Study on the assessment and reduction technology of carbon dioxide from cementing material manufacturing sector

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Abstract. For the purposes of simplifying the calculation task, adjusting production processes in time and solving the inconsistent requirements for carbon emissions, this paper investigates the calculation methods of carbon dioxide emissions from cement production, for example IPCC, WBCSD-CSI, MEE-CBMA, CNIS and BNU. Then a simplification and intuitive method is proposed. Based on the intuitive method, CO$_2$ emission of 21 cement plants in China are calculated and analyzed, of which the error between the calculation results and those obtained by HJ 2519-2012 is less than 0.5%. About the carbon reduction technology in cement industry, there is limited reduction space that rely on energy efficiency improvements and clinker substitution. The technology of alternative fuels still needs to be further expanded. China has operated the first demonstration production line of CCUS technology at the Anhui Baimashan Conch cement plant with a capacity of 20,000 tons/year of industrial-grade liquid CO$_2$ products and 30,000 tons/year of food-grade liquid CO$_2$ products. Alternative raw material technology may be one developing direction to cut carbon emission; only 6.18% of steel slag was added to the raw meal at a 2500t/d production line, CO$_2$ emission from process emissions were reduced by nearly 10%.

1. Introduction

Cement industry is the fundamental industry sector for the economic construction and production development, which is also a typical resource and energy consumption industry sector. With China’s rapid economic and infrastructures growth requirements, 2.33 billion tons of cement was produced by 3427 cement plants, 1712 NSP clinker production lines of China’s cement industry in 2019, accounting for nearly 60% of global cement output. According to the cement production processes, a large amount of limestone, coal and power resources are consumed in the preparation of raw meal, clinker calcination and other main processes, which would cause direct or indirect CO$_2$ emission. Cement industry has become the second largest source of CO$_2$ emission in the manufacturing sector, nearly 7% of total CO$_2$ emission. However, carbon dioxide emission reduction application technology in the cement industry lags far behind the advanced level [1].

Facing the climate change and the requirement of carbon management, several organizations have formed CO$_2$ emission calculation and measurement systems of cement manufacturing sector. For example, the Intergovernmental Panel on Climate Change (IPCC) and the World Business Council for Sustainable Development (WBCSD) have promulgated a series of universal measurement methods. The United States and the European Union also have proposed their own measurement standards. Since 2012, China also established series CO$_2$ emission calculation methods for cement plant, providing guidelines for the low carbon cement product certification and national carbon emission trading market in the
cement industry. For example, China established the statistical accounting system for GHG emissions of key industries and enterprises, which was including cement industry, and in further started up National Carbon Emission Trading Market of cement industry with the scale of 1.2 billion ton, since January 11, 2016.

The carbon dioxide accounting and trading experiences demand that the employees of cement plant learn how to calculate CO$_2$ emissions during cement production, and adjust production processes to reduce or control carbon emissions timely. It may be a big challenge for these [2].

In this paper, to solve those issues, a new, simplification and intuitive method is proposed. The method is a look-up table query method to calculate the CO$_2$ emissions of cement plant, which is simplifying the calculation steps, and making the self-examination more efficient. According the domestic calculation examples and data analysis in China, explore the causes of deviations in the results, and give some suggestions about the future developing direction of cement production emission reductions, such as alternative raw materials, carbon capture, utilization and storage technologies.

2. Principle of carbon dioxide calculation methods

2.1. Analysis of existing carbon dioxide calculation methods

The following mainly introduces the calculation methods of carbon dioxide emissions from cement production from IPCC, WBCSD-CSI, MEE-CBMA, CNIS and BNU.

The 2006 IPCC Guideline for National Greenhouse Gas Inventories (2006 IPCC Guideline) is provided for greenhouse gas inventory arrangements and management, data gathering, compilation, reporting and estimating anthropogenic emissions by sources and removals by sinks of greenhouse gases, which were published in 2006, and then refined in 2019 [3]. The Greenhouse Gas Protocol for the Cement Industry [4] is provided for a method to calculate the CO$_2$ emission from the cement industry, which was published in 2001, 2005 and 2011.

