Journal of Natural Gas Science and Engineering 52 (2018) 591–608

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

Synergistic management of flowback and produced waters during the upstream shale gas operations driven by non-cooperative stakeholders

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ARTICLE INFO

Keywords:
Shale gas
Supply chains
Bi-level programming
Wastewater disposal
Water supply

ABSTRACT

Shale gas has been denoted as one of alternative energy sources for meeting future energy demands and received global attention, especially with aid of technological advances in horizontal drilling and hydraulic fracturing. This study focuses specially on synergistic optimization of the Marcellus shale-gas-water supply chains with consideration of economics and pollutants mitigation through a mixed-integer bi-level programming model. This model could account for conflicting objectives and interactions between different stakeholders. Operational decisions regarding well drilling schedule, production planning, freshwater withdrawals, wastewater disposal, and infrastructure expansion would be provided for both leader and follower in a sequential manner. Moreover, comparative analyses among the bi-level model and the two single-level models disclose that the bi-level decisions would increase nearly 8.6% of shale gas production, 12.3% of economic benefits, 8.0% of water consumption, and 4.5% of pollutants discharge as compared with the environmentally-aggressive policies. By contrary, the bi-level decisions would lead to 8.5% decrease of shale gas production, 6.1% decrease of economic benefits, 7.3% decrease of water usage, and 6.0% decrease of pollutants discharge when compared with the economically-aggressive solutions. These findings could assist the stakeholders in resolving of conflicts among pollutants reduction, economic performance, and water supply security.

1. Introduction

Today, nearly 80.0% of total world energy consumption has been provided by fossil fuels like coal, oil and natural gas (Hosseini and Wahid, 2014; Chen et al., 2016), which is believed to continue until 2035 with an expected share of 81.0%. Among them, the contribution of natural gas to the global energy structure is increasingly appearing, attributable to the rapid development of shale gas in the US (Vidic et al., 2013; Hao et al., 2016; Yang et al., 2017). Shale gas production in the US had increased from 0.32 trillion cubic feet (tcf) in 2000 to 6.84 tcf in 2011. At the end of 2012, shale gas accounted for 24.0% of the US natural gas production, and it would be anticipated to double again by 2035 according to the Energy Information Administration (Konschnik, 2014; Weijermars, 2014). Despite its large resource and economic potentials (Howarth et al., 2011; Laurenzi and Jersey, 2013; Warner et al., 2013), the increasing expansion of shale gas in the US has around a heated debate over depletion and degradation of water sources (Brittingham et al., 2014; Annevelink et al., 2016; Chen et al., 2017a), particularly with technological advances in horizontal drilling and hydraulic fracturing (Olmstead et al., 2013; Centner, 2016). As one of the essential factors of hydraulic fracturing, millions of water are required to get efficient and economic flow of gas (Dale et al., 2013; Liang et al., 2014). After then, a majority of water would remain underground where it is trapped within the shale formation itself, but 10.0% and 40.0% of the injected water would return to the surface known as flowback and produced waters mixed with a variety of activities (Li et al., 2017), which have long-term implications over time and space due to their latent and cumulative effects (Olmstead et al., 2013; McFarland, 2012; Melikoglu, 2014; Zhao and Yang, 2015). Therefore, strategic design of the shale-gas supply chains becomes a complicated and challenging problem where economic and environmental concerns must be highly enhanced.

Mathematical optimization techniques are critical tools in implementing cost effectiveness and environmentally sustainable strategies in support of shale gas development (Rahm and Riha, 2012; Vandecasteele et al., 2015; Chen et al., 2018). Previously, numerous efforts have been made with considering water-energy nexus or water quality control for the shale-gas supply chains (Knudsen and Foss, 2013;

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https://doi.org/10.1016/j.jngse.2018.02.018
Received 23 August 2017; Received in revised form 3 January 2018; Accepted 19 February 2018
Available online 21 February 2018
1875-5100/

Jiang et al., 2014; Guerra et al., 2016), such as a discrete-time two-stage stochastic mixed-integer linear programming developed for supporting the Marcellus shale play (Yang et al., 2014), a mixed-integer linear fractional programming proposed for optimal design of the Marcellus shale (Gao and You, 2015), a novel mathematical programming approach based on disjunctive programming and Monte Carlo simulations advanced to optimize the Burgos basin (Arredondo-Ramírez et al., 2016). Summarily, the previous effects and applications have focused exclusively on single-level or single-objective approaches. Such an ideal assumption deviates from the practice and the corresponding decisions maybe suboptimal or even infeasible due to without consideration of a hierarchical structure during the decision-making process (Ikonnikova et al., 2015; Liu et al., 2017). Most significantly, single-level approaches cannot only hardly deal with the tolerances under a non-cooperative environment, but also ignore how the individual decision directly or indirectly influence others decisions (Vicente and Calamai, 1994; Madani, 2010; Li et al., 2015). These limitations in traditional single-level approaches will be further identified when some challenges arise. The first challenge is to maximize the economic and environmental performances of the shale gas supply chain network with considering a leader-follower relationship between different stakeholders. The second one is to optimize a more effective strategy for wastewater treatment with regard to disposal wells, centralized treatment, onsite treatment according to their respective strengths and weaknesses of their features and design. The third one is sizing, timing and siting for infrastructure development associated with transportation modes and treatment facilities. The last one is quantification of the amount of pollutants that could be avoided through an integrated shale-gas management.

