CHEMICAL ENGINEERING TRANSACTIONS
VOL. 45, 2015
A publication of
AIDIC
The Italian Association
of Chemical Engineering
www.aidic.it/cet
Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Sharifah Rafidah Wan Alwi, Jun Yow Yong, Xia Liu

ISBN 978-88-95608-36-5; **ISSN** 2283-9216
DOI: 10.3303/CET1545083

Sustainable Design and Operation of Shale Gas Supply Chain Networks with Life Cycle Economic and Environmental Optimisation

Jiyao Gao, Fengqi You*

Department of Chemical and Biological Engineering, Northwestern University, Evanston, IL, 60201, USA
you@northwestern.edu

In this work, we address the functional-unit based life cycle optimisation of the design and operations of shale gas supply chain networks considering both the economic and environmental performance. The system covers the well-to-wire life cycle of electricity generated from shale gas, consisting of a number of stages including freshwater acquisition, shale well drilling, fracking, and completion, shale gas production, wastewater management, shale gas processing, electricity generation as well as transportation and storage. The resulting problem is formulated as a multi-objective non-convex mixed-integer nonlinear programming (MINLP) problem. By solving this problem with a global optimisation algorithm, we obtain the Pareto-optimal frontier, which reveals the trade-off between the economic and environmental objectives. A case study based on the Marcellus shale play shows that the environmental impact of shale gas generated electricity ranges from 454 to 508 kg CO_2eq/MWh, and the levelised cost of electricity ranges from 66 to 170 \$/MWh.

1. Introduction

In the U.S., the shale gas contribution to the total natural gas production has increased from less than 5 % to 35 % from 2005 to 2012, and it is expected to reach 50 % by 2035 (EIA, 2011). The shale gas production system is a complex multi-stage network, including water acquisition, shale gas production, wastewater management, shale gas processing, inventory, usage, and transportation. A variety of decisions are involved in each stage of this system (Yang and Grossmann, 2014). Therefore, the optimal design and operations of the shale gas supply chain has great economic potential (Seydor et al., 2012). Another perspective to note is on its environmental sustainability performance. Natural gas has long been recognised as a clean energy. However, as the primal composition of natural gas, methane is an extremely potent greenhouse gas (Howarth, 2014). Moreover, the supply chain activities such as shale gas production, processing, transportation, and power generation would incur large amount of GHGs. Therefore, the climate benefits from shale gas use depend on the overall environmental performance of the whole system. Due to the significant economic and environmental impacts, it is essential to simultaneously take both of these two criteria into account when addressing the optimal design and operations of shale gas supply chains.

From the review of existing work in the field, we found a shortage of decision-support tools and methodologies dedicated to the environmentally conscious design and operations of shale gas supply chain systems (Garcia and You, 2015). Thus, the main goal of this work is to develop a functional-unit based life cycle optimisation model for optimal design and operations of shale gas supply chain, which can simultaneously evaluate and optimise the economic and environmental performance by optimisation of decisions for network design, drilling scheduling, technology selection, facility location and sizing, natural gas storage, and transportation, etc. To address this challenging problem, we propose a multi-objective, multi-period non-convex MINLP model with nonlinear terms regarding capital investment in the fractional-form objective function to account for the functional unit of this study. In the proposed life cycle optimisation model, we consider seasonality of freshwater supply, scheduling of

Please cite this article as: Gao J., You F., 2015, Sustainable design and operation of shale gas supply chain networks with life cycle economic and environmental optimisation, Chemical Engineering Transactions, 45, 493-498 DOI:10.3303/CET1545083

shale well drilling, wastewater management, shale gas processing, underground reservoir, electric power generation, and transportation. Levelised cost of electricity generated from shale gas is chosen as the main economic indicator for the projected economic performance of the shale gas supply chain. The environmental impact associated with the production of unit amount of electricity from shale gas is chosen as the environmental indicator, which is evaluated based on the well-to-wire life cycle assessment (LCA) (Weber and Clavin, 2012). It is worth noting that due to the combinatorial nature and non-convexity of the MINLP problem, it is challenging to globally optimise the large-scale supply chain problems. To address this issue, we present a global optimisation method integrating the parametric algorithm with a branch-and-refine method that is much more efficient than general-purpose MINLP solvers.

