry was not considered in this analysis because current analyses indicate that its use in the cement industry will not be significant before 2030. Specifically, CCS is not expected to be commercially available before 2020 and will face challenges with high costs and energy penalty (ECRA, 2009; IEA and WBCSD, 2009). Third, although reducing the clinker-to-cement ratio reduces the amount of energy required and CO2 emissions to produce one t of cement in theory, the clinker-to-cement ratio of China's cement production is already very low. Depending upon what materials are mixed in with the clinker, reducing the clinker-to-cement ratio may also affect the cement quality. This has been raised as a concern in China. Thus, the clinker-to-cement ratio is not expected to be significantly lower than the current level, assuming there is no large change in China's cement production technologies and products. Therefore, we use the clinker-to-cement ratio in 2009 (i.e., 65.8%) as the reference value in the scenario analysis.

The use of alternative fuels, especially the use of waste to replace traditional fossil fuels has numerous environmental benefits (CEMBUREAU, 1997; ICF International, 2008; Murray and Price, 2008). Depending on types and mix of alternative fuels, using alternative fuels may or may not reduce the direct CO2 emissions from cement plants, but could reduce total CO2 emissions from life cycle assessment perspective (CEMBUREAU, 1999; CSI, 2003). We assume an average emission factor of 73.3 t CO2 per TJ for alternative fuels in this study, which indicates that using alternative fuels could reduce about 23% of CO2 emissions overall compared to burning bituminous coal of which assumed emission factor is 94.6 t CO2 per TJ (IPCC, 2006).

4.2. Modeling results and analysis

Given the three cement production projections described in Section 3, energy consumption and CO2 emissions for different scenarios are calculated and the results are shown in Figure 6 and Tables 9 and 10. Figure 6 shows the projected annual final energy consumption for different scenarios in 2011-2030. Table 9 shows the projected cement output and CO2 emissions for different scenarios in 2015, 2020 and 2030. Table 10 shows the projected cumulative final energy consumption and CO2 emissions for different scenarios in 2011-2030.

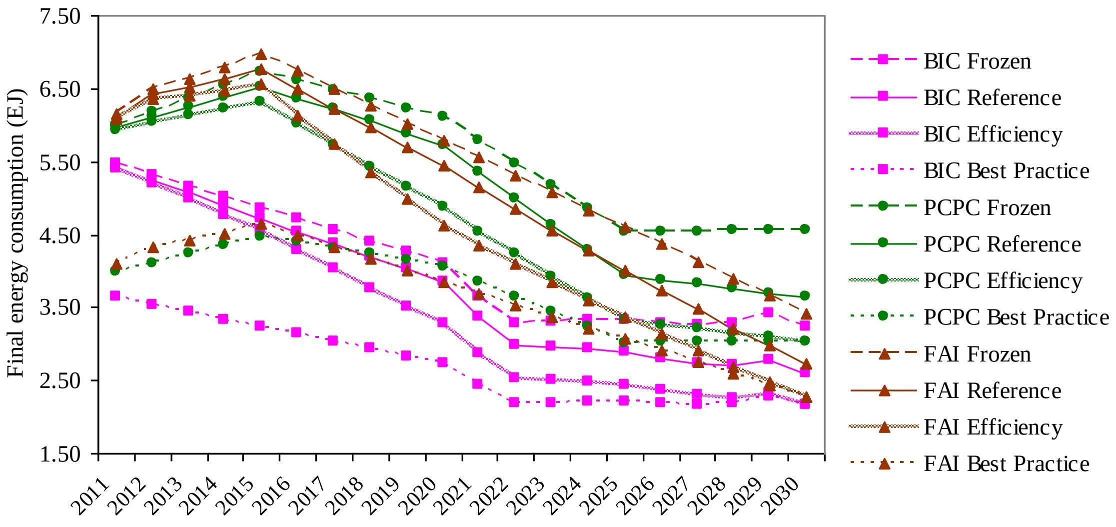

Figure 6. Projected Annual Final Energy Consumption for Different Scenarios in 2011-2030

Note: BIC (Building and Infrastructure Construction-based), PCPC (Peak Consumption Per Capita-based) and FAI (Fixed Assets Investment-based) represent different projections of cement production levels.