Multi-objective decisions could assist in developing a comprehensive strategy through setting multiple objective functions for the optimization framework, but depend greatly on the chosen weights, probably leading to subjective discrepancy in judging the priority of each objective (He et al., 2011; Chen et al., 2017b). In addition, they can hardly reflect a leader-follower relationship between different stakeholders (Calvete and Galé, 2010). Actually, multiple non-cooperative stakeholders are normally considered across the supply chains, where the environmental and economic concerns are frequently managed in a decentralized manner by different stakeholders. Besides, each stakeholder has distinct objectives in spite of facing the same supply chain, resulting in conflicts of interest and compromised schemes in reality. To better capture the leader-follower performance of supply chains, there is a need to model and analyze the non-cooperative feature by using a bi-level programming (BLP) for meeting the conflicting objectives (Kalashnikov et al., 2010; Li et al., 2016; Tookanlou et al., 2015; Bahramara et al., 2016; Fonseca et al., 2016). Compared with the traditional single-level and multi-objective optimization methods, this framework could explicitly consider the objectives of various stakeholders. Following the leader-follower decision process, the leader normally enjoys his/her priority of developing strategies and has the knowledge of potential reactions of the follower. The leader usually pays more attention to the environmental concern due to its essential position and community acceptance. When the leader's decisions are made, the follower reacts rationally to address his/her optimization problem. The follower is mostly driven by the economic objective because of the energy, resources and environmental constraints. However, the existing studies on bi-level optimization of supply chain problem solely center on the economic performance and fail to consider the corresponding environmental concern, especially on water withdrawal and contamination (Cheng et al., 2016). In terms of environmental concern, corresponding regulations on damages to the ecosystems should be implemented to promote a sustainable development (Gao and You, 2017; He et al., 2017). Moreover, the discrete decisions associated with transportation mode determination and capacity expansion are as important as the continuous ones. Nevertheless, most of the BLP approaches rarely took into account these discrete decisions, which would lead to infeasible strategies for stakeholders.

Therefore, this study aims to develop a mixed-integer bi-level programming (MIBLP) model for sustainable design and operations of shale gas supply chains, which can significantly address the synergic optimization of two objectives established by different decision-making levels. Apart from minimizing amount of pollutants discharge that is the upper-level objective raised by the environment sector, the maximization of shale-gas system benefits forms the lower-level objective from the energy sector perspective (assumed as MGU-MBL model). The developed MGU-MBL model is then applied into Marcellus shale-gas supply chain problem in Pennsylvania and West Virginia. The following strategic and operational decisions could be achieved based on an improved possibility solution algorithm: (a) selection of freshwater sources and transportation modes, (b) well drilling schedule at different shale sites, (c) wastewater treatment with regard to various technologies, (d) total quantity control of pollutants discharge, and (e) installation and expansion of transportation modes and treatment facilities. These decisions could provide an effective basic for stakeholders to gain insight into the trade-off among environmental impact, economic performance, and water supply security.

2. General problem statement

2.1. Water management options

This study puts more emphasis on the upstream shale gas supply chains, which mostly involve activities associated with well pad preparation, drilling and fracturing multiple well for shale gas production, freshwater supplies and wastewater disposal. Specially, a large water amount must be transported from multiple freshwater sources ($i \in I$) with specific water availability in each period ($k \in K$). Some life cycle studies indicated that the process of hydraulic fracturing was the most significant contributor to the total water consumption (Jiang et al., 2014), while the drilling process accounted for a minor percent of total water consumption with a requirement between 300 and 380 m^3 of water per well. For handing the flowback and produced waters, three main wastewater management options are included, namely direct injection into disposal wells or underground injection control (UIC) wells ($d \in D$) without any treatment, centralized wastewater treatment (CWT, $c \in C$), and onsite treatment for reuse. The first option is injection into disposal wells. As illustrated in Fig. 1, the stored water is directly pumped into disposal well after interim wastewater storage. Disposal wells within the Marcellus shale are not preferred by the stakeholders because of their higher transportation costs. The second option is CWT facilities with common treatment technologies like softening, ultrafiltration, and reverse osmosis. Notably, the special technologies applied in CWT facilities might differ from those shown in Fig. 1. After CWT treatment, two options can be selected: recycled to shale sites or directly discharged into rivers only if it can meet the corresponding discharge standards. The last option is onsite treatment with three levels of technologies. The primary treatment aims to remove suspended mater, free oil and grease (FOG), iron and microbiological contaminants; the secondary treatment can effectively remove hardness ions like Ba^{2+}, Sr^{2+}, Ca^{2+}, and Mn^{2+}, while the tertiary treatment focuses on removal of total dissolved solids (TDS). And there is no transportation cost for onsite treatment. Then, the treated water is sent to shale sites for blending with a certain proportion of freshwater, but the blended water must accord with fracture fluid. In addition, the shale-gas supply chains depend strongly on some transportation modes ($t \in T$) to transit the freshwater and the waste flows via tuck and pipeline. Furthermore, the overall drilling process consists of many points with multiple pollutants ($g \in G$) production. Generally, there are five pathways of pollutants discharge, including transportation spills, poor processing practices at facilities, shale site discharge, leakage from fractured rock, and well casing leaks.