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Full Length Article

Energy-environmental implications of shale gas extraction with considering a stochastic decentralized structure

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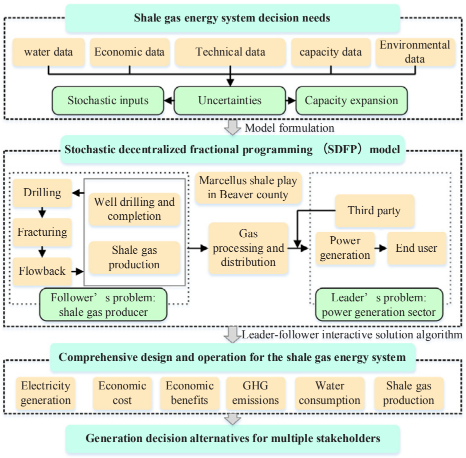
GRAPHICAL ABSTRACT



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ABSTRACT

Major challenges in the shale gas supply chains are identification of the relationship between different stakeholders and evaluation of the environmental impacts under uncertainties. This study develops a stochastic decentralized fractional programming (SDFP) for the life cycle shale gas energy system planning, where the downstream optimization problem is treated as the upper-level model, and the upstream optimization problem is formulated as the lower-level model. Stochastic uncertainties in the estimated ultimate recovery (EUR) and greenhouse gas (GHG) emissions are considered into the decision making process. A SDFP based energy and environmental workflow is then formulated for a real-work case study of Marcellus shale play in Beaver County. Design and operational decisions for both leader and follower are generated in a sequential manner, involving well drilling schedule, energy flows, water resources management, and GHG emissions control. Results reveal that a higher certainty level of EUR value would correspond to a higher reliably in shale gas production, then to increased GHG emissions and economic benefits. Compared with the decentralized linear programs, the SDFP would provide more sustainable strategies, while the linear programs would generate either environment-oriented or economics-oriented strategies. These findings can help stakeholders to achieve the overall satisfaction of the supply chains and to provide useful information for regional GHG emissions control.

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1. Introduction

According to the U.S. Greenhouse Gas (GHG) Emissions Inventory, the natural gas has accounted for approximately a quarter of the U.S. total methane emissions in 2011 [1]. Shale gas is expected to represent the most significant source of growth in the U.S. natural gas industry, especially when there is wide application of horizontal drilling and hydraulic fracturing technologies [2]. However, the pressing request for reduction of climate change has resulted in considerable pressure to mitigate GHG effects, particularly in the natural gas industry [3]. In response to the above issues, there is an urgent need for a comprehensive technique to promote sustainable design and operation of the shale gas energy system.

Life cycle assessment (LCA) has been demonstrated as a practical and effective tool in estimating all GHG emissions from natural gas utilization [4–6]. Nevertheless, classical LCA approaches frequently encounter difficulties when the shale gas system requires a decision-support or systematic methodology for optimizing the discussed problem to improve current environmental performance [7]. Synergistic methods based on mathematical approaches and system analysis are available to assist in understanding the interrelationships between the economic and environmental interests [8–10]. A functional-unit-based life cycle optimization method is then given for effectively addressing the problems with multiple conflicting objectives and providing more cost-effective and environmentally sustainable polices in support of shale gas sustainable development. The advantage of this method has been verified by a number of applications, such as a LCA-based multi-objective mixed-integer programming for the Marcellus play [11], and a multi-objective program for life cycle flowback management in shale wells [12]. Notably, these effects relied exclusively on centralized or single-level programs, where the entire system is managed by a single decision maker or a universal objective [13,14]. A major drawback of these techniques is lack of considering a hierarchical structure within the general shale gas energy system, where conflict of objectives between different stakeholders normally appears and their operations are usually decentralized. Actually, multiple life cycle stages of a typical shale gas system are frequently determined by different stakeholders in a decentralized manner. Each of them strives to obtain their own benefits, leading to generation of either too environmentally-aggressive or economically-aggressive policies [15,16]. To handle such problem, a bi-level optimization model was proposed for the Marcellus shale across Pennsylvania and West Virginia, where a non-cooperative leader-follower relationship was illustrated [17]. Additionally, a multi-level programming model was developed for performing the shale-gas supply chain system from a life cycle perspective, in which a set of leader-follower-interactive goals with emphases of environmental, economic and energy concerns was incorporated into the decision-making process [2,18].