In China, HJ 2519-2012 Technical requirement for environmental labeling products-Cement was provided for developing and implementing the CO$_2$ statistics, monitoring and assessment methods for the cement industry sector by Ministry of Ecology and Environment (MEE) and China Building Materials Academy (CBMA), and further for the starting up the low carbon cement product certification in 2012. In 2014, Certification and Accreditation Administration of the People’s Republic of China (CNCA) published the Certification Implementation Rules of Low Carbon Product, and then officially launched the first national batch of low-carbon product certification of ordinary Portland cement. Until 2015, GB/T 32151.8-2015 Requirements of the greenhouse gas emission accounting and reporting—Part 8: Cement enterprise was provided by China National Institute of Standardization (CNIS) for the accounting and reporting of greenhouse gas emissions from cement manufacturers. And with the popularization and application of alternative raw material technologies, GB/T 33756-2017 Technical specification at the project level for assessment of greenhouse gas emission reductions—Alternative of raw materials in cement clinker production industry was provided by Beijing Normal University (BNU). And in 2018, RB/T 260-2018 Technical specifications for carbon emissions verification in cement enterprises was provided by CNCA.

The comparison of calculation items with five calculation methods was list in table 1.
Table 1. Comparison of IPCC, CSI, MEE-CBMA, CNIS and BNU methods.

| Emission resources | IPCC | WBCSD-CSI | MEE-CBMA | CNIS | BNU |
|--------------------|------|-----------|----------|------|-----|
| CO₂ from raw materials | Clinker calcination | ✓ | ✓ | ✓ | ✓ | ✓ |
| Dust calcination | ✓ | ✓ | ✓ | ✓ | ✓ |
| Organic carbon burning | ✓ | ✓ | ✓ | ✓ | ✓ |
| Traditional fuel | ✓ | ✓ | ✓ | ✓ | ✓ |
| Fossil alternative fuel | ✓ | ✓ | ✓ | ✓ | ✓ |
| CO₂ from fuel burning | Biomass alternative fuels | ✓ | ✓ | ✓ | ✓ | ✓ |
| Non-fuel carbon | ✓ | ✓ | ✓ | ✓ | ✓ |
| CO₂ from waste heat utilization | ✓ | ✓ | ✓ | ✓ | ✓ |
| CO₂ from outsourcing electricity | ✓ | ✓ | ✓ | ✓ | ✓ |
| CO₂ from outsourcing heat | ✓ | ✓ | ✓ | ✓ | ✓ |
| CO₂ from outsourcing clinker | ✓ | ✓ | ✓ | ✓ | ✓ |
| CO₂ from outsourcing fine grinding admixture materials | ✓ | ✓ | ✓ | ✓ | ✓ |

In terms of research scales and calculation emission factor resources, the calculation methods based on the plant data and clinker emission factor is the mainstream approach.

2.2. Principle of intuitive method

2.2.1. Major sources of CO₂ emissions from cement production. CO₂ emissions of cement production are resourced from direct and indirect emissions, which are shown in Table 2 and Figure 1, according to China's cement production processes, equipment, the consumption of raw materials and fuels, electricity consumption, and types of cement products [5-6].

Table 2. Major sources of CO₂ emissions from cement production.

| Emission resources | Explanation |
|--------------------|-------------|
| decomposition of carbonate minerals in raw meal | CaCO₃, MgCO₃ |
| material coal consumption in production processes | diesel |
| non-fuel carbon burning in raw meal | waste oil, waste plastic, FRP (glass fiber reinforced plastic), etc. |
| fuel oils consumption in production process | cement production process, auxiliary production management |
| alternative fuel consumption | pre-treatment, storing and transferring systems |
| coal and fuel oils consumption in waste co-processing process | excluding this item when facing the statistics at the national level |
| power consumption in cement production process | |
| power consumption in waste co-processing process | |
| outsourcing clinker and fine grinding admixture materials | |
2.2.2. Calculation procedures of intuitive method. It needs three steps to calculate the CO$_2$ emissions per unit of cement product based on the intuitive method. The first step is to inquire these data, including the CaO and MgO mass fraction in the clinker, the weighted average low heat value of material coal, the material coal consumption per unit of clinker, the ratio of material to cement, the mass percentage of non-fuel carbon in raw meal and other production data [7-8]. And then the second step is to obtain relative parameters, through the look-up table of CO$_2$ emission from the decomposition of carbonate minerals in raw materials, look-up table of CO$_2$ emission from material coal consumption, look-up table of CO$_2$ emission from non-fuel carbon in clinker, look-up table of correction factor of unit comparable quantity emissions of cement clinker production. The last step is to calculate the unit comparable quantity of CO$_2$ emission of cement clinker and cement, through those parameters and equation (1) and equation (2).

