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Game-based analysis of energy-water nexus for identifying environmental impacts during Shale gas operations under stochastic input

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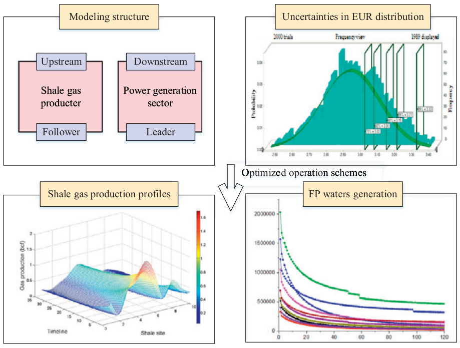
HIGHLIGHTS

- A hierarchical model is developed for optimal design of the shale gas supply chains.
- CCP and MIP approaches are used for identifying uncertain impacts on the decisions.
- Life cycle economic and environmental performances are given in a sequential manner.
- A case study of the Marcellus Shale is given to verify effectiveness of the model.
- Multiple strategies under distinct probability levels are provided for stakeholders.

GRAPHICAL ABSTRACT



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ABSTRACT

Environmental issues have become some of the greatest challenges encountered across the life cycle Shale gas operations, and mostly involve the management, disposal, and spill of flowback and produced (FP) waters during the process of hydraulic fracturing. This study evaluates Shale gas resources, addresses water resource management problems, and identifies the corresponding environmental implications of FP waters under uncertainty. Multiple tools, including structural optimization, process design, cost analysis, environmental assessment, and stochastic technology, are integrated into a general modeling framework based on game theory. This mathematic framework corresponds to a dominant-subordinate-interactive problem, where two major participants are identified as the downstream decision maker at the dominant level (e.g., power generation sector) and the upstream decision maker at the subordinate level (e.g., Shale gas producer). The Monte Carlo technique is used for simulating the estimated ultimate recovery (EUR) of a single well. Thereafter, the developed model is applied to a special case study of the Marcellus Shale play in Beaver County, Pennsylvania. Multiple decisions regarding gas production, processing, water management, as well as electricity generation would been examined under different probability levels. Results indicate that the changes in violation levels would lead to distinct environmental and economic performances of the supply chain. A lower probability level of the EUR value would correspond to an increased reliability on fulfilling the system demands, and then to higher economic benefits and freshwater supply; conversely, a higher probability level of the EUR value would result in lower economic benefits and lower freshwater supply, and the risk of violating the EUR value would also increase.

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1. Introduction

Following the depletion of conventional oil and gas, countries are beginning to turn to Shale gas (Annevelink et al., 2016), especially the United States (U.S.), which is evidenced by the widespread application of horizontal drilling and hydraulic fracturing technologies. Shale gas production from the largest plays in the U.S. has increased from less than 1 billion cubic feet (bcf) per day in 2000 to approximately 42 bcf per day in 2016, which has made the U.S. a net exporter of natural gas since 2009 (Sovacool, 2014). In addition, Shale gas is expected to account for almost 50% of the U.S. natural gas supply by 2035 (EIA, 2011; Lauer et al., 2016). Accompanying the rapid development of the Shale gas industry, environmental issues have been recognized as some of the greatest challenges across the product life cycle, mostly involving the management, disposal, and spill of flowback and produced (FP) waters during the process of hydraulic fracturing (McLaughlin et al., 2016; Chen et al., 2017a). The current hydraulic fracturing process requires a large quantity of water resources mixed with a variety of chemicals and suspended sand. It has been reported that approximately 3.8×10^6 gal of fracturing water were used for the individual Marcellus Shale wells (Cheng et al., 2016). Most of the water would remain underground, but 10% to 40% of the injected water would return to the surface as FP waters (Guerra et al., 2016), which contain a high concentration of total dissolved solids (TDS) and may contaminate the aquatic environment (Chen et al., 2016a). Most importantly, some of the chemicals used in hydraulic fracturing fluids are closely related to adverse human health risks, such as carcinogenicity and neurotoxicity (Ma et al., 2018; Lu et al., 2017). Over the past decade, the most commonly-used option for wastewater management is direct injection of FP waters into disposal wells or underground injection control (UIC) wells. However, this may increase the risk of earthquake. Recently, there is increasing interest in evaluating the potential for reuse of FP waters (Kausley et al., 2017; Jiang et al., 2014; Kondash et al., 2016). Long-term practices indicate that recycling technologies could play a critical role in FP waters treatment with a potential economic revenue of \$3.8 billion by 2025 (Gregory et al., 2011). Therefore, economic production of Shale gas calls for effective water management and wastewater treatment to minimize freshwater consumption while ensuring a sufficient water supply for fracturing operations, during which time environmental and economic concerns should be synergistically taken into consideration.

