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Environmental impacts of shale gas development in China: A hybrid life cycle analysis

Jianliang Wang[a,*], Mingming Liu[b], Benjamin C. McLellan[c], Xu Tang[a], Lianyong Feng[a]

[a] School of Business Administration, China University of Petroleum, Beijing, 102249, China
[b] Academy of Chinese Energy Strategy, China University of Petroleum, Beijing, 102249, China
[c] Graduate School of Energy Science, Kyoto University, Yoshida-honmachi, Sakyo-ku, Kyoto 606-8501, Japan

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ABSTRACT

As the largest shale gas resources holder in the world, China has set ambitious goals for its shale gas development. To better understand the environmental impacts and the net energy return of shale gas development in China, this paper develops a hybrid life cycle inventory (LCI) model to estimate the energy use and greenhouse gas (GHG) emissions of China's shale gas development, and presents an energy return on investment (EROI) analysis for estimating its net energy return. Results suggest a total average energy use per well of 123 TJ (range: 74–165 TJ) and total average GHG emissions per well of 9505 tCO_2e (range: 5346–13551 tCO_2e). Most of the energy use and GHG emissions are indirect impacts embodied in fuels and materials. Energy use and GHG emissions from the drilling stage comprise the largest share in both totals due to large amounts of diesel used as fuel in the well drilling process and the materials used in the well casing process. The EROI of China's shale gas is estimated to be about 33 (range: 31–42), which is higher than China's conventional oil & gas but lower than U.S. shale gas.

1. Introduction

According to the Energy Information Administration of the U.S. Department of Energy, China has the largest shale gas resources in the world, and its technically recoverable resources of shale gas are 31.5 trillion cubic meters (tcm) (EIA, 2013). To meet its soaring gas demand (197 billion cubic meters (bcm) in 2015 (BP, 2016)) and reduce its carbon emissions, China is vigorously promoting the development of its shale gas resources (Zhao et al., 2014; Wang et al., 2016). For example, the National Development and Reform Commission of China (NDRC) forecast that China's shale gas production will reach 60–100 bcm by 2020 (NDRC, 2012). Extracting shale gas resources has become practicable due to two predominant techniques: horizontal drilling and hydraulic fracturing (Wang et al., 2016). However, both mass media and the academic literature have pointed out that the application of these two techniques in shale gas development may have serious impacts on environment (Burnham et al., 2012; Vidic et al., 2013). It is therefore very important for China to analyze the environmental impacts of its shale gas development, preferably before the wide-scale expansion of the industry.

Shale gas development requires a range of activities that have various significant environmental impacts, such as GHG emissions, large amounts of water consumption, induced earthquakes, and effects on regional air quality (Burnham et al., 2012; Vidic et al., 2013; Frohlich, 2012; Pacsi et al., 2013; Laurenzi and Jersey, 2013). Of these, GHG emissions from energy use and methane leakage are one key issue that has attracted significant attention in the past several years (Howarth et al., 2011; Jiang et al., 2011; Weber and Clavin, 2012). However, the results among current literature differ sharply. For example, a study carried out by Howarth et al. (2011) showed that the life-cycle GHG emissions for shale gas are at least 30% more than those from conventional gas due to significant methane leakage in the upstream shale gas industry. Hultman et al. (2011) estimated shale gas GHG emissions to be 11% higher than conventional gas, while Jiang et al. (2011) only showed 3% higher emissions since their estimation of methane leakage in the upstream shale gas industry is much lower than Howarth et al. (2011). A number of reasons could be responsible for these differences, most important of which is likely to be the difference in geological conditions of different shale basins or blocks because the well depth and the amount of fracturing fluids required are related to the geological conditions (Chang et al., 2014a). Therefore, one of the key measures to improve the world's understanding

* Corresponding author.
E-mail addresses: wangjianliang305@163.com, wangjianliang@cup.edu.cn (J. Wang).

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on GHG emissions and other environmental impacts of shale gas development is to expand the geographical areas of study.

Currently, quantitative studies of GHG emissions and other environmental impacts mainly focus on the U.S. because of its relatively mature shale gas industry and the large amount of data accumulated (Burnham et al., 2012; Jiang et al., 2011; Weber and Clavin, 2012). On the other hand, despite being the largest shale gas resource holder in the world, there have only been a small number of quantitative environmental impact assessments focusing on China, such as Chang et al. (2014a,b, 2015), Yu et al. (2016) and Guo et al. (2016), while all other studies for this nation have been qualitative analyses (Feng et al., 2012; Hu and Xu, 2013; Krupnick et al., 2014; Wang et al., 2014; Guo et al., 2015). Drawing on the experience of studies on US shale gas development, Chang et al. (2014a) constructed a good modeling framework and used this in the first quantitative analysis of the environmental impacts of China's shale gas development. However, due to the reality of lack of data, the study of Chang et al. (2014a) was only based on China's first onshore horizontal well – W201H1. As noted in Chang et al. (2014a), W201H1 was a test well, rather than a production well. Therefore, in terms of data representatively, Chang et al.'s study can be seen as a very preliminary study. Thereafter, Chang et al. quantitatively analyzed the overall environmental impacts for tapping China's total shale gas reserves (Chang et al., 2014b) and compared the life-cycle GHG emissions for coal and shale gas in China if both of them are used for power generation (Chang et al., 2015). However, the critical data for energy use and GHG emissions per shale well used in Chang et al. (2014b, 2015) are still from Chang et al. (2014a).