(1) Unit comparable quantity of CO$_2$ emission of cement clinker

Unit comparable quantity of CO$_2$ emissions of cement clinker should be calculated following the equation (1) with the parameters in Table 3, Figure 2, Table 4, Table 5, equation (14) and equation (15):

$$C_{ck} = (P_{rc} + P_{bcl} + P_{ro} + P_{ei} + P_{oil}) \times K_{ck} \quad (1)$$

Where:
- $P_{rc}$—CO$_2$ emission from the decomposition of carbonate minerals in raw materials, in units of kg per ton of clinker (kg/tcl);
- $P_{bcl}$—CO$_2$ emission from material coal, in units of kg per ton of clinker (kg/tcl);
- $P_{ro}$—CO$_2$ emission from non-fuel carbon combustion in raw meal, in units of kg per ton of clinker (kg/tcl);
- $P_{ei}$—indirect CO$_2$ emission from power consumption, in units of kg per ton of clinker (kg/tcl);
- $P_{oil}$—indirect CO$_2$ emission from fuel combustion in various production processes during the statistical period, in units of kg per ton of clinker (kg/tcl).

(2) Unit comparable quantity of CO$_2$ emission of cement

Unit comparable quantity of CO$_2$ emissions for cement with different type and strength grade should be calculated following the equation (2) and (3) with the relative parameters of unit comparable quantity of CO$_2$ emission of cement clinker, mass fraction of clinker to cement, mass fraction of outsourcing fine grinding admixture materials and the power consumption of cement grinding:

When outsourcing cement clinker and outsourcing fine grinding admixture materials were used for producing the cement, it should be calculated following the equation (2):

$$C_{cel} = (Q_{ck} \times C_{ck} \times K_{c} \times \delta_{c} \times \delta_{sl} > F_{e}) \times \sqrt{S_{q} \times S_{c} \times S_{e}} \quad (2)$$

When there were no outsourcing cement clinker and outsourcing fine grinding admixture materials were used for producing the cement, it should be calculated following the equation (3):

$$C_{cel} = (Q_{ck} \times \delta_{c} \times \delta_{sl} \times F_{e}) \times \sqrt{S_{q} \times S_{c} \times S_{e}} \quad (3)$$
Where:

- \( C_{\text{cel}} \) — unit comparable quantity of \( \text{CO}_2 \) emissions for cement with different type and strength grade in the statistics period, in the units of kg per ton of cement (kg/t);
- \( K_c \) — amount of outsourcing cement clinker in the statistics period, in the units of ton (t);
- \( F_p \) — unit comparable quantity of \( \text{CO}_2 \) emission of outsourcing cement clinker, in the units of kg per ton of cement (kg/t); if missing statistical data, 940 kg/t can be used as the default value;
- \( \delta_{\text{cl}} \) — mass fraction of clinker in cement with different type and strength grade in the statistics period, in %;
- \( F_s \) — \( \text{CO}_2 \) emission factor of outsourcing fine grinding admixture materials in the units of kg per ton of cement (kg/t); if missing statistical data, 50 kg/t can be used as the default value;
- \( e_l \) — in the statistics period, power consumption for cement grinding with different type and strength grade, kW·h/t;
- \( \delta_{\text{fr}} \) — mass fraction of outsourcing fine grinding admixture materials in the cement with different type and strength grade, %;
- \( S_q \) — strength grade of cement when it leaves the factory, in units of MPa;
- \( S_{\text{cel}} \) — actual average 28 day compressive strength for cement with different type and strength grade in the statistics period, in units of MPa.

(3) \( \text{CO}_2 \) emission from the decomposition of carbonate minerals

\( \text{CO}_2 \) emissions from the decomposition of carbonate minerals are composed by \( \text{CO}_2 \) emission from the decomposition of carbonate minerals in raw meal, \( \text{CO}_2 \) emission from the carbonate minerals in the flue gas dust of kiln exhaust stack (kiln outlet) and bypass dust. In actual practice, there is few companies use bypass venting, which can be ignored. Therefore they can be calculated by the equation (4):

\[
P_{\text{rc}} = \left( C_c \times \frac{44}{56} + C_m \times \frac{44}{40} \right) \times 1000 \times (1 + \frac{U_e}{1000})
\]  

(4)

Where:

- \( C_c \) — CaO mass fraction in the clinker, %;
- \( C_m \) — MgO mass fraction in the clinker, %;
- \( 44/56 \) — molecular weight conversion between \( \text{CO}_2 \) and CaO;
- \( 44/40 \) — molecular weight conversion between \( \text{CO}_2 \) and MgO.
- \( U_e \) — the dust amount in the flue gas of kiln exhaust stack (kiln outlet) per ton of clinker, in unit of kg per ton clinker (kg/t); when no tested data available, 0.15 kg/t can be used as the default value.

