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Temporal validation of life cycle greenhouse gas emissions of energy systems in China

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A R T I C L E I N F O

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A B S T R A C T

When assessing the environmental impact of a product or system, the life cycle assessment (LCA) is one of the most accepted methods. However, LCA relies heavily on the fundamental data sources, especially for energy related inventory database. The energy related inventory database is the basis of life cycle assessment for a product or system. Due to the great variety and the frequent updates of the energy related inventory database, the effect of temporal variables on life cycle inventory results should be quantified and interpreted in LCA case studies. In this study, a life cycle greenhouse gas (GHG) emissions calculation model for various energy sources is developed, and the life cycle GHG emissions of six types of energy in China in 2003 and 2013 are calculated and compared. There are significant reductions of 10.60–33.40% for different types of energy when using database of 2013 compared to 2003. To fill the temporal gaps, we develop a generic methodology for screening out the key temporal parameters in life cycle inventory analysis of energy upstream. Nine key temporal parameters related to the life cycle GHG emissions of six types of energy are screened out by sensitivity analysis coupled temporal variability analysis. The update interval of these parameters is quantified and suggested to ensure the reliability of analysis results. This methodology can help to reduce the maintenance workload of the database, and to provide a foundation for improving the reliability of life cycle analysis results for a product or system.

1. Introduction

Global energy consumption is predicted to be twice as high in the year 2040 compared to that of 2010, with the largest increase expected in the developing world (EIA, 2013). LCA is an important decision-making tool for products or system selection and management, due to its ability to systematically analyze energy use, environmental impacts, and cost benefit. LCA can help avoid a narrow outlook on environmental concerns by compiling an inventory of relevant energy and material inputs and environmental emissions, evaluating the potential impacts associated with identified inputs and emissions, and interpreting the results to help make a more informed decision (ISO14040, 2006).

There are three main LCA approaches: Process-based LCA, IO-based LCA (input-output based LCA) and hybrid LCA. One limitation of process-based LCA is that they inherently truncate analysis system boundaries (Suh, 2004), thus cause truncation errors and difficulty to collect the onsite data of upstream process of products. These disadvantages can be avoided or offset by using IO-based LCA, but it difficult to gain a detailed understanding of production. To overcome these shortcomings in process-based LCA and IO-based LCA, I-O based hybrid analysis method was developed by Treloar (Treloar, 1997) and has been used in several life cycle studies (Crawford et al., 2006), which require extracting energy pathways from I-O data, and then replaces the energy path generated by the I-O model with reliable and accurate process data. The I-O based hybrid model has been considered as a nearly perfect tool for life cycle assessment (Finnveden et al., 2009). However, such model needs sufficient process data (Suh et al., 2004). And for most of the countries like China, the classification of sectors is too coarse to target a specific product, and the sector definitions used by sectoral energy and environmental pollution statistics usually fails to exactly match that in the economic I–O table (Chang et al., 2011).

Process based LCA, a bottom-up approach to evaluate environmental emissions considering the activities in the process, can be an alternative approach to evaluate LCA analysis. In a specific case study analysis, process based analysis is suited to analyzing large atypical products such as an energy system to evaluate environmental impacts (Mao et al., 2013). However, the process based LCA

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relies heavily on the databases (Björklund, 2002), thus the availability and accuracy of data play an important role in the reliability of energy life cycle inventory. The energy database involved in each phase of products' or systems' whole life cycle is especially important. Therefore, the accuracy and availability of energy database should be identified and enhanced. Energy production and use are the main sources of many greenhouse gases, and substantial LCA studies have been carried out on energy consumption and GHG emissions of power generation systems from alternative energy sources, such as biomass-based power (Thakur et al., 2014), hydropower (Valente et al., 2015), wind power (Xue et al., 2015), nuclear power (Nian et al., 2014), and fossil fuels power generation systems (Atilgan and Azapagic, 2015). Several studies are available for life cycle energy consumption and emissions for alternative fuels, such as biodiesel (Gnansounou and Kenthorai Raman, 2016), methanol (Li et al., 2012), ethanol (Yan and Boies, 2013), and fuel cell (Nease and Adams Ii, 2015), etc. The literatures mentioned above have paid enough attention to analyzing the process itself, however, little attention has been paid to the temporal validation of the life cycle inventory analysis results. Data quality is one of the key factors that determine the consistency and accuracy of the LCA. Additionally, data should be collected and estimated considering its spatial and temporal representativeness. But in most LCA related studies, data regarding upstream flows were obtained from database of LCA software, and few studies focus on the temporal representativeness of data. Actually, energy efficiency in energy production, transmission, and distribution have all improved rapidly in the past decades, especially in developing countries. For instance in China, the electricity consumption in coal production decreased from 27.0 kWh/t in 2005 to 17.7 kWh/t in 2012 (NBSC, 2014). After the energy consumption and GHG emissions are reduced due to the promotions of energy conversion and pollution mitigation technologies, significant inaccuracies and errors may be introduced in LCA of products or systems when an outdated energy database is used for calculating. Some researchers have pointed out that it is very difficult to obtain yearly variations of environmental interventions for the entire life cycle, caution is needed in the interpretation of the yearly variations, and it seems very hard to operationalize temporal variability in inventory data for the whole life cycle of a product system (Huijbregts, 1998). Therefore, it is necessary to perform applicable and reliable LCA studies of energy systems, and update state-of-the-art results to match the rapid upgrade of technological level in China. However, hundreds of parameters are involved in energy database, and they cannot be all updated in time due to the difficulty in acquiring the data. Therefore, the effect of temporal variability of data on the analysis results of energy upstream should be taken into consideration.

