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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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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; Jahandideh 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-Ramírez 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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Nomenclature

Objective

C_{CWT}	CWT treatment cost
C_{elec}	Cost related to electricity generation
C_{energy}	Cost related to energy consumption
$C_{fresh,acq}$	Cost related to freshwater acquisition
$C_{fresh,trans}$	Cost related to freshwater transportation
C_{gas}	Cost related to shale gas production operations
C_{onsite}	Onsite treatment cost
C_{UIC}	Underground injection cost
C_{waste}	Cost related to wastewater treatment
$GWP_{CWT,s,k}$	GHG emissions from CWT treatment
$GWP_{elec,s,k}$	GHG emissions from electricity generation
$GWP_{fresh,s,k}$	GHG emissions from freshwater acquisition
$GWP_{onsite,s,k}$	GHG emissions from onsite treatment
$GWP_{prod,s,k}$	GHG emissions from shale gas production
$GWP_{tsd,s,k}$	GHG emissions from transport, storage and distribution
$GWP_{UIC,s,k}$	GHG emissions from UIC treatment
$GWP_{waste,s,k}$	GHG emissions from wastewater treatment
$GWP_{well,s,k}$	GHG emissions from shale well drilling and completion
R_{elec}	Revenues associated with electricity sale
R_{fresh}	Revenues associated with freshwater income sale
R_{gas}	Revenues associated with natural gas sale
R_{NGLs}	Revenues associated with NGLs sale

Parameters

DD_s	The distance from shale site s to disposal wells at time period k
$ftc_{s,t,k}$	The unit capital investment of transportation mode t from shale site s to CWT facilities at time period k
$ftd_{s,t,k}$	The unit capital investment of transportation mode t from shale site s to disposal wells at time period k
$fts_{i,s,t,k}$	The unit capital investment of transportation mode t from water source i to shale site s at time period k
$RACR_{s,j}$	The ratio of wastewater from process j transported into CWT facilities for recycling at shale site s
DC_s	The distance from shale site s to CWT facilities at time period k
$DF_{i,s}$	The distance from water source i to shale site s
DRI_s	The unit cost for well drilling and complete at shale site s
EC_s	The unit cost for per electricity generation
$eelec$	The emission related to process of electricity generation based on natural gas
$efresh$	The emission related to transportation of per amount of freshwater
$EM_{s,j,m,k}$	The requirement of energy m for drilling at shale site s and time period k
$EN_{s,j,n,k}$	The requirement of energy n for hydraulic fracturing at shale site s and time period k
$eonsite_o$	The emission related to treatment of unit amount of wastewater at onsite facility by technology o
$eprod$	The per emission during the process of shale gas production
$etsd$	The emission related to process of transport, storage and distribution for per gas
EW	The amount of water for per electricity generation
$ewell$	The emission during the processes of per well drilling and completion
exc	The emission related to treatment of unit amount of wastewater at CWT facility
exd	The emission related to treatment of unit amount of wastewater at UIC facility
ext_t	The emission related to transportation of unit amount of wastewater based on transportation mode t
$FB_{s,k}$	The freshwater effectiveness at shale site s and time period k
$FC_{i,s,k}$	The unit acquisition cost of water source i at shale site s and time period k
$FWA_{i,s,k}$	The availability of water source i at shale site s and time period k
$FWD_{s,j,k}$	The total water use for shale gas extraction at each shale site
FW_s	The total amount of freshwater at shale site s
$GE_{s,k}$	The life-cycle electricity generation
lo_o	The recovery factor for treating wastewater based on technology o
mc_s and lc_s	The methane and NGLs compositions at shale site s
$PE_{s,k}$	The per revenue of electricity at shale site s and time period k
$PL_{s,k}$	The revenue of NGLs at shale site s and time period k
$PM_{s,j,m,k}$	The unit cost for energy sources during drilling well
$PN_{s,j,n,k}$	The unit cost for energy sources during hydraulic fracturing
$proce$	The processing efficiency for the raw shale gas
PR_s	The unit cost for shale gas production at shale site s
$RAC_{s,j,min}$, $RAC_{s,j,max}$	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
$RADR_{s,j}$	The ratio of wastewater from process j transported into CWT facilities for discharging at shale site s
$RAD_{s,j,min}$, $RAD_{s,j,max}$	The minimum and maximum ratios of wastewater treated by disposal wells to the total amount of flowback generated from process j at shale site s
$RAO_{s,j,min}$, $RAO_{s,j,max}$	The minimum and maximum ratios of wastewater treated by onsite facilities to the total amount of flowback generated from process j at shale site s
$RW_{s,j,min}$, $RW_{s,j,max}$	The minimum and maximum proportions of water source i at shale site s
$spp_{s,k\text{-}k'}$	The shale gas production profile of a well drilled that at time period k' at shale site s and time period k
$SP_{s,j}$	The flowback rate of process j at shale site
$TCA_{s,t}$	The transportation capacity of transportation mode t from shale site s to CWT facilities
$TCD_{s,t}$	The transportation capacity of transportation mode t from shale site s to disposal wells
TC_s	The unit CWT treatment cost
TD_s	The unit UIC treatment cost
$TG_{s,k}$	The maximum allowable emission at each shale site s and time period k
TO_o	The unit cost of onsite treatment by technology o
$TSA_{i,s,t}$	The transportation capacity of transportation mode t from water source i to shale site s
$UW_{s,j,k}$	The water use per well for process j at shale site s at time period k
$VFTC_{s,t}$	The unit CWT variable cost of transportation mode t at shale site s
$VFTD_{s,t}$	The unit UIC variable cost of transportation mode t at shale site s
$VFTS_{i,s,t}$	The unit freshwater variable cost of transportation mode t from water source i to shale site s
ξ	The unit conversion factor

Variables

$xc_{s,t}$	The binary variable
$fw_{i,s,j,t,k}$	The amount of freshwater for technological process j transported by transportation mode t from water source i