Since the measured value of \( U_e \) generally fluctuates around the default value, 0.15 kg/t can be used as the default value of \( U_e \) in this method. According to the value range of \( C_c \) and \( C_m \) and the Matlab software, the full array of \( \text{CO}_2 \) emission from the decomposition of carbonate minerals are obtained as shown in Table 3.
Table 3. Look-up table of CO₂ emission from the decomposition of carbonate minerals in raw materials, kg/tcl.

| MgO % | CaO % | 64.1 | 64.3 | 64.5 | 64.7 | 64.9 | 65.1 | 65.3 | 65.5 | 65.7 | 65.9 | 66.1 | 66.3 | 66.5 |
|-------|-------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 0.6   | 510   | 512  | 513  | 515  | 517  | 518  | 520  | 521  | 523  | 524  | 526  | 528  | 529  |
| 0.8   | 512   | 514  | 516  | 517  | 519  | 520  | 522  | 523  | 525  | 527  | 528  | 530  | 531  |
| 1.0   | 515   | 516  | 518  | 519  | 521  | 523  | 525  | 526  | 528  | 529  | 531  | 533  | 534  | 536  |
| 1.2   | 517   | 518  | 520  | 522  | 523  | 525  | 526  | 528  | 529  | 531  | 533  | 534  | 536  |
| 1.5   | 520   | 522  | 523  | 525  | 526  | 528  | 530  | 531  | 533  | 534  | 536  | 537  | 539  |
| 1.7   | 522   | 524  | 525  | 527  | 529  | 530  | 532  | 533  | 535  | 536  | 538  | 540  | 541  |
| 1.9   | 525   | 526  | 528  | 529  | 531  | 532  | 534  | 536  | 537  | 539  | 540  | 542  | 543  |
| 2.1   | 527   | 528  | 530  | 531  | 533  | 535  | 536  | 538  | 539  | 541  | 542  | 544  | 546  |
| 2.3   | 529   | 531  | 532  | 534  | 535  | 537  | 538  | 540  | 542  | 543  | 545  | 546  | 548  |
| 2.5   | 531   | 533  | 534  | 536  | 537  | 539  | 541  | 542  | 544  | 545  | 547  | 548  | 550  |
| 2.7   | 533   | 535  | 536  | 538  | 540  | 541  | 543  | 544  | 546  | 547  | 549  | 551  | 552  |
| 2.9   | 536   | 537  | 539  | 540  | 542  | 543  | 545  | 547  | 548  | 550  | 551  | 553  | 554  |
| 3.1   | 538   | 539  | 541  | 542  | 544  | 546  | 547  | 549  | 550  | 552  | 553  | 555  | 557  |
| 3.3   | 540   | 542  | 543  | 545  | 546  | 548  | 549  | 551  | 553  | 554  | 556  | 557  | 559  |
| 3.5   | 542   | 544  | 545  | 547  | 548  | 550  | 552  | 553  | 555  | 556  | 558  | 559  | 561  |
| 3.7   | 544   | 546  | 547  | 549  | 551  | 552  | 554  | 555  | 557  | 558  | 560  | 562  | 563  |
| 3.9   | 547   | 548  | 550  | 551  | 553  | 554  | 556  | 558  | 559  | 561  | 562  | 564  | 565  |
| 4.1   | 549   | 550  | 552  | 553  | 555  | 557  | 558  | 560  | 561  | 563  | 564  | 566  | 568  |
| 4.3   | 551   | 553  | 554  | 556  | 557  | 559  | 560  | 562  | 564  | 565  | 567  | 568  | 570  |
| 4.5   | 553   | 555  | 556  | 558  | 559  | 561  | 563  | 564  | 566  | 567  | 569  | 570  | 572  |
| 4.7   | 555   | 557  | 558  | 560  | 562  | 563  | 565  | 566  | 568  | 569  | 571  | 573  | 574  |
| 4.9   | 558   | 559  | 561  | 562  | 564  | 565  | 567  | 569  | 570  | 572  | 573  | 575  | 576  |


\(^a\) CO₂ emission in Table 3 excludes CO₂ emissions from the decomposition of carbonate minerals in byproduct.

\(^b\) Ue is determined as 0.15 kg/t.