Table 9. Projected Cement Output and CO_2 Emissions for Different Scenarios in 2015, 2020 and 2030

Scenario	Cement output (Gt)			Direct CO_2 emissions (Gt) [a]			Indirect CO_2 emissions (Gt) [b]		
	2015	2020	2030	2015	2020	2030	2015	2020	2030
BIC frozen	1.56	1.32	1.04	0.97	0.82	0.65	0.09	0.07	0.04
BIC reference	1.56	1.32	1.04	0.95	0.79	0.58	0.07	0.05	0.02
BIC efficiency	1.56	1.32	1.04	0.93	0.73	0.53	0.07	0.04	0.02
BIC best practice	1.56	1.32	1.04	0.80	0.68	0.53	0.04	0.03	0.02
PCPC frozen	2.16	1.96	1.46	1.34	1.22	0.91	0.13	0.10	0.06
PCPC reference	2.16	1.96	1.46	1.31	1.17	0.81	0.10	0.08	0.03
PCPC efficiency	2.16	1.96	1.46	1.29	1.09	0.75	0.09	0.06	0.02
PCPC best practice	2.16	1.96	1.46	1.11	1.00	0.75	0.05	0.04	0.02
FAI frozen	2.24	1.86	1.10	1.39	1.15	0.68	0.13	0.10	0.04
FAI reference	2.24	1.86	1.10	1.36	1.11	0.61	0.10	0.07	0.03
FAI efficiency	2.24	1.86	1.10	1.34	1.03	0.56	0.10	0.06	0.02
FAI best practice	2.24	1.86	1.10	1.15	0.95	0.56	0.05	0.04	0.02

Note: BIC (Building and Infrastructure Construction-based), PCPC (Peak Consumption Per Capita-based) and FAI (Fixed Assets Investment-based) represent different projections of cement production levels.

[a] Direct emissions include cement process and fossil fuel combustion emissions.

[b] Indirect emissions only include CO_2 emissions from external electricity production and are calculated according to LBNL projected China's annual national average grid emission factor (Zhou et al., 2010). Electricity transmission and distribution losses are excluded (CSI, 2005).

Table 10. Projected Cumulative Energy Consumption and CO_2 Emissions for Different Scenarios in 2011-2030

Scenario	Cumulative cement output (Gt)	Cumulative final energy consumption (EJ)	Cumulative WHR power generation (TWh)	Cumulative direct CO_2 emissions (Gt) [a]	Cumulative indirect CO_2 emissions (Gt) [b]
BIC frozen	26.0	81.1	0.0	16.2	1.4
BIC reference	26.0	75.1	480.9	15.5	1.0
BIC efficiency	26.0	68.0	525.2	14.8	0.9
BIC best practice	26.0	54.0	616.0	13.3	0.6
PCPC frozen	35.9	112.1	0.0	22.3	1.9
PCPC reference	35.9	103.5	668.7	21.3	1.4
PCPC efficiency	35.9	93.2	732.2	20.3	1.2
PCPC best practice	35.9	74.6	851.0	18.4	0.8
FAI frozen	35.0	109.2	0.0	21.8	1.9
FAI reference	35.0	101.3	648.1	20.8	1.4
FAI efficiency	35.0	91.5	708.6	19.9	1.2
FAI best practice	35.0	72.7	829.2	18.0	0.8

Note: BIC (Building and Infrastructure Construction-based), PCPC (Peak Consumption Per Capita-based) and FAI (Fixed Assets Investment-based) represent different projections of cement production levels.

[a] Direct emissions include cement process and fossil fuel combustion emissions.

[b] Indirect emissions only include CO_2 emissions from external electricity production and are calculated according to LBNL projected China's annual national average grid emission factor (Zhou et al., 2010). Electricity transmission and distribution losses are excluded (CSI, 2005).

