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Life cycle assessment of greenhouse gas emissions and water-energy optimization for shale gas supply chain planning based on multi-level approach: Case study in Barnett, Marcellus, Fayetteville, and Haynesville shales

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ABSTRACT

This study develops a multi-level programming model from a life cycle perspective for performing shale-gas supply chain system. A set of leader-follower-interactive objectives with emphases of environmental, economic and energy concerns are incorporated into the synergistic optimization process, named MGU-MEM-MWL model. The upper-level model quantitatively investigates the life-cycle greenhouse gas (GHG) emissions as controlled by the environmental sector. The middle-level one focuses exclusively on system benefits as determined by the energy sector. The lower-level one aims to recycle water to minimize the life-cycle water supply as required by the enterprises. The capabilities and effectiveness of the developed model are illustrated through real-world case studies of the Barnett, Marcellus, Fayetteville, and Haynesville Shales in the US. An improved multi-level interactive solution algorithm based on satisfactory degree is then presented to improve computational efficiency. Results indicate that: (a) the end-use phase (i.e., gas utilization for electricity generation) would not only dominate the life-cycle GHG emissions, but also account for 76.1% of the life-cycle system profits; (b) operations associated with well hydraulic fracturing would be the largest contributor to the life-cycle freshwater consumption when gas use is not considered, and a majority of freshwater withdrawal would be supplied by surface water; (c) nearly 95% of flowback water would be recycled for hydraulic fracturing activities and only about 5% of flowback water would be treated via CWT facilities in the Marcellus, while most of the wastewater generated from the drilling, fracturing and production operations would be treated via underground injection control wells in the other shale plays. Moreover, the performance of the MGU-MEM-MWL model is enhanced by comparing with the three bi-level programs and the multi-objective approach. Results demonstrate that the MGU-MEM-MWL decisions would provide much comprehensive and systematic policies when considering the hierarchical structure within the shale-gas system.

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1. Introduction

In the 21th century, securing energy sources and mitigating global warming have been widely recognized as critical concerns of the whole world, particularly when the world fossil fuels consumption has been dramatically increased [1–5]. Shale gas, however, has been emerged as an increasingly strategic and promising energy resource for meeting global energy demand [6]. The large-scale development of shale gas industry depends primarily on the combined application of the horizontal drilling and hydraulic fracturing, especially in the Barnett, Marcellus, Fayetteville, and Haynesville Shales in the US [7]. Shale gas is expected to contribute to the largest source of growth in the US natural gas supply as a consequence of these technological improvements. According to a report from the Energy Information Administration (EIA), 16.0% of the US natural gas, on average, was provided by shale gas in 2009, then changed to 24.0% in 2012. It is anticipated that, by 2035, its share will increase to 47.0% [8,9]. However, the unwanted side-effects of shale gas, consisting of a huge amount of greenhouse gas emissions and large quantities of water use associated with the hydraulic fracturing, have posed both environmental and economic changes to its sustainable development. As reported,

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Nomenclature

Objectives

$TGWP$ the expected life cycle GHG emissions (kg CO_2-eq)
$TBenefit$ the expected economic benefits over the lifetime ($)
$profit$ and $cost$ the system profit and system cost obtained from shale gas activities ($), respectively
$TFrew$ the expected life cycle water use (gallon)