2. Life Cycle Optimisation Approach

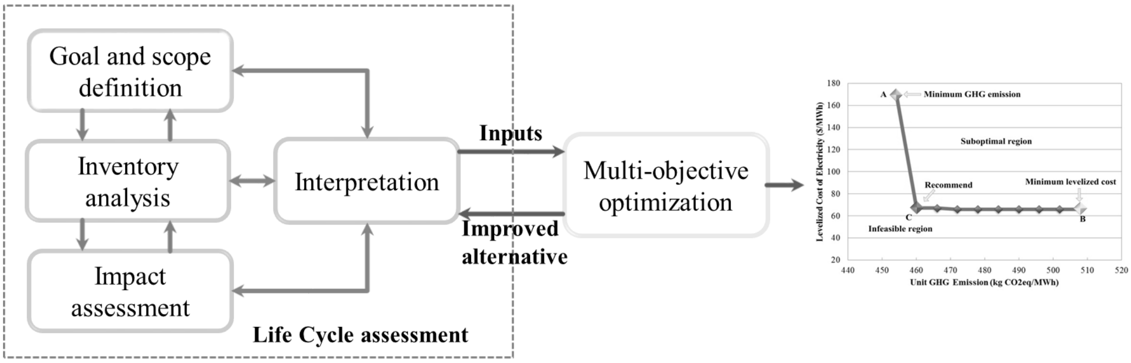

Figure 1: Life cycle optimisation modelling framework (Yue et al., 2013)

In this work, we apply the life cycle optimisation to overcome the drawbacks of classical LCA methodology that cannot automatically generate alternatives for better design and operations decisions (Wan et al., 2014). The framework of the life cycle optimisation can be illustrated by Figure 1, which integrates the classical four-step process-based LCA methodology with the multi-objective optimisation method (Gong and You, 2014a), providing design and operation alternatives as well as identifying the optimal decisions in terms of environmental performance (Wan et al., 2014). The main information regarding the LCA of this shale gas supply chain networks is presented as follows.

The primary goal of this study is to identify the shale gas supply chain network with the least direct and indirect emissions from the production of shale gas at shale sites to the electricity generation at power plants. We note that in most cases the shale gas ends in combustion for power generation (Weber and Clavin, 2012). We restrict the domain of study to all the life cycle stages from “well-to-wire” following the existing literature on shale gas LCA studies (Laurenzi and Jersey, 2013), as well as a pioneer work by Heath et al. (2014). The whole system of the shale gas life cycle is depicted in Figure 2. The system boundaries include processes as the freshwater acquisition, well drilling, hydraulic fracturing, and completion, shale gas production, wastewater management, shale gas processing, transmission, underground storage, and power generation (EPA, 1996). Shale sites acquire freshwater for drilling and hydraulic fracturing from freshwater sources, where potential shale wells can be drilled and fracked at each site. Shale gas is produced together with the flowback wastewater. The wastewater can be transported to remote Class-II disposal wells for underground injection, transported to CWT facilities for treatment, or treated by some mobile onsite treatment units for treatment and reuse (Gao and You, 2015). The raw shale gas is delivered to processing plants, where natural gas and NGLs are separated (He and You, 2014). NGLs are directly sold or temporarily stored near the processing plant, while natural gas can either be delivered to power plants for electricity generation, or transported to underground reservoirs for storage (He and You, 2015). This system can be divided into the “upstream” section and the “downstream” section (Laurenzi and Jersey, 2013). The “upstream” section involves all the phases of the shale gas life cycle preceding the power plant, including well pad preparation, well drilling, hydraulic fracturing, well completion, water management, shale gas production, processing, and storage. The “downstream” section mainly involves the power generation. All the these processes and activities within this system boundary not only have economic impacts on this system, but also generate GHG emissions, bringing about environmental impacts as well.