(4) CO₂ emission from the combustion of material coals

CO₂ emission from the combustion of material coals in production processes should be calculated following the equation (5):

\[ P_{bcl} = \frac{P_{cl}\times Q_{bcl}\times J}{29.307 \times 1000} \]  

Where:

- \( P_{bcl} \) — comprehensive coal consumption per unit of clinker in the statistical period, in t/t;
- \( Q_{bcl} \) — the weighted average low heat value of material coal for various batches into plant in the statistical period, in kcal/kg;
- \( J \) — the mechanical equivalent of heat, which is 4.186 kJ/kcal;
- \( F_b \) — CO₂ emission factor of standard coal, in t/tce; it is determined uniformly by the state as 2.75 t/tce;
- 29.307 — the calorific value of standard coal, in MJ/kgce.

Though Matlab software and all relative parameters, Figure 2 can be obtained by simplifying the equation and taking the contour. And CO₂ emission from the combustion of material coals per ton of clinker can be found in the Figure 2, through the comprehensive coal consumption per unit of clinker and the weighted average low heat value of material coal.
Figure 2. Look-up chart of CO$_2$ emission from material coal consumption (Pbc)

(5) CO$_2$ emission from the burning non-fuel carbon of raw meal

CO$_2$ emission from the burning non-fuel carbon of raw meal should be calculated following the equation (6):

$$P_{\text{ro}} = r_a \times R_o \times \frac{44}{12} \times 1000$$

(6)

Where:

- $r_a$—the ratio of material to cement; if missing statistical data, 1.52 can be used as the default value;
- $R_o$—the non-fuel carbon fraction of raw meal, %; if missing statistical data, 0.1%~0.3% (in dry state) can be used as the default value. When coal gangue and high carbon fly ash are used in the raw meal preparation, it is taken as 0.3%; otherwise it is taken as 0.1%;
- 44/12—molecular weight conversion between CO$_2$ and C;

In actual calculation process, the actual value of $r_a$ is generally between 1.5~1.6. Table 4 is obtained by doing a full permutation of $P_{\text{ro}}$.

Table 4. Look-up table of CO$_2$ emission from non-fuel carbon burning per ton clinker, kg/tcl.

| $r_a$  | $R_o$ % | 0.10 | 0.12 | 0.14 | 0.16 | 0.18 | 0.20 | 0.22 | 0.24 | 0.26 | 0.28 | 0.30 |
|-------|---------|------|------|------|------|------|------|------|------|------|------|------|
| 1.50  | 5.5     | 6.6  | 7.7  | 8.8  | 9.9  | 11.0 | 12.1 | 13.2 | 14.3 | 15.4 | 16.5 |      |
| 1.51  | 5.5     | 6.6  | 7.8  | 8.9  | 10.0 | 11.1 | 12.2 | 13.3 | 14.4 | 15.5 | 16.6 |      |
| 1.52  | 5.6     | 6.7  | 7.8  | 8.9  | 10.0 | 11.1 | 12.3 | 13.4 | 14.5 | 15.6 | 16.7 |      |
| 1.53  | 5.6     | 6.7  | 7.9  | 9.0  | 10.1 | 11.2 | 12.3 | 13.5 | 14.6 | 15.7 | 16.8 |      |
| 1.54  | 5.6     | 6.8  | 7.9  | 9.0  | 10.2 | 11.3 | 12.4 | 13.6 | 14.7 | 15.8 | 16.9 |      |
| 1.55  | 5.7     | 6.8  | 8.0  | 9.1  | 10.2 | 11.4 | 12.5 | 13.6 | 14.8 | 15.9 | 17.1 |      |
| 1.56  | 5.7     | 6.9  | 8.0  | 9.2  | 10.3 | 11.4 | 12.6 | 13.7 | 14.9 | 16.0 | 17.2 |      |
| 1.57  | 5.8     | 6.9  | 8.1  | 9.2  | 10.4 | 11.5 | 12.7 | 13.8 | 15.0 | 16.1 | 17.3 |      |
| 1.58  | 5.8     | 7.0  | 8.1  | 9.3  | 10.4 | 11.6 | 12.7 | 13.9 | 15.1 | 16.2 | 17.4 |      |
| 1.59  | 5.8     | 7.0  | 8.2  | 9.3  | 10.5 | 11.7 | 12.8 | 14.0 | 15.2 | 16.3 | 17.5 |      |
| 1.60  | 5.9     | 7.0  | 8.2  | 9.4  | 10.6 | 11.7 | 12.9 | 14.1 | 15.3 | 16.4 | 17.6 |      |