As shown in Figure 6 and Tables 9 and 10, higher cement production corresponds to greater energy consumption and CO2 emissions, which indicates that slowing or reducing the growth of cement production is the most direct way to reduce total energy consumption and CO2 emissions. For example, reducing cumulative cement production from 35.9 Gt for PCPC frozen scenario to 26.0 Gt for BIC frozen scenario can reduce 31 EJ of final energy consumption16 and 6.1 Gt of direct CO2 emissions17 cumulatively without energy efficiency improvement. However, it is difficult to reduce cement production given the fact that investment, especially fixed assets investment, will likely play an important role in Chinese GDP growth and the Chinese government wants to develop its infrastructure rapidly in the near future. Given the constraints of China's economic structure and current development goals, improving cement grade and quality can help reduce the cement consumption required for construction and therefore reduce cement production. One policy that can help drive quality improvement in cement production is strengthening building material requirements in building and construction codes and standards (Lei, 2011).

Figure 7 shows the annual potential final energy savings for different scenarios in 2011-2030, and Figure 8 shows the annual potential energy-related direct CO2 emissions reduction for different scenarios in 2011-2030. Table 11 lists the cumulative potential final energy savings and energy-related CO2 emission reductions in 2011-2030 for the reference and efficiency and best practice scenarios compared to the corresponding frozen scenario. As the results show, the potential energy savings and energy-related CO2 emission reductions are large for all reference and efficiency and best practice scenarios compared to the corresponding frozen scenario. In other words, China's cement industry has large potential for energy savings and energy-related CO2 emissions reduction, if proper policies and energy efficiency and carbon reduction measures are taken. It should be noted that the absolute potential for energy savings and energy-related CO2 emissions reduction from the PCPC and FAI cases is larger than the BIC case because the PCPC or FAI cases will result in higher cement production than the BIC case.

Calculations show that best practice energy savings and energy-related direct CO2 emissions reduction potential accounts for about 33% and 20% of the cumulative final energy consumption and total direct CO2 emissions (including cement process and fossil fuel combustion emissions) of China's cement industry, respectively. The continuous improvement potential is smaller than the best practice savings potential, given the realistic constraint that China's entire cement industry cannot meet the world best practice energy intensity level and implement all aggressive energy efficiency and carbon reduction

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[16] The reduction of 31 EJ final energy consumption is the difference of the cumulative final energy consumption in the PCPC frozen scenario (112.1 EJ) and the cumulative final energy consumption in the BIC frozen scenario (81.1 EJ).

[17] The reduction of 6.1 Gt direct CO2 emissions is the difference of the direct CO2 emissions in the PCPC frozen scenario (22.3 Gt) and the direct CO2 emissions in the BIC frozen scenario (16.2 Gt).

measures in one year. Depending on the paces of efficiency improvement and carbon reduction (i.e., reference or efficiency scenario), the continuous improvement energy savings potential can reach 22% to 49% of the best practice scenario energy savings potential, and the continuous improvement energy-related direct CO2 emissions reduction potential can reach 31% to 54% of the best practice scenario energy-related direct CO2 emissions reduction potential.