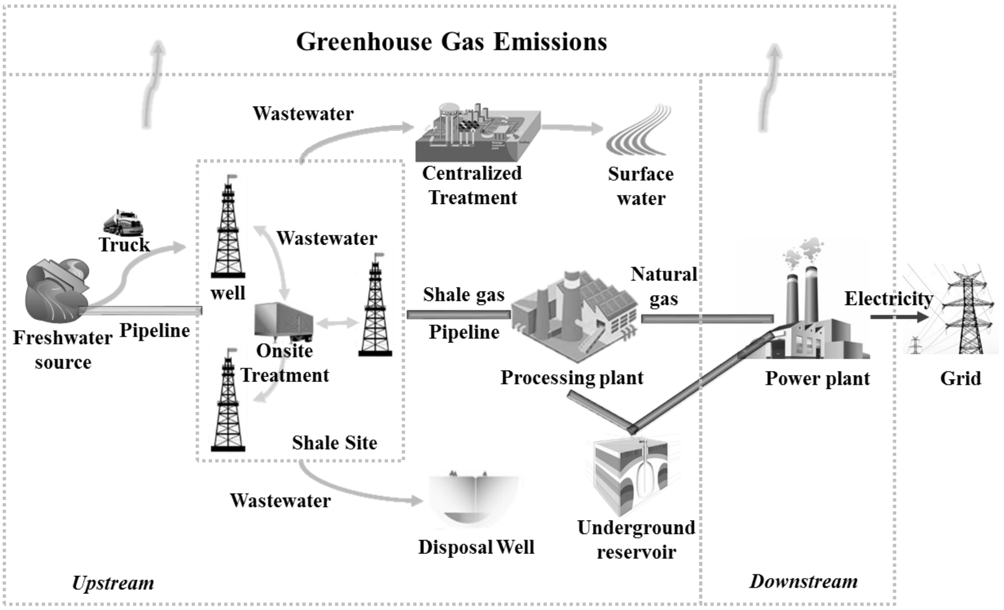

Figure 2: Illustration of general shale gas supply chain networks

In this work, natural gas from Marcellus shale play is considered as a fuel for electric power generation. We employ a functional unit of one MWh of electric power generated at the power plant following existing LCA work. All the economic input data used in this work are directly or indirectly derived from the best literature we can find. All the LCA data are derived based on reviewing the existing LCA study of shale gas, especially those of the Marcellus shale play.

The life cycle inventory is analysed based on processes/activities in the life cycle stages within the predefined system boundary. We are able to identify and quantify the most relevant inputs/outputs of materials and energy use associated with corresponding activities based on the mass balance as well as energy balance. By conducting the inventory analysis, we are able to quantify the impacts that we are concerned about and make decisions accordingly.

In this work, emissions are quantified in units of CO_2-equivalents, which is a metric that compares the radiative forcing associated with a GHG relative to that of CO_2. More specifically, we utilised 100-year global warming potentials (GWP) to assess the environmental impacts of different GHGs. As a result, the environmental impact is evaluated based on GHG emissions per unit electricity generation as kg CO_2eq/MWh.

LCA results are analysed to provide criteria and quantitative measurements for comparison of different supply chain decision alternatives. In this work, we couple the optimisation tool with environmental impacts assessment to provide a systematic approach for generating alternatives and identifying the environmentally optimal decision. By solving the multi-objective optimisation problem, we can obtain the Pareto-optimal frontier consisting of a set of Pareto-optimal solutions revealing the trade-off between the economic objective as well as the environmental objective, which helps us develop a more sustainable shale gas supply chain network.

3. Model formulation

The entire optimisation model is formulated as a multi-objective non-convex MINLP problem with linear constraints and nonlinear fractional objective functions, denoted as (P),

$$\min \ LC = \frac{TC}{TGE} \qquad \text{(Economic Objective)} \qquad (1)$$

$$\min \ UE = \frac{TE}{TGE} \qquad \text{(Environmental Objective)} \qquad (2)$$

s.t. mass balance constraints
capacity constraints
composition constraints
bounding constraints
logic constraints

We note that LC is the levelised cost of electricity, expressed as the total life cycle cost, which is denoted as TC, divided by the total lifetime electricity generation, denoted as TGE. UE is the GHG emission corresponding to unit electricity generation, expressed as the total GHG emission TE divided by the total electricity generation TGE.