(6) indirect CO$_2$ emission from power consumption
Indirect CO\textsubscript{2} emission from power consumption includes all the CO\textsubscript{2} emission from power consumption excluding cement grinding, shipping and packaging, which should be calculated following the equation (7):

\[
P_{\text{ecl}} = \frac{(E_1+E_2+E_3-E_r+E_5)\times F_e}{Q_{\text{ck}}}
\]

Where:
- \(E_1\) — power consumption in mining and mineral transportation, kW\cdot h
- \(E_2\) — power consumption in raw meal preparation, kW\cdot h
- \(E_3\) — power consumption in clinker calcination, kW\cdot h
- \(E_5\) — net power generation by waste heat, kW\cdot h
- \(E_r\) — CO\textsubscript{2} emission factor of electric power, in kg/kW\cdot h; it is determined uniformly by the state as 0.86 kg/kW\cdot h.

(7) indirect CO\textsubscript{2} emission from fuel consumption

Indirect CO\textsubscript{2} emission from fuel consumption includes all the CO\textsubscript{2} emission from the fuels of in-plant vehicle transportation and kiln startup ignition, which should be calculated following the equation (8):

\[
P_{\text{oilcl}} = \frac{O_{\text{ildi}}\times Q_{\text{noldi}}\times F_{di} + O_{\text{ilgl}}\times Q_{\text{nolgl}}\times F_{gl}}{Q_{\text{ck}}}
\]

Where:
- \(O_{\text{ildi}}\) — the amount of diesel oil used in each production process during the statistic period, in t;
- \(O_{\text{ilgl}}\) — the amount of gasoline used in each production process during the statistical period, in t;
- \(Q_{\text{noldi}}\) — low calorific value of diesel oil, as 43 MJ/kg;
- \(Q_{\text{nolgl}}\) — low calorific value of gasoline, as 44.3 MJ/kg;
- \(F_{di}\) — CO\textsubscript{2} emission factor of diesel oil, as 0.0741 kg/MJ;
- \(F_{gl}\) — CO\textsubscript{2} emission factor of gasoline, as 0.0700 kg/MJ.

In the self-examination or rough calculation of the cement enterprise, since the gasoline consumption in the plant is generally small, the gasoline consumption can be integrated into the uniform calculation of the diesel, thereby for reducing the calculation content, of which the error value is below 1‰.

(8) correction factor of unit comparable quantity CO\textsubscript{2} emissions of cement clinker (K\textsubscript{ck})

It is necessary to obtain the unit comparable quantity of CO\textsubscript{2} emission of cement clinker when carrying the self-examination or rough calculation of the cement enterprise, then the correction coefficient (K\textsubscript{ck}) is introduced, which is mainly the conversion of strength and altitude for the cement enterprise. Through the Matlab software, the total arrangement of K\textsubscript{ck} is programmed as shown in Table 5.

Table 5. Look-up table of correction factor of unit comparable quantity CO\textsubscript{2} emission of cement clinker, K\textsubscript{ck}.

| 2nd compressive strength, MPa | Altitude, m |
|-----------------------------|-------------|
| 54                          | 54.5        |
| 55                          | 55.5        |
| 56                          | 56.5        |
| 57                          | 57.5        |
| 58                          | 58.5        |
| 59                          | 59.5        |
| 60                          | 60.5        |
| 61                          | 61.5        |
| 62                          | 62.5        |
| 63                          |             |

| 1-999                       | 0.9960       | 0.9963       |
| 1000                        | 0.9964       | 0.9967       |
| 1200                        | 0.9971       | 0.9974       |
| 1400                        | 0.9976       | 0.9979       |
| 1600                        | 0.9981       | 0.9984       |
| 1800                        | 0.9986       | 0.9989       |
| 2000                        | 0.9991       | 0.9994       |
| 2200                        | 0.9996       | 0.9999       |
| 2400                        | 0.9999       | 1.0002       |
| 2600                        | 1.0001       | 1.0004       |
| 2800                        | 1.0003       | 1.0006       |
| 3000                        | 1.0004       | 1.0007       |
| 3200                        | 1.0006       | 1.0009       |
| 3400                        | 1.0008       | 1.0011       |
| 3600                        | 1.0009       | 1.0012       |
| 3800                        | 1.0010       | 1.0013       |
| 4000                        | 1.0011       | 1.0014       |
3. Case study of assessment of carbon dioxide in China cement plants

Though the above intuitive method, CO$_2$ emission of 21 cement manufacturers in China are calculated and shown in Table 6, which include direct CO$_2$ emissions, indirect CO$_2$ emissions, and CO$_2$ emission from the carbonate decomposition, CO$_2$ emission from coals. The error between the calculation result of this intuitive method and the result obtained by using the method of HJ 2519-2012 Technical requirement for environmental labeling products-Cement is less than 0.5%.