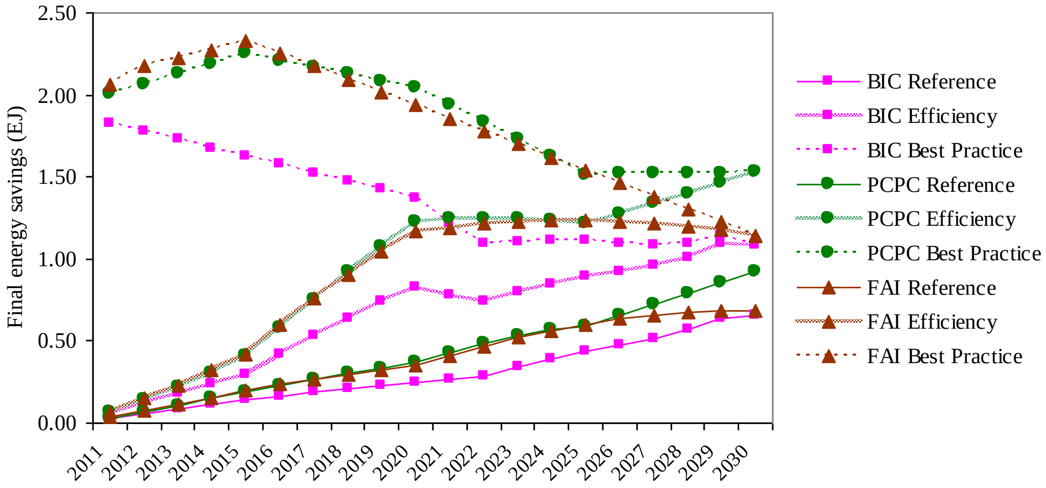

Figure 7. Annual Potential Final Energy Savings for Different Scenarios in 2011-2030

Note: BIC (Building and Infrastructure Construction-based), PCPC (Peak Consumption Per Capita-based) and FAI (Fixed Assets Investment-based) represent different projections of cement production levels.

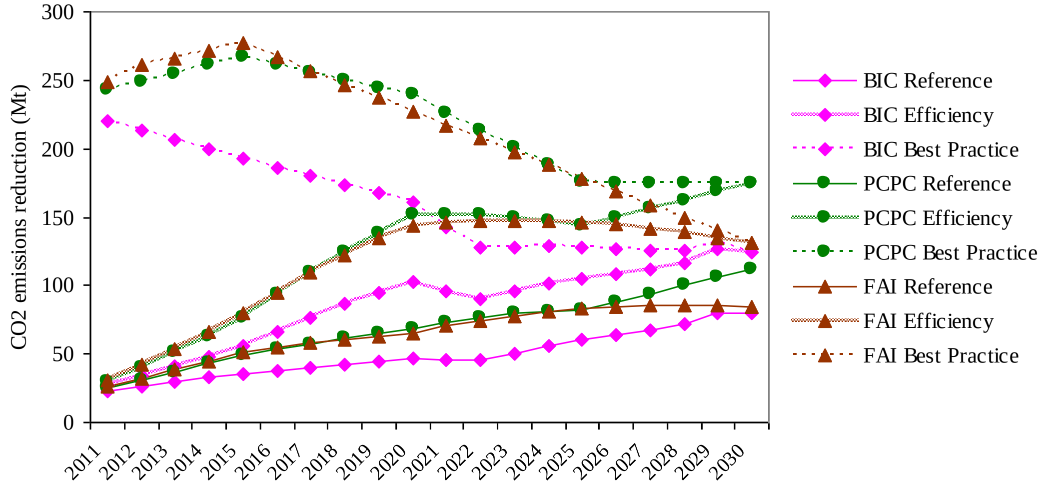

Figure 8. Annual Potential Energy-related Direct CO_2 Emissions Reduction for Different Scenarios in 2011-2030

Note: (1) BIC (Building and Infrastructure Construction-based), PCPC (Peak Consumption Per Capita-based) and FAI (Fixed Assets Investment-based) represent different projections of cement production levels; (2) Energy-related direct CO_2 emissions reduction includes fossil fuel combustion emission reductions and avoided emissions due to waste heat recovery (WHR) power generation.

Table 11. Cumulative Potential Final Energy Savings and CO_2 Emission Reductions for Different Scenarios in 2011-2030

Scenario	Cumulative final energy savings (EJ)	Cumulative energy-related direct CO_2 emission reductions (Gt)			Cumulative indirect CO_2 emission reductions (Gt) [c]
		Cumulative fossil fuel combustion emission reductions (Gt)	Cumulative avoided CO_2 emissions due to WHR power generation (Gt) [a]	Total (Gt) [b]	
BIC reference	6.0	0.7	0.3	1.0	0.1
BIC efficiency	13.2	1.4	0.3	1.7	0.2
BIC best practice	27.1	2.8	0.4	3.2	0.5
PCPC reference	8.6	1.0	0.4	1.4	0.1
PCPC efficiency	18.9	2.0	0.4	2.4	0.3
PCPC best practice	37.5	3.9	0.5	4.4	0.6
FAI reference	7.9	0.9	0.4	1.3	0.1
FAI efficiency	17.7	1.9	0.4	2.3	0.3
FAI best practice	36.5	3.8	0.5	4.3	0.6

Note: BIC (Building and Infrastructure Construction-based), PCPC (Peak Consumption Per Capita-based) and FAI (Fixed Assets Investment-based) represent different projections of cement production levels.

