Evaluation of Life-Cycle Assessment Studies of Chinese Cement Production: Challenges and Opportunities

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ABSTRACT

The use of life-cycle assessment (LCA) to understand the embodied energy, environmental impacts, and potential energy-savings of manufactured products has become more widespread among researchers in recent years. This paper reviews recent LCA studies in the cement industry in China and in other countries and provides an assessment of the methodology used by the researchers compared to ISO LCA standards (ISO 14040:2006, ISO 14044:2006, and ISO/TR 14048:2002). We evaluate whether the authors provide information on the intended application, targeted audience, functional unit, system boundary, data sources, data quality assessment, data disaggregation and other elements, and draw conclusions regarding the level of adherence to ISO standards for the papers reviewed. We found that China researchers have gained much experience during last decade, but still have room for improvement in establishing boundaries, assessing data quality, identifying data sources, and explaining limitations. The paper concludes with a discussion of directions for future LCA research in China.

Introduction

Life-cycle assessment (LCA) is an important tool for understanding total energy consumption, identifying energy-saving opportunities, and informing decision-makers regarding policies and energy-efficient investments. Recently, there have been a number of LCAs conducted by Chinese scholars focused on China's cement industry. China is currently the world's largest cement producer and has held that position since 1985, experiencing average annual growth in cement production of 12% during China's Tenth-Five Year Plan (2000-2005). In 2008, China produced nearly 1.4 billion metric tons of cement, which accounts for almost one half of global production. Cement production emits carbon dioxide (CO_2) both through combustion of fossil fuels and through the calcination of limestone in the cement kilns, making cement production one of the largest greenhouse gas emitting industries. Compared to international best practices, cement produced in China is relatively inefficient, with consequently large CO_2 emissions. The use of LCA to evaluate this industry can play an important role in gaining additional understanding of its full impacts as well as possible energy-saving and emissions reduction opportunities.

This paper reviews recent LCA studies of the cement industry in China and in other countries and compares the methodology used by the researchers to ISO LCA standards (ISO 14040:2006, ISO 14044:2006, and ISO/TR 14048:2002). The analysis is presented as follows. First, a general description of China's LCA development in the last 10-15 years, including research areas, number of publications, and types of LCA studies is presented. Second, background information on Chinese cement production is provided to explain the reason for focusing our review on LCA studies of the cement industry. Third, the methodology used to compare the Chinese LCA studies to ISO standards and to international LCA studies is introduced. Fourth, comparison results and analysis of Chinese LCA studies are presented. Then major findings are summarized and suggestions for future direction are provided.

In this paper, we provide a preliminary assessment of the comprehensiveness and transparency of Chinese cement LCA studies to date by comparing these studies to International Organization for Standardization (ISO) standards for sound LCA practice and documentation. Here, the Chinese cement LCA studies are LCA studies of cement production conducted by Chinese researchers in China and the international cement LCA studies are LCA studies conducted outside China by researchers from other countries in the world. We assess eight Chinese cement LCA studies (Cui et al. 2006; Gong et al. 2006; Jiang et al. 2008; Jiang et al. 2008; Liu et al. 2008; Song et al. 2006; Wu et al. 2006; Zhuang et al. 2008.) relative to ISO standards. Further, we assess an additional five international cement LCA studies (Huntzinger et al. 2008; Josa et al. 2004; Kelly, 1994; Marceau et al. 2006; Navia et al. 2006) to provide a benchmark for comparison. By concentrating on the cement industry, we aim to explore the similarities and differences between the Chinese LCA studies and ISO standards as well as international practices. Specifically, we evaluate whether the authors provide transparent information on key elements of an LCA, including the intended application, targeted audience, functional unit, system boundary, data sources, data quality assessment, data disaggregation and other elements.