Under such a circumstance, the main objectives of this study are: (1) to identify the effect of temporal variability of database on life cycle GHG emissions of energy systems in China; (2) to provide a method to screen out the key temporal parameters in LCA of an energy system; (3) to estimate the update interval of key temporal parameters in energy database in China. Due to the fact that fossil energy dominates the energy consumption structure in China and the power sector heavily relies on coal (coal-fired electricity accounts for over 75% of total electricity supply in China in recent years (CEPYEC, 2014)), the focus is on four types of fossil fuels (raw coal, crude oil, fuel oil, natural gas), coal-based electricity and electricity mix.

2. Methodology

The research method in this study follows three steps. Firstly, we apply a LCA framework to inventory the GHG emissions for energy production, and calculate the GHG emissions of various energy system in the year 2003 and 2013 for identifying the growth trend of GHG emissions of energy systems. Secondly, we develop a method to identify the key factors through sensitivity analysis combined with temporal variation analysis. To screen out the key temporal relational parameters, GHG emissions in 2013 is selected as the baseline. Thirdly, we collect the yearly data of these key temporal parameters from 2003 to 2013 from China's national statistical reports, and summarize the data for computation of life cycle GHG emissions of energy system in different years. Finally, we develop an algorithm to calculate the minimum time interval of key temporal parameters which should be updated.

2.1. System boundary

Cradle to gate approach is selected to define the system boundary in this study. As shown in Fig. 1, life cycle of energy consists of two parts: direct energy consumption phase and upstream phase, the latter includes energy exploitation, transportation, and production stage, energy is involved in each stage. Furthermore, energy upstream can be divided into two parts, direct upstream and indirect upstream. While the former refers to the direct energy consumption and environmental emissions due to energy production and energy transportation processes, the latter includes environmental load for indirect processes such as higher order of energy upstream. Therefore, circular reference problem occurs in life cycle inventory calculation model for energy, and truncation error can be minimized by infinite iterative computations. In this study, cradle to gate approach refers to all GHG emissions associated with upstream process of energy. Construction of the infrastructure buildings such as power plants, labor input, and manufacture of machines are excluded from the system boundaries as their contributions are typically small over their lifetime; this is also the reason why decommissioning is not considered.

2.2. Analysis parameters and functional unit

The analysis parameters of the energy system life cycle inventory model is GHG emissions, including CO_2, CH_4 and N_2O. The emissions of CH_4 and N_2O are converted to carbon dioxide equivalent with the conversion coefficient 25 and 298 (IPCC, 2006), respectively. The functional unit for the study is 1 MJ as energy is produced for use, all the outputs are normalized to the functional unit for comparison.

2.3. Calculation model

In each process of energy life cycle, energy is consumed as fuel or feedstock. Seven types of energy, including raw coal, crude oil, diesel, gasoline, fuel oil, natural gas, and electricity are considered in calculation model, which are the main energy resources in China.

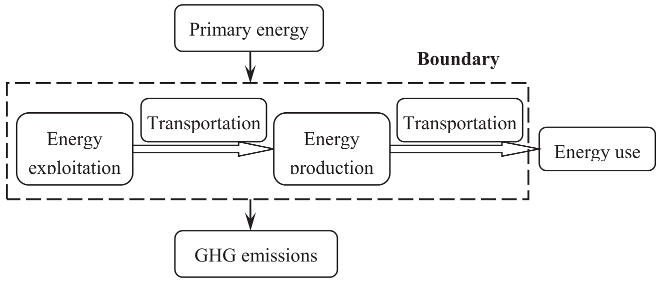

Fig. 1. Boundary of energy upstream life cycle.