Table 6. CO$_2$ emission of 21 China cement plant.

| No. | Output of clinker, tcl/y | Direct CO$_2$ emission, t | Indirect CO$_2$ emission, t | Total emission, t |
|----|-------------------------|--------------------------|--------------------------|------------------|
| Cb1 | 737700                  | 615690.51                | 49244.78                 | 664935.29        |
| Ca1 | 585288.79               | 483418.86                | 43000.81                 | 526419.67        |
| Cd1 | 1268114                 | 105225.053               | 91228.13                 | 114453.183       |
| Ce1 | 1506316                 | 1202021.69               | 90442.02                 | 1292463.718      |
| Ce1 | 1060888                 | 877774.777              | 85083.568                | 962858.344       |
| Cd2 | 1171002.77             | 989946.18                | 64477.37                 | 1054423.55       |
| Ce2 | 1470802                 | 122523.95               | 76741.91                 | 1301975.86       |
| Ef1 | 1650166.6              | 1395167.278              | 85608.557                | 1480775.84       |
| Ebf1| 2243245                 | 1948740.884              | 108980.367               | 2057721.251      |
| Ebb1| 1284766.19             | 1090148.171             | 62383.7228               | 1152531.894      |
| Nd1 | 1118050                 | 930540.74               | 70026.03                 | 1000566.77       |
| Nab1| 1698246                 | 1543593.403             | 114103.769               | 1657697.173      |
| Nbb1| 1608965                 | 1357448.235             | 426419.384               | 1783867.62       |
| Wdd1| 2988655.09             | 2629114.174             | 191738.7496              | 2820852.924      |
| Wc1 | 817631.48               | 688269.6                | 73275.61                 | 761545.21        |
| Wb1 | 906565                 | 743703.83               | 68913.72                 | 812617.55        |
| Wl1 | 1842964.58             | 1520948.9               | 89850.62                 | 1610799.52       |
| Wf1 | 3637524                 | 3046674.57              | 190955.93                | 3237630.5        |
| Wel1| 665495                  | 575292.784               | 51769.7833               | 627062.5681      |
| Wdl1| 1042461                 | 927387.51               | 85926.2952               | 1013313.805      |
| Wa1 | 794378.37              | 692955.8388             | 53063.9214               | 746019.7572      |
| Total| 30,099,224.87           | 25,534,296.94           | 2,173,235.00             | 27,707,531.94    |

*a* the cement plant is located in the east, west, south or north of China, respectively named as S, W, C, N;  
*b* the cement plant named as a, b, c, d, e, f is respectively corresponding for that with the designed scale of 2000t/d, 2500t/d, 3000t/d, 4000t/d, 4500t/d, 5000t/d;  
*c* when the cements with the same location and designed scale, the sequence numbers of them are named as 1, 2, 3, 4, 5.

Regarding to the Wf1 cement plant, it takes use of the sandstone, steel slag and fly ash for raw meal preparation, with the clinker output of 1.8429 million tons, dusts of 0 ton from kiln outlet and bypass system. And it consumes sandstone of 120,000 tons, steel slag of 150,000 tons (100,000 tons for cement grinding), fly ash of 50,000 tons (30,000 tons for cement grinding). The annual weighted CaO and MgO contents of clinker and alternative raw materials are shown in Table 7. Therefore, non-carbonate raw materials in the case include steel slag of 50,000 tons and fly ash of 20,000 tons. CO$_2$ emission from the raw material decomposition is calculated and shown in Table 8, starting from the perspective of process characteristics and material characteristics.