The Development of Life Cycle Assessment in China

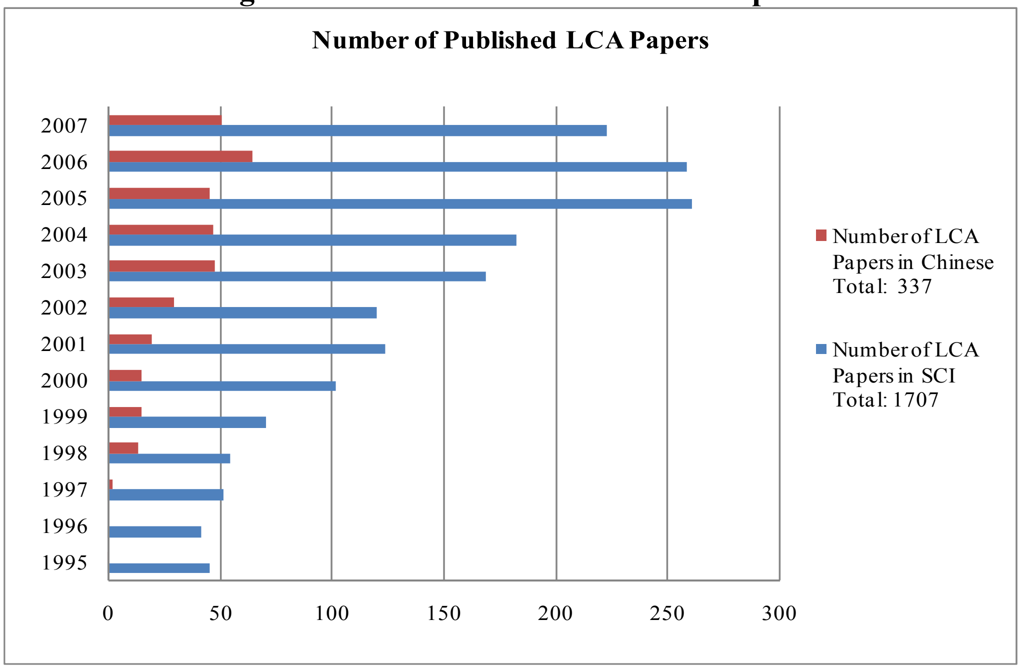
When undertaking analyses of energy consumption or calculating energy intensities in China, researchers and consultants usually have two common but also difficult questions, i.e., how to obtain the data and how to establish analysis boundaries in order to have a complete picture of the energy usage and environmental impacts required to produce a specific product. LCA is one method that not only requires practitioners to collect and verify data, but also provides a "cradle-to-grave" approach to assess inputs and outputs. Moreover, the LCA methodology identifies potential opportunities to increase energy efficiency and mitigate greenhouse gas emissions. By applying LCA to products, materials, and services, manufacturers and researchers can gradually establish a full dataset to measure embodied energy within the whole supply chain and thus provide technical suggestions to reduce energy consumption.

China has an ambitious target of reducing energy consumption per unit GDP by 20% by the end of 11^{th}-Five Year Plan (2010). LCA can be an important means to evaluate and identify opportunities to accomplish this goal. Chinese practitioners have conducted LCA research for a wide range of sectors and products, including: energy, building materials, appliances, packaging, metals, chemicals, electronics, automobiles, transportation fuels, and agriculture. China's national Ministry of Environmental Protection is responsible for promoting LCA studies at a macro level while researchers are conducting and improving LCA research mainly in academia. (Zakaria et al. 1999). Based on ISO Standards, the General Administration of Quality Supervision, Inspection and Quarantine and Standardization Administration of China released a Chinese LCA standard, which took effective on November 1, 2008 (GB/T 24044-2008). Recently, a number of conferences and seminars have been held to discuss LCA of materials and life-cycle management, and international cooperation on these subjects has begun.[1]

[1] See for example: http://www.iscp.org.cn/clcm2008en/default.aspx. In October 2008, the *China Life Cycle Management Conference* was held in Chengdu, Sichuan Province, co-organized by the United Nations Environment

China's experience with LCA studies is still at an initial stage. Only one Chinese paper covering LCA studies was identified prior to 1995. By 2007, the number of Chinese LCA papers had grown to 337 by 2007, as displayed in Figure 1 (Wang, 2008). Of these 337 Chinese LCA articles, more than half of them covered general LCA topics such as methodology and concept description, while 39% were quantitative LCA studies, impact assessments, and descriptions of LCA software development (Wang, 2008).