4. Solving approaches

In order to handle the multi-objective formulation, we apply the ε-constraint method and transform the environmental objective into an additional bounding constraint, resulting in a series of single-objective optimisation problems. By integrating the branch-and-refine algorithm (You et al., 2011) and the inexact parametric algorithm (Zhong and You, 2014), we are able to tackle the global optimisation of the nonconvex MIFP problem by solving a sequence of MILP subproblems (Gong and You, 2014b). The algorithm is summarized in Figure 3.

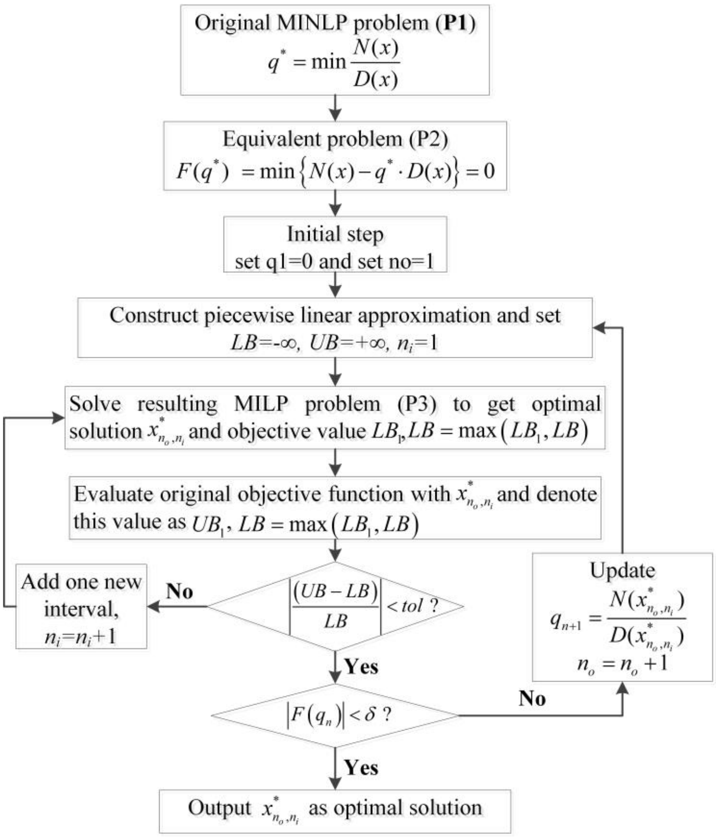

Figure 3: Flowchart of branch-and-refine Integrated parametric algorithm

5. Results and discussion

To illustrate the proposed models and solution approaches, we present one large scale case study based on Marcellus shale play. In this large scale case study, we considered 3 freshwater sources. Three shale sites are included, and each of them can drill up to 4 to 8 wells. We assume the pre-production process will take roughly three months (Cafaro and Grossmann, 2014), and at most 2 wells can be drilled at the same quarter (Ladlee and Jacquet, 2011). Drilling activities are confined in the first 3 years. We apply an exponentially decreasing approximation of the shale gas production profile (Cafaro and Grossmann, 2014). There are 5 Class II disposal wells, 3 commercial CWT facilities, and 3 types of onsite treatment technologies, namely MSF, MED, and RO (Al-Nory et al., 2014). We consider 2 conventional shale gas processing plants, 2 depleted natural gas fields as underground storage sites, and 3 natural gas fired power plants applying conventional combined cycle. The total planning horizon is 10 years, which is divided into 40 time periods, i.e. one quarter for a time period (Cafaro and Grossmann, 2014). The resulting problem has 5,028 continuous variables, 203 discrete variables, and 6,907 constraints.

As can be seen in Figure 4, the point A has the lowest GHG emission per unit electricity generation of 454 kg CO_2eq/MWh and the highest levelised cost of electricity as 170 \$/MWh. On the contrary, the point B has the lowest levelised cost of electricity of \$66/MWh while the highest GHG emission per unit electricity generation as 508 kg CO_2eq/MWh. Here we identify point C as the recommended point, which is characterised with both economic efficiency and environmental sustainability. The levelised cost of electricity of point C is 67 \$/MWh and the unit GHG emission is 460 kg CO_2eq/MWh. The production profiles of shale gas corresponding to point A and B are presented in Figure 5.