According to the operational definition, as pressure on the well is initially released, the water returns to the surface during the first few weeks and is referred to as flowback water. The typical flow rate of flowback water is approximately 0.26×10^6 gal per day (Guerra et al., 2016; Vengosh et al., 2014). In addition, the produced water is generated after the flowback period and continues to flow to the surface over the lifespan of the individual wells (Nicot et al., 2014; Gao and You, 2015). It should be specifically mentioned that the composition of FP waters varies spatially and temporally. Normally, the quantity of flowback water is significantly greater than that of produced water, while the latter has a higher concentration of TDS owing principally to its smaller flow rate and longer residence time downhole (Kaiser and Yu, 2012). Moreover, the existing effects on the Shale gas supply chain problem place more emphasis on production profiles prediction (Ikonnikova et al., 2015; Arredondo-Ramírez et al., 2016), design and operations of supply chains (Demissie et al., 2017), selection of transportation modes (Wang et al., 2011), as well as reduction of greenhouse gas (GHG) emissions from life cycle stages (Holding et al., 2015). With the aid of technological advances in horizontal drilling and hydraulic fracturing in recent years, there is a growing interest in freshwater supply and wastewater treatment. Some recently published papers have focused on surface water and groundwater contamination as a consequence of failures related to horizontal drilling and hydraulic fracturing, and the techno-economic analysis of water resources associated with Shale gas operations (Onishi et al., 2017; Chen et al., 2017b). Although investigators have begun working to address the corresponding environmental and economic concerns, much of the attention has been focused merely on the upstream decisions within the Shale gas supply chain from a centralized perspective. For example, water resources management and wastewater handling are individually determined by the upstream decision maker (e.g., Shale gas producer). When the downstream decision maker is considered, a competitive environment with autonomous supply chain participants is formed. Different life cycle stages of the supply chains, involving freshwater supply, wastewater disposal, transportation, gas processing, and end use of final products, are usually managed by different participants; these participants have their own decision objectives and decision variables, and, very often, conflicts of interest (Chen et al., 2016c; Garcia and You, 2015; Yue and You, 2017). With consideration of decision-making hierarchies and differences among different participants, this non-cooperative supply chain problem becomes a Stackelberg dominant-subordinate game that is generally expressed by a bi-level approach to capture different control levels of participants (Chen et al., 2017c). In the dominant-subordinate-interactive decision-making process, the dominant-level decisions are made first, and the subordinate-level participant then reacts rationally to optimize his own decisions (Grossmann et al., 2015).

In a real-world Shale gas supply chain, the discrete decisions (e.g., facility capacity expansion and transportation modes selection) are as important as the continuous decisions (e.g., freshwater withdrawals, wastewater distribution, energy flows, and production plans) (Chen et al., 2016b). However, most of the previous bi-level programming methods for supply chain design and operations have focused solely on linear programming while excluding the discrete decisions, which would lead to unfeasible strategies for participants. It is thus desired to integrate mixed-integer programming (MIP) into a bi-level modeling framework to present facility expansion schemes. Moreover, the previous bi-level studies would frequently encounter difficulties, especially when the supply chain was placed in a random environment. Multiple uncertainties widely exist in a general supply chain, such as stochastic parameters in the estimated ultimate recovery (EUR), water resources availabilities, and FP water flows. Stochastic analysis is therefore applied for identifying the impact of uncertainties on the optimal decisions. Chance-constrained programming (CCP), advanced from stochastic mathematical programming, is effective in addressing uncertainties on the right-hand side of the optimization model (Garcia and You, 2015; Lu et al., 2016). There are two special advantages of CCP as compared with traditional uncertainty methods, summarized as follows (Rahm and Riha, 2014): (a) CCP can effectively address uncertainties presented as probabilities in a model's right-hand side, and it is able to incorporate other uncertain optimization approaches within a general framework; (b) it has an ability to convert a stochastic programming model into an equivalent deterministic form and thus reduce the computation difficulty.

The goal of this study aims to develop a dominant-subordinate chance-constrained programming (DSCCP) model for planning a Shale gas supply chain in the Marcellus region. In the DSCCP model, both CCP and MIP approaches are merged into the bi-level modeling framework, where the downstream optimization problem is controlled by the downstream decision maker at the dominant level (e.g., power generation sector) while the upstream optimization system is managed by the upstream decision maker at the subordinate level (e.g., Shale gas producer). After identifying FP waters and TDS concentration obtained from the modeling solutions and historical data, this study also evaluates the dynamic volume variations of FP waters from multiple Shale sites.

2. Problem statement

2.1. Overview of the Shale gas supply chain system

As shown in Fig. 1, the typical Shale gas supply chain can be classified into three sections, namely upstream, midstream, and downstream, according to the corresponding characteristics. In the upstream section,