Figure 1. Number of Published LCA Papers



Source: Wang, 2008. Note: SCI = Science Citation Index

Cement Industry in China

Among the materials covered by Chinese LCA studies to date, we focus on cement for several reasons. First, China has been the largest cement producer in the world for 23 consecutive years since 1985, experiencing average annual growth of 12% during China's Tenth-Five Year Plan (2000-2005). There were more than 5,100 cement plants in China in 2005 (Wang, 2007). In 2008, China produced nearly 1.4 billion tons of cement, which accounted for 50% of global production (US Geological Survey, 2009). Second, China is also the largest cement consumer in the world. As China's National Bureau of Statistics reported, China consumed 1.37 billion tons of cement in 2008, an annual increase of 3.5% from last year (National Bureau of Statistics, 2009). China is rapidly urbanizing. More than 1 billion people will live in urban areas in China by 2030, 221 Chinese cities will have one million people, and 5 billion m^2 of roads will be paved and many more buildings will be constructed (Woetzel et al. 2008). Thus, cement consumption will continue rise in the near future. Most importantly, cement produced in China, compared to industrialized countries, is relatively inefficient, with large CO_2 emissions, as shown in Tables 1 and 2. Shaft kilns and wet process kilns are less efficient than dry process

Programme, SETAC Life Cycle Initiative, and Sichuan University, attracted people from academic institutes, industries, NGOs, and governmental agencies kilns. Dry rotary kilns with multi-stage preheaters and/or precalciners are more energy efficient and have lower emissions. While the developed countries adopted the technology of dry process kilns with preheaters in the 1970s, inefficient shaft kilns historically dominated the Chinese cement industry. Only 9.4% of cement production was from new suspension preheater (NSP) [2] cement plants in 2000, increasing to more than 50% by the end of 2007 (China Cement Almanac, 2008).

Table 1. Fuel Energy Usage by Processes in Cement Production

Cement Production Processes	West Europe			China		
	kBtu/t cement	GJ/t cement	kg ce/t cement	kBtu/t cement	GJ/t cement	kg ce/t cement
Shaft kilns	2938-3886	3.1-4.2	106-144	3962-5150	4.2-5.4	143-186
Wet process	4739-5687	5.0-6.0	171-205	5687	6.0	205
Dry process	4739	5	171	5687	6.0	205
Semi-dry Process	3128-4265	3.3-4.5	113-154	3882	4.1	140
Dry process with preheaters	2938-3980	3.1-4.2	106-144	3804	4.0	137
Dry process with precalciners	2843	3	103	3170-3656	3.3-3.8	114-129

Note: ce = coal equivalent, t = metric tonnes; energy values are in final units
Source: IPCC, 2000 and China Cement Association, 2005

Table 2. Comparison of Cement Technologies

	World Advanced Practice	China Average
NSP Production Capacity	98.3% (Japan)	45%
Equipment Operation Rate	92%	83%
Heat Consumption of Precalciners	2,888 kJ/kg clinker	3,550 kJ/kg clinker
Coal Consumption	100 kg ce/t clinker	123 kg ce/t clinker
Comprehensive Electricity Consumption of Cement	92 kWh/t cement	114 kWh/t cement

Note: ce = coal equivalent
Source: China Cement Almanac, China Cement Association, 2007

Methodology

In this paper, we used the latest version (2006) of ISO Standards: ISO 14040:2006, ISO 14044:2006, and ISO/TR 14048:2002. These standards offer general guidance on LCA principles and methods, as well as suggestions for data collection and proper documentation. ISO standards have been established to ensure transparency and comprehensiveness, which can improve the comparability of different LCA studies across sectors, regions, and countries. Although simple compliance with ISO standards may not guarantee high quality, ISO standards give practitioners, especially those new to the field, valuable guidance on how to collect data, how to check data quality, and how to document and communicate results.

