Journal of Environmental Management 226 (2018) 13–21

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Water use for shale gas extraction in the Sichuan Basin, China

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ARTICLE INFO

Keywords:
Shale gas
China
Life cycle inventory
Water use
Water intensity
Estimated ultimate recovery

ABSTRACT

This study investigates the use of water for extracting shale gas in the Sichuan Basin of China. Both net water use and water intensity (i.e., water use per unit of gas produced) of shale wells are estimated by applying a process-based life cycle inventory (LCI) model. The results show that the net water use and water intensity are around 24500 m^3/well and 1.9 m^3 water/10^4 m^3 gas respectively, and that the fracturing and completion stage of shale gas extraction accounts for the largest share in net water use. A comparison shows that China's water use for shale gas extraction is generally higher than that of other countries. By considering the predicted annual drilling activities in the Sichuan Basin, we find that the annual water demand for shale gas development is likely to be negligible compared to total regional water supply. However, considering the water demand for shale gas extraction and the water demand from other sectors may make water availability a significant concern for China's shale gas development in the future.

1. Introduction

Climate change resulting from the use of fossil fuel has become a critical issue which threatens the sustainable development of human society. An important way to deal with this issue is to promote the transition of the global energy system from high-carbon energy resources to low-carbon energy resources. Natural gas, a relatively clean energy source compared to coal and oil, has been recently characterized as a ‘bridge fuel’ for the world to achieve this transition process (Vidic et al., 2013). In this respect, the International Energy Agency (IEA) forecasts that the world may enter a ‘golden age’ of natural gas (IEA, 2011), in which case expanding the supply of natural gas has become a crucial task for the world.

Shale gas is natural gas that is found trapped within shale formations. Due to the vast resource base of shale gas and its wide distribution (EIA, 2013), shale gas development could play an important role in expanding the world supply of natural gas. Horizontal drilling and hydraulic fracturing have significantly reduced the barriers to shale gas development, and made the extraction of shale gas economically feasible (Vidic et al., 2013). However, these technologies are not free from environmental risks. In particular, the literature has pointed out that these two techniques are significantly water consuming, and large-scale development of shale gas resources can present a very large demand on local water resources (Jiang et al., 2014; Clark et al., 2013; Wan et al., 2014). Moreover, like climate change, the lack of water resources is potentially a significant threat for human society (Rijsberman, 2006). Humans should not wish to solve one problem by creating another, and hence it is necessary for the world to understand the impacts of shale gas development on water resources, and then deal with these impacts.

A number of studies have analyzed the water use of shale gas development. The various studies can be divided into three categories: The first category analyzes *qualitatively* the impacts of shale gas development on water use, such as Wan et al. (2014), Vengosh et al. (2014) and Guo et al. (2017); and where the contribution of such studies is to raise the public's overall awareness of environmental risks of shale gas development. The second category of studies estimates *quantitatively* the amount of water use of shale gas development, or the total demand on regional water resources, such as Dale et al. (2013), Clark et al. (2013), Chang et al. (2014a), Jiang et al. (2014) and Chen and Carter (2016); and where the contribution of these studies is to measure the environmental risks for industrial operators or policy makers. The third category is research into the potential ways to reduce the amount of water use by strengthening water resources management or developing advanced technologies; these studies include Rahm et al. (2013), Zhang et al. (2016) and Onishi et al. (2017).

Of all these studies, the scientific assessment of environmental

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https://doi.org/10.1016/j.jenvman.2018.08.031
Received 25 August 2017; Received in revised form 9 July 2018; Accepted 6 August 2018
0301-4797/

impacts (i.e. the second category of studies) is the most important, since it provides the base for controlling or reducing risks. A review of this second category of studies shows that their results differ significantly. For example, Nicot and Scanlon (2012) conclude that the average water use per well for shale gas development is less than 11000 m^3, while this number in Clark et al. (2013) is more than 23000 m^3. A number of reasons could be responsible for these differences, the most important of which is likely to be the differences in geological conditions of different shale basins, because the well depth and the amount of fracturing fluids required are related to the geological conditions (Chang et al., 2014a; Wang and Feng, 2016). Therefore, one of the key ways to improve the world's understanding of the environmental impacts of shale gas development is to expand the geographical areas of study.

Most current studies have focused on the U.S., mainly because of its relatively mature shale gas industry and the large amount of data accumulated (Jiang et al., 2014; Clark et al., 2013; Stephen et al., 2014). However, as potentially the world's largest resource of shale gas (EIA, 2013), China has made ambitious development plans for its shale gas resources, and a number of international institutes forecast that China will be the largest developer of shale gas outside the U.S. (BP, 2016). Therefore, analyzing the environmental impacts of China's shale gas development will help in the public understanding of the worldwide environmental impacts of shale gas development.