[a] Avoided CO_2 emissions due to waste heat recovery (WHR) power generation are calculated according to LBNL projected China's annual national average grid emission factor (Zhou et al., 2010). Electricity transmission and distribution losses are excluded (CSI, 2005).

[b] Total energy-related direct emissions reduction includes fossil fuel combustion emission reductions and avoided emissions due to WHR power generation.

[c] Indirect emissions only include CO_2 emissions from external electricity production and are calculated according to LBNL projected China's annual national average grid emission factor (Zhou et al., 2010). Electricity transmission and distribution losses are excluded (CSI, 2005).

As described in Section 4.1, reductions in fossil fuel combustion emissions can be attributed to three energy efficiency and carbon reduction measures: energy intensity reduction, technology switching and fuel switching. We calculate the contributions of these three measures in the cumulative fossil fuel combustion emission reductions and the results are shown in Table 12. As shown in Table 12, energy efficiency, especially energy intensity reduction (technology switching essentially results in energy intensity reduction), accounts for the largest share of fossil fuel combustion emission reductions.

Table 12. Contributions of Three Energy Efficiency and Carbon Reduction Measures in Cumulative Fossil Fuel Combustion Emission Reductions for Different Scenarios in 2011-2030

Scenario	Energy intensity reduction (%)	Technology switching (%) [a]	Fuel switching (%) [b]
Reference	39	34	27
Efficiency	51	28	21
Best practice	58	23	19

[a] From shaft kilns to rotary kilns.

[b] From coal to alternative fuels. Assume an average emission factor of 73.3 t CO2 per TJ for alternative fuels in this study.

The analysis presented here estimates the potential for different scenarios and reflects the consequences of different future economic, technological or policy conditions of China's cement industry. The different scenarios also show that regardless of the cement production levels examined in this analysis, there are important, albeit of varying degrees, energy savings and emission reduction potentials from assumed scenarios in this study.

5. Future Outlook of China's Cement Industry

Investment - and fixed assets investment in particular - has played an important role in China's rapid GDP growth. As cement is one of the most important raw materials for building and infrastructure construction, China's cement industry grew rapidly with large state investment and market demand. China's per capita cement consumption was 1,380 kg in 2010, while the average per capita cement consumption in the rest of the world in the same year was only about 260 kg. Over the next twenty years of China's development, rising urbanization will drive continued growth of infrastructure construction. At the same time, investment in building and infrastructure construction will remain an important policy for the Chinese government to promote economic growth.

Though cement investment and output could still increase because of the significant demand from building and infrastructure construction in the near future, this fast pace of growth will unlikely continue for a long time. Once China's building and infrastructure construction reaches or is close to the level of developed countries, the demand for cement is expected to decrease significantly. At this point, cement production capacity will be much larger than cement demand and serious capacity surpluses may occur. Furthermore, almost all of the cement production capacity by then will be the new dry process and outdated production capacity will be phased out. As a result, domestic competition will be intense and it is likely that the profit margin of cement production will be reduced (Gao, 2010). This is not a good future for China's cement industry from the view of investment and economic growth. However, the possibility of cement production capacity surplus could force the cement producers to improve efficiency to reduce costs. Energy cost is one of the most critical factors for the cement industry, energy prices will most likely rise, and the possibility of charging carbon tax on carbon-intensive products is increasing in China. As a result, this cement production capacity surplus will speed up the elimination of outdated capacity and drive a large portion of those relatively energy inefficient small new dry process capacities out of the market (Lei, 2011) if the local governments do not protect them from market competition. From the view of energy efficiency, this capacity surplus is a kind of passive, market-driven energy efficiency measure.