We compare the following elements within the Chinese and international LCA papers to ISO standards. The order is not by priority, but rather by the process of conducting an LCA.

- **Goal:** intended application and targeted audiences
- **Scope:** functional unit, system boundary, rationale of the boundary, and allocation procedures

[2] NSP technology applies to clinker-making in dry process kilns. The raw mix in the dry process has much lower moisture content than that used in wet process kilns, thus reducing energy used for evaporation. While fuel usage in a wet rotary kiln is about 5.3-7.1 GJ/t clinker, a dry rotary kiln with four or five stage preheaters consumes 3.2-3.5 GJ/t clinker. A six stage preheater kiln can reduce energy consumption even more (Worrell and Galitsky, 2008).

- **Life cycle inventory:** data coverage, sources of data, relating data to functional unit, uncertainty of data/information, data quality assessment and data disaggregation
- **Life cycle impact assessment:** selection, classification and characterization
- **Life cycle interpretation:** limitation and recommendation

We classify how closely the practitioners adhered to ISO standards for each element as either "stated unambiguously", "stated but not clear" or "not defined/performed."

Comparison Results and Analysis

Table 3 provides an overview of 13 LCA studies' attributes, including type, institutions, products and language. All of the Chinese LCA studies are journal articles written by researchers from universities, research institutes and cement companies. Of the five international studies, three are academic studies, one is a technical report by an industrial association and one is a company report.

Table 3. Overview of LCA Studies of Cement Production

#	Type	Institutions	Products	Language
Chinese LCA Studies of Cement Production				
1	J	Academic	Sulphoaluminate cement	Chinese
2	J	Academic	Common Portland cement	Chinese
3	J	Academic and cement company	425 Common Portland cement	Chinese
4	J	Academic	Common Portland cement	Chinese
5	J	Academic	425 Common Portland cement	Chinese
6	J	Academic and cement company	Not clear	Chinese
7	J	Academic	Portland cement	Chinese
8	J	Academic	Common Portland cement	Chinese
International LCA Studies of Cement Production				
9	J	Academic	Traditional Portland cement, blended cement	English
10	J	Academic	Portland cement or Portland/cementitious blend	English
11	T	Industrial Association	Portland cement	English
12	C	Consulting company	Cement made from coal and cement made from hazardous waste fuel	English
13	J	Academic	Common cement compared to cement made from spent volcanic soil	English

Key: C=Company report; J=Journal article; T=Technical report

Based on ISO standards requirements and guidelines, we constructed a "LCA checklist" for comparison. The criteria listed in the tables are a subset of ISO requirements and guidelines, which we believe are crucial for conducting sound and transparent LCA studies. The detailed comparison results are displayed in Table 4 (Chinese LCA studies) and Table 5 (International LCA studies). The numbers in the tables indicate how many papers were judged to fall into each category. For example, in the first row of Table 4, "8" indicates that eight Chinese studies "stated unambiguously" their "intended applications" for the LCA study.

Goal

Defining the LCA goal involves explaining the intended application of the assessment and the target audiences. Every Chinese and international LCA study reviewed clearly defined their intended applications; while defining "targeted audiences" was usually neglected by researchers. This is a small but important omission, since a core goal of LCA is to inform the decisions of end users, whose needs for LCA data documentation and discussion may vary significantly (e.g., a researcher may require detailed data and calculation assumptions, while a policy maker may require more detailed discussions of uncertainty and policy relevance). Six out of eight Chinese papers did not identify their intended readers, and only one international study defined their intended audience.