However, a primary shortcoming of these multi-level models is that they ignore the possible interactions between the downstream customers and the upstream shale producer within a non-cooperative energy system. Rather than integrating an aggregated stakeholder in charge of the overall shale gas energy system, different stakeholders with various objectives are considered as explicit decision makers that are placed at different levels [19–21]. The leader usually enjoys the priority to make decisions first. In view of the sufficient natural gas supply, a buyer's market is considered in this study. The downstream power generation sector is thus the major player of the shale gas energy system, whose energy demands can significantly affect the total shale gas production and the entire GHG emissions. Thus, the power generation sector is presented as the leader of the Stackelberg game. In this control level, environmental sustainability and economic efficiency would be highly emphasized. However, the leader's concern is heavily dependent on the follower's performance. After observation of leader's decisions, the follower takes actions to optimize the corresponding optimization problem. In this study, the follower's concern is raised from the shale gas producer who focuses on the economic benefits and life cycle water resources consumption in support of shale gas development. Accordingly, the relationship between the power generation sector and shale gas producer can be formulated as a decentralized optimization problem. Nevertheless, a gap between recognition of the importance of uncertainty and its actual inputs inevitably exists during the decision-making process. Scenario assumption and sensitivity analysis can hardly quantify the relative importance of uncertainties and can be incapable of assisting the stakeholders in identifying the most optimal scheme before uncertainties are effectively addressed [22]. Actually, the practical shale gas energy system is surrounded with multiple uncertainties because many stochastic factors (e.g., GHG-emission intensity, shale gas production profits, and water-use efficiency) are involved [23,24]. For example, the production and the estimated ultimate recovery (EUR) are affected by stochastic initial production of a single well. These factors and their interactions result in uncertainties in modeling inputs that further complex the corresponding decision-making process.

The objective of this study is to develop a LCA-based optimization model for non-cooperative shale gas energy system planning, where the upstream and downstream of a typical supply chain are highlighted in a sequential manner. The Stackelberg game-based optimization framework is used for reflecting different roles of stakeholders in the non-cooperative energy system. Following the Stackelberg game, the follower must follow the leader, which in turn must attempt to satisfy with the follower in an incentive or disincentive manner for their targets to be synchronously optimized [25]. With consideration of stochastic information associated with the shale-gas activities, the resulting problem can be modeled as a stochastic decentralized fractional programming (SDFP) model. Four special characteristics of the SDFP model make it unique as compared with the previous bi-level studies. First, life cycle environmental and economic performances are integrated into the SDFP modeling framework for representing the interaction between different stakeholders. Second, this study considers four functional-unit-based fractional objectives for enhancing the robustness of model solutions and providing more sustainable strategies than their linear forms. Third, a leader-follower interaction solution algorithm is used to improve computational efficiency. Fourth, stochastic information is considered for addressing uncertainties in the shale gas energy system. Moreover, carbon capture and storage (CCS) technologies are expected to be installed in power plants for GHG emissions reduction. Then, the SDFP model is applied into a real-world shale gas energy system in the Marcellus region.

2. General problem statement

2.1. Superstructure of life cycle shale gas supply chain

A general shale gas supply chain can be divided into upstream, midstream, and downstream sectors according to the corresponding development activities [26]. It should be specially noted that this study simplifies the three-echelon structure as a two-echelon one, where the upstream focuses on all the processes before gas end use and the downstream emphasized on the end-use of natural gas for electricity generation and other customers. Specifically, the upstream carters on the operations regarding shale site preparation, freshwater acquisition, drilling and fracturing multiple wells for gas production, which is run by the shale gas producer. After gas gathering, the produced raw shale gas would be transported to processing plants for processing, storage, and distribution through pipelines. In this phase, the major by-product known as liquefied natural gas (LNG) would be generated and can be separately sold with a high price. The downstream presents the end use of natural gas. Demands can be classified into four major sectors based on the end-user types, namely, electric power plants, commercial customers, residential customers, and industrial applications [7,27]. The power generation sector, as the most significant decision maker in the