In 2009, China announced a goal to reduce its carbon intensity (CO2 emissions per unit of GDP) by 40-45% over 2005 level by 2020 (Fu et al., 2009). China's emissions reduction target is based on economic emissions intensity, and it is not absolute emissions reduction. Economic emissions intensity is associated with economic development. Cement is necessary for building and infrastructure construction, but it is typically ahigh energy intensity, high emissions and low value-added product. In order to meet the national carbon intensity reduction target, China's government may need to adopt some effective or emergency measures, such as to greatly increase energy prices, reduce the power supply or mandate reduced manufacturing of some products which have high energy and emissions intensity but are low value-added products. This strategy has already been adopted by local governments in 2010, the last year to meet China's 20% energy intensity reduction target for the Eleventh Five-Year Plan. Because the national target was decomposed to the provinces, Hainan, the southernmost province of China, faced difficulty in meeting its energy intensity reduction target. From August 2010, Hainan reduced the power supply to its own cement production which subsequently reduced cement production by 0.8 Mt cement per month. However, during the second half of 2010, Hainan's cement consumption rose quickly due to demand for building and infrastructure construction, especially for some key state projects. This caused a short supply of cement and a sharp increase in cement prices. Therefore, Hainan had to import cement from Shandong, which is 2700 kilometers away, but the province was ultimately able to meet its target (Ren and Chen, 2010). This illustrates the leakage issue of carbon intensity targets with trade between cement producers and emphasizes continued challenges for China in its path to reduce energy and carbon intensity.

6. Conclusions

The cement industry will remain one of the critical sectors for China to meet its CO2 emissions reduction target. China's cement production will continue to grow in the near future given its close relationship with fixed assets investment, which is expected to continue growing because fixed assets investment has been a main driver of China's GDP growth. Over the long term, China's cement production will decline because of saturation effects such as floor area per capita, slowdown of urbanization, and low population growth. Yet China's CO2 emissions from the cement industry will rise with increased cement production, especially if there is no significant efficiency improvement in the cement production process and CCS is not taken into consideration. Significant energy savings and CO2 emissions reduction potential of China's cement industry is mainly attributable to the large quantity of cement production. Thus, if China wants to slow the growth of cement production and consumption, then it should consider adopting more effective regulations and suitable policies for the cement industry. In the short term, this cannot be easily done given the economic structure and development goals set by the Chinese government. However, improving the cement grade and quality through policies such as strengthened building and construction codes and standards can help reduce cement consumption required for construction and therefore reduce cement production.

With the rapid development of the new dry process of cement manufacture and phasing out of outdated production capacity in recent years and in the absence of CCS, there is diminishing potential for process-related emissions reduction in China's cement industry. Thus, energy efficiency will be crucial to reducing the energy and emissions intensity of the cement industry. This analysis examined the energy savings and energy-related CO2 emissions reduction potential of different energy efficiency and carbon reduction measures and policies in China's cement industry through analysis of different scenarios of future cement output and energy efficiency improvements and carbon reductions. Under a theoretical best practice scenario, final energy savings and energy-related direct CO2 emissions reduction potential can account for as much as 33% and 20% of the cumulative final energy consumption and total direct CO2 emissions from 2011 to 2030, respectively, if China could achieve current world best practice and implement aggressive energy efficiency and carbon reduction measures in all cement production in 2011. This translates into 27.1 to 37.5 EJ of cumulative final energy savings and 3.2 to 4.4 Gt of energy-related direct CO2 emissions reduction from 2011 to 2030, depending on the projected cement production. Depending on the paces of efficiency improvement, the more realistic continuous improvement scenarios can reach 22% to 49% of the best practice scenario final energy savings potential, and 31% to 54% of the best practice scenario energy-related direct CO2 emissions reduction potential.

These results highlight that while policies to reduce total cement production are the most direct way to reduce total energy consumption and CO2 emissions, it is difficult in the short term given China's economic structure and development goals and suggests energy efficiency is the most important policy measure for reducing the cement industry's energy and emissions intensity.

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