Table 4. Comparing Chinese Life Cycle Assessment Studies for the Cement Sector to ISO Standards

ISO Standards Guidelines	8 Chinese LCI/LCA Papers		
	Stated unambiguously	**Stated but not clear**	**Not defined/performed**
Goal			
Intended application	8	0	0
Targeted audiences	1	1	6
Scope			
Functional unit	8	0	0
System boundary	7	1	0
Rationale (including, the criteria used in establishing the system boundary and deletion/omit life cycle stages, processes, inputs and outputs)	0	4	4
Explicit allocation procedures	0	3	5
Life Cycle Inventory			
Time-related, geographical and technology coverage	3	3	2
Sources of data			
Primary sources	4	0	0
Secondary sources	7	0	0
Uncertainty of the data/information	0	4	4
Relating data to functional unit	5	2	1
Data quality assessments *Completeness check* *Consistency check* *Sensitivity check*	0	0	8
Data disaggregation	3	3	2
Life Cycle Impact Assessment			
Selection of impact categories, indicators and characterization models	7	0	1
Assignment of LCI results (classification)	7	0	1
Calculation of category indicator results (characterization)	7	0	1
Life Cycle Interpretation			
Identification of the significant issues based on LCI or LCA results	8	0	0
Conclusion	7	0	1
Recommendation	6	1	1
Limitation	0	0	8

Scope

Defining the scope of the LCA involves identifying a functional unit which is used to normalize inputs and outputs (such as “1 kg of clinker” or “1 kg of Portland cement”), defining and providing a rationale for the system boundary, and defining allocation procedures. The functional unit used in the LCA should be clear and measurable. All of the eight Chinese studies and five international studies defined a functional unit, though some are more explicit than others.

Table 5. Comparing International Life Cycle Assessment Studies for the Cement Sector to ISO Standards

ISO Standards Guidelines	5 International LCI/LCA Papers		
	Stated unambiguously	Stated but not clear	Not defined/performed
Goal			
Intended application	5	0	0
Targeted audiences	1	0	4
Scope			
Functional unit	5	0	0
System boundary	5	0	0
Rationale (including, the criteria used in establishing the system boundary and deletion/omit life cycle stages, processes, inputs and outputs)	1	2	2
Explicit allocation procedures	3	1	1
Life Cycle Inventory			
Time-related, geographical and technology coverage	3	2	0
Sources of data			
Primary sources	2	0	0
Secondary sources	5	0	0
Uncertainty of the data/information	3	2	0
Relating data to functional unit	4	1	0
Data quality assessments			
Completeness check	1	0	4
Consistency check	1	1	3
Sensitivity check	2	0	3
Data disaggregation	4	1	0
Life Cycle Impact Assessment			
Selection of impact categories, indicators and characterization models	2	0	3
Assignment of LCI results (classification)	2	0	3
Calculation of category indicator results (characterization)	2	0	3
Life Cycle Interpretation			
Identification of the significant issues based on LCI or LCA results	5	0	0
Conclusion	5	0	0
Recommendation	3	2	0
Limitation	5	0	0

The system boundary is the interface between the product system and the environment system. It determines which processes are included in the product system and hence in the LCA. Except for one, all Chinese papers defined system boundary unambiguously. All international studies clearly defined the system boundary. Most international studies provided a chart or graph to illustrate the system boundary, but only three Chinese studies provided such an illustration.

Regarding the explanation of the rationale behind the system boundary or in the discussion of allocation procedures, both the Chinese and international LCA studies showed room for improvement. For example, in “explicit allocation procedures”, only 60% of international studies gave clear explanations and only around 40% of the Chinese studies discussed this in a meaningful way. In some Chinese studies, although the boundary of the LCA study is discussed, no detailed data were allocated to each stage of the life cycle. Instead, some of them provide data by fuel or types of emissions.

Life Cycle Inventory

The life cycle inventory (LCI) section of the analysis should explain the data coverage and the sources of data, relate the data to the functional unit, describe data uncertainties, assess data quality, and explain strategies for data aggregation.