Table 7. weighted CaO and MgO content of clinker and alternative raw materials.

| Name of raw materials | weighted CaO content/% | weighted MgO content/% |
|----------------------|------------------------|------------------------|
| Clinker              | 64.56                  | 2.9                    |
| Sandstone            | 0.09                   | 0.31                   |
| Steel slag           | 40.68                  | 9.76                   |
| Fly ash              | 10.5                   | 2.4                    |
Table 8. CO$_2$ emission from the raw material decomposition.

| Name of raw materials | Quantity/t | CaO fraction/% | MgO fraction/% | CaO fraction from non-carbonates in the clinker/% | MgO fraction from non-carbonates in the clinker/% | Total CO$_2$ emission from raw material decomposition/t |
|-----------------------|------------|----------------|---------------|-----------------------------------------------|-----------------------------------------------|---------------------------------------------------|
| Clinker               | 1 842 900  | 64.56          | 2.9           | 1.25                                          | 0.30                                          | 946 955.43                                       |
| Steel                 | 50 000     | 40.68          | 9.76          |                                               |                                               |                                                  |
| Fly ash               | 20 000     | 10.5           | 2.4           |                                               |                                               |                                                  |
| Dust (kiln outlet)    | 0          | /              | /             | /                                             | /                                             |                                                  |
| Dust (bypass)         | 0          | /              | /             | /                                             | /                                             |                                                  |

4. CO$_2$ reduction technology of cement plant

Carbon emission factor involve all carbon sources, throughout the life cycle of cement production from materials input to cement output, which would give support for the direction of carbon reduction in the cement production. WBCSD and other research institutions propose four main approaches for reducing carbon emissions from the cement industry, namely improvement technology of energy efficiency, alternative fuels, clinker substitution, and carbon capture and storage technology. In addition, alternative raw material technologies are also commonly used in the cement industry to reduce emissions.

China’s cement industry has made great progress, for examples, construction of new dry cement production lines with a daily output of more than 10,000 tons, the pure low-temperature waste heat power generation technology, the no-spherical grinding technology, and the efficient grate cooler technology, which make the energy consumption per unit of cement product in China decreased year by year. They have led to a gradual reduction in indirect CO$_2$ emissions. There is limited reduction space for future emission reductions that rely on energy efficiency improvements.

Alternative fuels are better for the environment and carbon reduction, than fossil fuels in the cement production, which is RDF, BRAM, SIBRCOM, INBRE etc. The carbon emission intensity of alternative fuels is 20%-25% lower than that of coal. However, there is less than 1% of the cement clinker production lines using alternative fuels in China. The technology is largely constrained and affected by policies and legal frameworks, its substantial reduction space still needs to be further expanded.

In order to actively respond to climate change, the global cement clinker coefficient (CK ratio) is gradually decreasing; in 2019, the global cement clinker coefficient decreased steadily to 70%, while China’s is 60%. The low CK ratio reduces the CO$_2$ emission per unit of cement product, but causes large dosage application of mixed materials and admixtures. That promotes the increase of cement amount used per unit of concrete, which has a potential impact on building safety.

CCUS technology, geopolymer application, and cement produced from oil shale are all still in the research and demonstration stage. The development of CCUS technology in the cement industry is relatively slow. Anhui Conch Group plant takes the lead in industrial demonstration production of “Multi-effect pretreatment + absorption + resolver + refinement” CCUS technology, with a capacity of 20,000 tons/year of industrial-grade liquid CO$_2$ products and 30,000 tons/year of food-grade liquid CO$_2$ products in China, which is shown in Figure 3. It successfully started the construction at Anhui Baimashan Cement plant in August 2017, operated since October 2018 and sent the first batch of liquid CO$_2$ products to the market on October 30, 2018 [9]. Another cement group in China, Fujian Longlin Cement Group, are promoting the CCUS demonstration project using “rotary kiln production technology and equipment with high-temperature calcined minerals”, designed to capture and purify food-grade carbon dioxide products of 50,000 t/a. The development of CCUS technology has a long way to go in the cement industry due to the problems of high operating cost and large production cost.
Replacing traditional carbonates with alternative raw materials such as industrial waste could significantly reduce CO$_2$ emissions. Carbonate decomposition generates more than 50% of CO$_2$ emission in cement production. Taking one above 2500t/d production line as an example, only 6.18% of steel slag was added to the raw meal, but CO$_2$ emission from process emissions were reduced by nearly 10%.

5. Conclusions
The initial problems and targets have been realized through the intuitive method, which covered simplifying the calculation steps, efficient CO$_2$ emission self-examination and CO$_2$ emission from raw material carbonate decomposition. With the application of the method, CO$_2$ emission of 21 cement plants in China are assessed and analyzed. Carbon sources throughout the life cycle of cement production give suggestion about the future developing direction of cement production, such as alternative raw materials, carbon capture, utilization and storage technologies.

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