Parameters

CHs the bulk gas methane content at shale site s (80.0%)
η the unit conversion factor (MJ/bcf)
G_{wc}, G_{equip}, G_{proce}, G_{tsd} and $G_{electic}$ the unit global warming potential for shale gas associated with the processes of well completion, routine venting and equipment, processing, transport, storage and distribution, as well as electricity generation (kg CO_2-eq/MJ), respectively
me_{mc}^{min}, me_{equip}^{min}, me_{proce}^{min}, and me_{tsd}^{min} the minimum fugitive methane emissions related to the processes of well completion, routine venting and equipment, processing, as well as transport, storage and distribution (%), respectively
me_{mc}^{max}, me_{equip}^{max}, me_{proce}^{max}, and me_{tsd}^{max} the maximum fugitive methane emissions related to the processes of well completion, routine venting and equipment, as well as processing, transport, storage and distribution (%), respectively
GWP_{mc}^{max}, GWP_{equip}^{max}, GWP_{proce}^{max}, GWP_{tsd}^{max} and GWP_{electc}^{max} the allowable global warming potential pertinent to the processes of well completion, routine venting and equipment, processing, transport, storage and distribution, as well as electricity generation (kg CO_2-eq), respectively
PG_s the benefit of per unit shale gas at site s ($/bcf)
$PW_{i,s}$ and $CW_{i,s}$ the unit freshwater effectiveness and acquisition cost of water source i at shale site s ($/gallon), respectively
PE_s the unit electricity benefit at shale site s ($/MJ)
EW_s the amount of water for per electricity generation at site s (gallon/MJ)
PEC_s the water acquisition cost for electricity generation at site s ($/gallon)
$TF_{s,t}$, $TC_{s,t}$ and $TD_{s,t}$ the unit transportation cost of water by transportation mode t at shale site s ($/mile gallon)
DF_s, DC_s and DD_s the distance between water source and shale site, CWT facility and shale site, as well as disposal well and shale site (mile), respectively
TG_t the transportation cost to transfer shale gas to end users by transportation mode t ($/bcf)
OC_s and OD_s the unit operation cost of wastewater treated by CWT facility and disposal well at shale site s ($/gallon), respectively
EPC_s the unit GHG-pollutant abatement cost at shale site s ($/bcf)
$EDM_{s,m}$ the requirement of energy m for drilling and constructing a typical well at shale site s (tonne/well)
$PEM_{s,m}$ the cost for energy m for drilling and constructing a typical well at shale site s ($/tonne)
$EDN_{s,n}$ the requirement of energy n for hydraulic fracturing at shale site s $PEN_{s,n}$ the cost for energy n for hydraulic fracturing and wastewater management at shale site s
$UW_{s,j}$ the water use per well for process j at shale site s (gal/well)
TCC_s and TCD_s the initial handing capacity of CWT facility and disposal well at shale site s (gallon/week), respectively
L the length of lifetime (week)
$TSV_{i,s,t}$ the initial transportation capacity of mode t between water source i and shale site s (gallon/week)
$TCV_{s,t}$ the initial transportation capacity of mode t between CWT facility and shale site s (gallon/week)
$TDV_{s,t}$ the initial transportation capacity of mode t between disposal well and shale site s (gallon/week)
$FR_{s,j}$ the flowback rate of technological process j at shale site s (%)
$DRC_{s,j,\min}$ and $DRC_{s,j,\max}$ the minimum and maximum ratios of wastewater treated by CWT facility to the totaling flowback from technological process j at shale site s (%), respectively
$DRD_{s,j,\min}$ and $DRD_{s,j,\max}$ the minimum and maximum ratios of wastewater treated by disposal well to the totaling flowback from technological process j at shale site s (%), respectively
$SR_{s,j,\min}$ and $SR_{s,j,\max}$ the minimum and maximum ratios of recycled water to the totaling flowback from technological process j at shale site s (%), respectively
$DRCR_s$ the ratio of wastewater from CWT facility to recycling at site s (%)
$DRCD_s$ the ratio of wastewater from CWT facility into revers at site s (%)
DRS_{min} and DRS_{max} the minimum and maximum ratios of flowback to make up reused water (%), respectively
WN_s^{min} and WN_s^{max} the minimum and maximum number of wells at site s, respectively
SG_s^{min} and SG_s^{max} the minimum and maximum gas production at site s, respectively
USG_s^{min} and USG_s^{max} the minimum and maximum lifetime shale gas production per well at shale site s (bcf/well), respectively
$FW_{i,s}$ the availability in water source i at shale site s (gallon)
FP_s^{min} and FP_s^{max} the minimum and maximum ratios of surface water to the totaling freshwater withstand (%), respectively

Variables

wn_s the number of wells at shale site s
usg_s the lifetime shale gas production per well at shale site s (bcf/well)
me_{wc}, me_{equip}, me_{proce}, and me_{tsd} the fugitive methane emissions related to the processes of well completion, routine venting and equipment, processing, as well as transport, storage and distribution (%), respectively
$frew_{i,s,j,t}$ the amount of freshwater for technological process j transported by transportation mode t from water source i to shale site s (gallon)
$wtc_{s,j,t}$ the amount of wastewater from technological process j by transportation mode t between shale site s to CWT facility (gallon)
$wtd_{s,j,t}$ the amount of wastewater from technological process j by transportation mode t between shale site s to disposal well (gallon)
$wtcr_{s,t}$ the amount of treated water recycled to shale site s by transportation mode t (gallon)
$wtcd_{s,t}$ the amount of water discharged into rivers by transportation mode t at shale site s (gallon)
$wp_{s,j}$ the amount of wastewater from process j at shale site s (gallon)
$wr_{s,j}$ the amount of recycled water from process j at shale site s (gallon)

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