As stated in the ISO requirements and guidelines, ideally LCI data should have time-related coverage, geographical (regional, national or case studies) coverage, and technology coverage. It should be noted that journal papers may differ from technical reports, due to space constraints or narrower focuses in journal articles. The Chinese LCA studies are all journal articles; among the five international LCA studies, three are journal papers, one is a technical report, and one is a company report, as shown in Table 3. Table 6 lists information relating to technology coverage and geographical coverage found in the 13 LCA articles. There are case studies and broader analysis at the regional/national level in both Chinese and international LCA papers. However, the greatest difference is in technology coverage. Only three of eight Chinese journal articles have information on process/technologies, and the Chinese studies typically addressed one single product at a time. The international studies were found to be more diverse in this respect. One technical paper compared four different processes in cement production, one company report compared cement made from different fuels, the three journal papers were also found to compare multiple types of cement products or compare one product that is made from different materials.

LCI data usually come from two sources: primary data, which are from on-site surveys/investigations; or secondary data, which are collected by others, such as statistical yearbooks, academic studies, reports from corporate companies and industrial associations and commercial software databases. Both the Chinese and international cement LCAs relied on secondary data to a large extent, but only one Chinese paper utilized commercial software compare to three of the international studies.

Another factor that needs to be considered is data quality. According to ISO standards, practitioners can perform three assessments of data quality: completeness check, to verify whether information is sufficient to reach conclusions; consistency check, to verify whether assumptions, method and data are in accordance with established goals and scope, and sensitivity check, to evaluate the effects of choices made on methods and data on the results of LCAs studies. A dataset that has good quality should fulfill the following features: current, representative, accurate, precise, consistent and reproductive. The Chinese LCA studies considered in this paper do not have detailed discussions or assessments of data quality. Table 7 displays how the Chinese LCA studies perform regarding data quality checks compared to international studies. In addition, while seven out of eight Chinese papers did relate their data to a functional unit, only three did data disaggregation. Data disaggregation includes data information on either each process, or each life cycle stage. This makes the LCA more transparent, and it enable reviewers or other practitioners to replicate the process if needed. The international LCA studies were only slightly better than the Chinese studies regarding their assessments of data quality. One of the five studies performed a completeness check well, one performed a consistency check well while another mentioned it but did not describe it clearly, and two studies undertook sensitivity checks.

Impact Assessment

Impact assessment evaluates the products' impact on the environment and human health by classification and characterization of LCI results. From the 13 articles reviewed, seven out of eight Chinese papers did life cycle impact assessments (LCIAs) while only two of the international studies performed LCIAs. Impacts considered by the Chinese studies include energy depletion potential (EDP), global warming potential (GWP), abiotic depletion potential (ADP), acidification potential (AP), photochemical ozone creation potential (POCP), and human toxicity (HT). There are three types of characterization factors used by the Chinese researchers, which are Chinese depletion characterization factors (developed by Chinese scholars), global pollutants equivalents at 1990 level, and EcoPoints.

Table 6. Comparison of Data Coverage

Articles	Cement Production Technologies	Geographical Coverage
Chinese LCA Studies		
1	Suspension preheater	China
2	NSP with waste heat generation and alternative fuels	Beijing
3	Not clear	Beijing
4	Not clear	China
5	Not clear	Beijing
6	NSP with waste heat generation	Beijing
7	Not clear	China
8	Not clear	Beijing
International LCA Studies		
9	Preheater and kiln system with control devices to capture cement kiln dust	United States
10	Not clear	European Union
11	Four processes: wet, long dry, dry with preheater, and dry with preheater and precalciner	United States
12	Not clear on kilns, but compares coal to hazardous waste	Texas
13	Rotary kilns, partially used alternative fuels, and assessed cement production using spent volcanic soil as alternative raw material	Chile

Table 7. Qualitative Measures of Data Quality

ISO Guidelines	8 Chinese LCA Studies		5 International LCA Studies	
	# of Yes	# of No	# of Yes	# of No
Are the data as current as possible?	7	1	5	0
Do the data provide time, geographical and technological coverage?	6	2	5	0
Is the source of data reliable?	8	0	5	0
Are the data documented?	8	0	5	0
Does the study has information on data accuracy and errors?	1	7	4	1
Do the data meet the requirements of boundary?	8	0	5	0
Does the paper provide completeness check?	0	8	1	4
Does the paper provide consistency check?	0	8	2	3
Does the paper provide sensitivity check?	0	8	2	3
Are the data transparent?	3	5	4	1
Are the data verified independently?	0	8	1	4

