Full length article

A three-level framework for balancing the tradeoffs among the energy, water, and air-emission implications within the life-cycle shale gas supply chains

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ARTICLE INFO

Keywords:
Greenhouse gas
Shale gas
Three-level modeling
Life cycle analysis
Water management

ABSTRACT

Two critical challenges, namely high water resources consumption and growing greenhouse gas (GHG) emissions, are encountered across the current shale gas supply chains. This study presents a three-level modeling framework for economic and environmental life-cycle optimization of the shale gas supply chains. Life cycle analysis (LCA) approach and Stackelberg leader-follower game are integrated into the optimization framework to account for a hierarchical structure.

This hierarchical framework is capable of not only addressing the sequential decision-making problem raised by decision makers at different levels (e.g., the whole-system decision maker as a leader and the environment-development decision maker as a follower), but also developing multilevel cooperative control of water management and GHG-emission mitigation. An application to the Marcellus Shale is then given to demonstrate the capabilities of the developed three-level model. An improved leader-follower-interactive solution algorithm based on satisfactory degree is presented to tackle the computational challenge of the three-level program. The overall satisfaction solution is generated for satisfying the goals of different decision makers by compromising the trade-offs among energy, water, and air-emission implications. Optimal solutions with respect to well drilling schedule, shale gas production, freshwater supply, wastewater treatment, GHG emissions, and electricity generation would be obtained. These analyses are capable of helping decision makers adjust their tolerances to make informed decisions for the supply chains. Moreover, the decision making is not kept static but improved by repeatedly communicating with both different models and sensitivity analysis. Through the communications, the robustness and objectivity of the model solutions can further be enhanced.

1. Introduction

It is projected that the global gas consumption will continuously increase with an average growth rate of 1.5% per year, half of which will be supplied by shale gas (Knudsen et al., 2014; Guerra et al., 2016). Shale gas is widely recognized as one of alternative energy sources for meeting future energy demands, and has received increasing attention worldwide, especially with the aid of advance in horizontal drilling and hydraulic fracturing technologies (Fathi and Ameri, 2015; Jahangideh and Jafarpour, 2016; Figueiredo et al., 2017; Onishi et al., 2017). Although it has obvious economic benefits to optimally conduct shale-gas operations (Bilgili et al., 2016), environmental concerns, regarding greenhouse-gas (GHG) emissions and high-level water consumption, can hardly be ignored (Howarth et al., 2011; Zavala-Araiza et al., 2015; Gao and You, 2015), which have considerably limited the large-scale shale gas development (Zavala-Araiza et al., 2009; Eaton, 2013; Bern et al., 2015). Consequently, comprehensive assessment of environmental impacts of shale gas should take into accounts its economy, climate and resource benefits from a life cycle perspective.

Optimal design of supply chain is now attracting growing emphases (Mohaghegh, 2013; Patwardhan et al., 2014; Arredondo-Ramirez et al., 2016). One of the most critical challenges is synergic optimization of environmental and economic performances that are suitable for shale gas engineering practices (Chen et al., 2018), i.e., quantification of the amount of GHG emissions and identification of cost-effective strategies. Summarily, the previous mathematical programming applications in the shale gas industry can be divided below: firstly, some studies focused specifically on reducing life-cycle costs for achieving economic benefits (Kaiser, 2012; Yang et al., 2014; Calderón et al., 2015); secondly, environment quality improvement was significantly enhanced

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https://doi.org/10.1016/j.resconrec.2018.02.015
Received 8 July 2017; Received in revised form 5 February 2018; Accepted 12 February 2018
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The emission of natural gas from drilling at shale site $i$ and time period $k$.

The ratio of wastewater from process $j$ to disposal wells at time period $k$.

The minimum and maximum proportions of wastewater treated by disposal wells to the total amount of wastewater generated from process $j$ at shale site $s$.

The ratio of wastewater from process $j$ to fresh water at disposal wells.

The unit capital investment of transportation mode.

The unit cost for shale gas production at shale site $s$.

The unit cost for energy sources during drilling well.

The per revenue of electricity at shale site $i$ and time period $k$.

The unit conversion factor.

The total water use per well for process $j$ at shale site $s$.

The processing efficiency for the raw shale gas.

The water use per well for process $j$ at shale site $i$.

The transportation capacity of transportation mode.

The unit CWT variable cost of transportation mode.

The CWT treatment cost.

The CWT facilities for discharging at shale site $s$.

The minimum and maximum ratios of wastewater treated by CWT facilities to the total amount of flowback generated from process $j$ at shale site $s$.

The unit capital investment of transportation mode.

The unit UIC treatment cost.

The maximum allowable emission at each shale site $s$ and time period $k$.

The unit cost of onsite treatment by technology $o$.

The transportation capacity of transportation mode.

The per revenue of NGLs at shale site $s$.

The recovery factor for treating wastewater based on natural gas.

The per revenue of electricity at shale site $i$ and time period $k$.

The ratio of wastewater from process $j$ to shale site $s$.

The unit variable cost of transportation mode.

The unit variable cost of energy sources during hydraulic fracturing.

The processing efficiency for the raw shale gas.

The amount of freshwater for technological process $j$ transported by transportation mode $t$ from water source $i$.
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