Just as Chang et al. (2014a) stated, to achieve a better understanding of the environmental impact of shale gas development in China, more specific data should be used as they become available. Following the modeling framework of Chang et al. (2014a), this paper will present a comparatively comprehensive assessment of energy use and GHG emissions for China's shale gas development by considering more specific data for Chinese shale wells and more practical production behaviors. In addition, to measure the contribution of shale gas to society from the perspective of energy, this paper also analyzes the net energy return of shale gas development in China by calculating the energy return on energy investment (EROI) of shale gas wells (Hall et al., 2014; Lambert et al., 2014). The Sichuan basin is one of the highlighted areas of shale gas exploration and development in China, and most current shale gas development is concentrated in this basin (Dong et al., 2014), therefore, this study is geographically focused there.

2. Methodology and data

2.1. Hybrid LCI model for estimation of energy use and GHG emissions

Energy use and GHG emissions for shale gas development include not only direct energy use and emissions, but also indirect energy use and emissions associated with the materials and fuel consumed in shale gas development. To fully reflect the energy use and GHG emissions of China's shale gas development, this paper uses a hybrid life cycle inventory (LCI) model: (1) evaluating the direct energy use and GHG emissions by developing a process-based life cycle inventory (P-LCI), and (2) estimating the indirect energy use and GHG emissions by using an economic input-output-based life cycle inventory (EIO-LCI). This type of approach has been widely used in studies of environmental impacts (Chang et al., 2014a; Jiang et al., 2014; Aurangzeb et al., 2014; Bartzas and Komnitsas, 2015; Hossain et al., 2016).

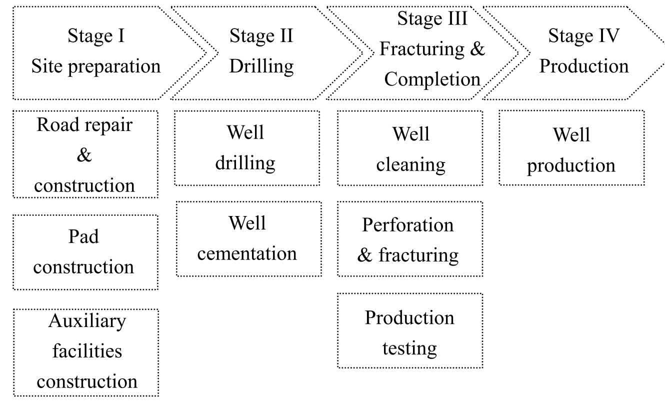

Fig. 1. System boundary of the hybrid LCI model in this paper.

The principal aim of this study is to analyze the energy use and GHG emissions of shale gas development in China; therefore, the system boundary of the hybrid LCI model only includes four stages in the upstream shale gas industry, i.e. site preparation stage, drilling stage, fracturing and completion stage, and production stage, while other downstream shale gas industry stages are not considered in this paper. Furthermore, attributable processes or activities for each stage are also defined (see Fig. 1), as described in detail in the Supplementary Information (SI).

Based on the above description, the total energy use and GHG emissions could be described as Eqs. (1) and (2):

$$E_{tot.} = E_D + E_{ID} = \sum_m \sum_n \sum_l P_{D.mnl}\lambda_l + \sum_m \sum_n \sum_l P_{ID.mnl}\lambda_l \quad (1)$$

Where $E_{tot.}$ is the total energy use for shale gas development in terajoule (TJ); E_D is the total direct energy use in TJ; E_{ID} is the total indirect energy use in TJ; $P_{D.mnl}$ is the direct energy l used in process/activity n in stage m, which is expressed as physical quantity, such as ton (t), kilogram (kg), cubic meters (m^3) or kilowatt-hour (kWh); λ_l is the default net calorific value for energy l in TJ/t, TJ/kg, TJ/m^3 or TJ/kWh. The default net calorific values for different energy resources are from the Intergovernmental Panel on Climate Change (IPCC) (2006).

$$GE_{tot.} = GE_D + GE_{ID} = \sum_m \sum_n \sum_l P_{D.mnl}\lambda_l EF_l + \sum_m \sum_n \sum_l P_{ID.mnl}\lambda_l EF_l \quad (2)$$

Where $GE_{tot.}$ is the total GHG emissions; GE_D is the total direct GHG emissions; GE_{ID} is the total indirect GHG emissions; EF_l is the emission factor for energy l. The emission factors for different energy resources are also from IPCC (2006). Other parameters are the same with Eq. (1).

For GHG emissions, this paper only considers the emissions of CO_2 and methane (CH_4), which are assessed in the units of CO_2-equivalents (CO_2e) as specified by the IPCC (2013). CO_2-equivalency is a metric that compares the radiative forcing associated with a GHG relative to that of CO_2. Since different GHGs have different atmospheric lifetimes, the IPCC reports "global warming potentials" (GWPs) for each GHG for three-horizons: 20 year, 100 year, and 500 year (Laurenzi and Jersey, 2013). Since 100 year GWPs are recommended by IPCC and widely used by many other climate analyses (Jiang et al., 2011), this paper also uses 100 year GWPs recommended in IPCCAR5 to convert CH_4 emissions to CO_2-equivalent emissions (IPCC, 2013), i.e. 34 kg CO_2e/kg CH_4.

In Eqs. (1) and (2), direct energy use can be assessed directly by presenting a P-LCI analysis for shale gas development, while indirect energy use embodied in materials and fuels needs to be assessed by using an economic input-output (EIO) model. The detailed description of EIO model can be found in many studies, such as Chang et al. (2011), Crishna et al. (2011), Zhu et al. (2012),