Progress and Limitations of Chinese LCA Studies

After ten years of development, China appears to have gained much experience in the field of LCA, especially in the study of materials such as cement. Based on ISO standards and Chinese LCA standards, the majority of the eight Chinese LCA studies clearly stated their intended purposes, defined a functional unit, charted the system boundary, collected data, provided data analysis, and made recommendations related to cement production based on LCI/LCIA findings.

However, by comparing the LCA studies of the cement industry in China and in the world to ISO standards, we found that there are some areas in the China cement LCA studies that need more attention and development.

First, explanations regarding the criteria used in establishing system boundaries could be improved. The selection of boundary, which means deciding which processes to include or omit in the product system, is closely related to the costs of the study and the requirements related to data quality. Therefore, explanations of the criteria are necessary. In the Chinese LCA studies, detailed discussion of this topic is very limited. Researchers in the China cement LCA studies sometimes used "due to unavailable data" or "commonly we do not include this stage in our LCA studies" as a simple explanation.

Second, only a few Chinese cement LCAs did comprehensive data quality assessments, which including completeness checks, consistency checks, and sensitivity checks. Data quality has a direct impact on LCI interpretation and LCA evaluation. Completeness checks can reveal whether all the needed data are complete; sensitivity checks can evaluate whether the final results are reliable or whether the results will be affected by uncertainty or allocation methods; consistency checks can determine whether assumptions, methods, and data are consistent with goals and scope. Although we found data in most of the Chinese cement LCAs to be well documented, there is still a lack of detailed quality assessment and information on data accuracy/errors. This might be because little attention is paid to verifying data, or because checking data quality is even more difficult than data collection in China.

Third, we found that the Chinese cement LCA studies were limited in their use of on-site surveys and investigations, more heavily relying on secondary sources. Cement enterprises or industrial associations did not play a major role in the Chinese cement industry LCAs we evaluated. In contrast, the LCA conducted by the Portland Cement Association organized surveys, collected data from plants, and provided several LCI and LCA assessments on cement and cement-related products (Marceau, 2006).

Last but not least, it is also important to note that few Chinese papers identified their limitations or provided any information on how to improve the study in the future. In the ISO standards, a conclusion should include: a) identifying critical issues within the system boundary, such as which process consumes most energy, or which life cycle stage has great potential to increase energy efficiency; b) reviewing LCA methodology and checking data quality; c) making conclusions and evaluating whether the results are in accordance with the goal and scope; d) making recommendations to decision-makers based on assessment findings. In the Chinese LCA studies, although seven papers pointed out critical issues in cement production and six studies provided related suggestions such as adopting waste heat generation technology or using alternative fuels, none of them discussed the uncertainty of the data or information clearly. Since China's LCA work is at an initial stage, it would be very helpful for practitioners to understand these potential areas of improvement and make progress on critical issues.

Conclusion and Future Directions

Chinese researchers are rapidly gaining experience in LCA studies. In contrast with one decade ago—when most LCA studies mostly covered LCA concept and methodology descriptions - the eight LCA studies we evaluated more fully emphasized the key elements of required for conducting an LCA, such as the intended purpose, functional units, system boundary, and impact assessment. Nevertheless, compared to international studies in the same field, the Chinese LCA studies need to elaborate on boundary criteria, provide comprehensive data quality assessments, expand to various types of data sources, and critically identify their limitations.

To further increase the awareness of LCA and strengthen the quality of LCA studies in China, industries, corporations, and associations should participate in the assessments and collaborate with LCA researchers more intensively. Government could support LCA research by subsidizing pilot projects. LCA can also be linked with energy audits and broader energy management through education, training and publicizing. In addition, international cooperation can play an important role for China's LCA researchers to better adopt international best practices.

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