In 2014, based on the limited data from China's first horizontal well-W201H1 in the Sichuan Basin, Chang et al. (2014a) carried out the first quantitative study of water use per well for China's shale gas development. However, as noted in Chang et al. (2014a), W201H1 was a test well, rather than a production well. Therefore, in terms of data, the study carried out by Chang et al. (2014a) should be seen as a preliminary study, and to achieve a proper understanding of the impact of shale gas development on water use, more specific data should be used as they become available. Following Chang et al. (2014a) a number of studies appeared which analyzed the overall water demand on local water resources by considering the amount of water use per well and the development plans for shale gas in a specific region; such as Chang et al. (2014b), Yu et al. (2016) and Guo et al. (2016). However, the key data inputs to these studies are originally from Chang et al. (2014a) or from a combination of U.S. and China sources.

Thus the main aim of this paper is to give a relatively comprehensive assessment of water use for shale gas production in China by using more specific data for Chinese shale wells, and reflecting production behavior in practice, and by then analyzing the overall water demand on local water resources based on these comprehensive results.

2. Methods

This paper focuses on not only the water use, but also the water intensity of the shale gas production (defined as net water use per well divided by the estimated ultimate recovery (EUR) of the well). Besides, Sichuan basin is chosen as the target area since it is one of the main prospective areas for shale gas exploration and development in China, and also most current activities of shale gas development are concentrated in this basin (Dong et al., 2014).

To evaluate the water use of shale gas development, a process-based life cycle inventory (P-LCI) model is developed. This section is organized as follows: 1) Definition of the system boundary; 2) Description of the life cycle of shale gas development; 3) Introduction of the estimation approach for EUR; and 4) Introduction of the estimation procedures.

2.1. System boundary

The system boundary includes four stages, i.e. site preparation, drilling, fracturing and completion, and production, while other stages, such as distribution, storage and use stages are not considered. The attributable processes or activities for each stage are also defined (Fig. 1), and are described in detail in the following parts of this section. Two metric functions are applied in this paper, one is cubic meter water use per well (m^3 water/well) to reflect the net water use; the other is the water intensity, given by cubic meters of water use per ten thousand cubic meter of gas production (m^3 water/10^4 m^3 gas).

2.2. Description of the shale gas life cycle

2.2.1. Site preparation stage

The site preparation stage usually includes three attributable activities, i.e. road repairing and construction, pad construction and auxiliary facilities construction. This paper only considers the water use in auxiliary facilities construction, since there is no significant water use in road repairing and construction and pad construction (Chang et al., 2014a). Auxiliary facilities mainly include a wastewater sink, freshwater impoundment, solidification and landfill, flare pit and some living facilities, such as temporary rooms for workers' cooking and living, toilets and garbage pits (PetroChina-SOC, 2014a, 2014b; 2014c). The construction of these living facilities is not considered in this paper due to little water use in their construction.

The wastewater sink is mainly used for treatment and storage of produced waste liquids during drilling and fracturing stages. The size of a wastewater sink ranges from 1200 m^3 to 3200 m^3 (average value: 2200 m^3), where detailed data sources can be seen in Table S1 in the Supplementary Information (SI). The concrete is prepared on site and used to prevent the percolation of the wastewater sink (PetroChina-SOC, 2014a, 2014b; 2014c). Therefore, the water use in the construction of the wastewater sink is the water used for concrete preparation. The detailed water use estimate is given in SI.

Freshwater impoundment is mainly used for storage of freshwater that is transported from off-site and mainly used for drilling and fracturing. The size of a typical freshwater impoundment ranges from 2800 m^3 to 10000 m^3 (average value: 7500 m^3; see Table S1 in SI). Different from the wastewater sink, the freshwater impoundment uses a waterproof fabric instead of concrete to prevent percolation, since its main function is to temporarily store the freshwater and freshwater has little impact on environment. Therefore, there is no water use in freshwater impoundment construction.

Solidification and landfill is mainly used for treatment of the solid waste produced during the stages of drilling and fracturing, such as drill cuttings. The size of the solidification and landfill facility ranges from 2400 m^3 to 5000 m^3 (average value: 3400 m^3; see Table S1 in SI). A flare pit is mainly used for flaring gas during the period of production testing after fracturing (NDRC, 2004). The size of the flare pit ranges from 50 m^3 to 400 m^3 (average value: 200 m^3; see Table S1 in SI). Similar to the wastewater sink, the concrete is used to prevent the percolation for both the solidification and landfill facility, and the flare pit. The estimated water use in the construction of these two facilities is given in SI.

In addition to the activities discussed above, workers' living activities also need water (i.e. on-site living water use). The water use for on-site living is estimated based on water use per person per day and the total days needed in this stage, and the detailed calculation is also included in SI.

It should be noted the water use estimated in this stage is for one pad rather than for one well, since for shale gas, one pad usually has six wells in the Sichuan basin to reduce extraction cost per well (this mode is called “well-factory”). To present a more practical analysis this paper estimates the average water use per well by dividing the volume of the water use for one pad by the number of wells (see Table S2 in SI).

2.2.2. Drilling stage

The drilling stage includes two processes or activities, i.e. well drilling and well cementation. A well will be firstly drilled in a vertical direction until a “kick-off point” (KOP) is reached, where the orientation of the drill bit will be changed. Then, this non-linear drilling directs