The changes of costs and emissions among the three points, A, B and C are due to their different drilling strategies. For point A minimizing the unit GHG emissions, almost half of the wells are drilled in the beginning to satisfy the necessary demand of markets, and the remaining wells are postponed to later times. For point B minimizing the unit cost, drilling activities tend to be evenly distributed. As a result, the corresponding facilities can be designed with a more suitable capacity, reducing the capital investment. Point C applied a similar strategy to point B in that wells are evenly drilled throughout the first few years. These are exactly the main factors leading to the decrease of costs from point A to point C, and causing the increase of GHG emissions at nearly constant costs between points C and B.

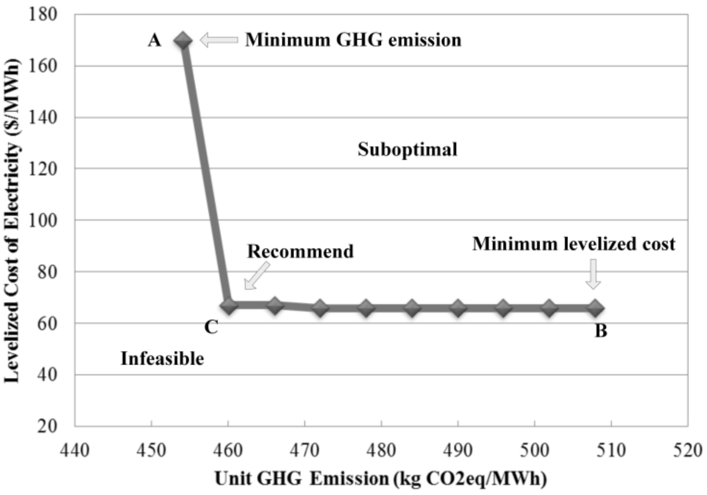

Figure 4: Pareto-optimal curve for shale gas supply chain

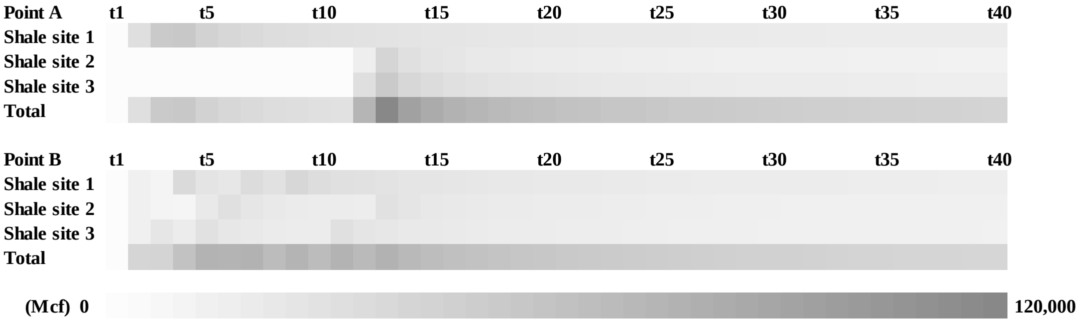

Figure 5: Shale gas production profile comparison between point A and point B

6. Conclusions

In this work, we proposed a multi-objective MINLP model for the sustainable design and operations of shale gas supply chain networks. This model was formulated following the life cycle optimisation framework to simultaneously optimise the levelised cost of electricity and unit GHG emission corresponding to the “functional unit” defined as one MWh of electric power generated from natural gas. The systems boundary covered the well-to-wire life cycle of electricity. By solving this problem, we obtained a Pareto-optimal curve demonstrating the trade-off between economic and environment criteria in decision making regarding the shale gas supply chain. The most environmentally sustainable result was identified with the lowest GHG emission as 454 kg CO_2eq/MWh and the highest levelised cost of electricity as 170 $/MWh, whereas the most economical result achieved the lowest levelised cost of electricity as 66 $/MWh and the highest unit GHG emission as 508 kg CO_2eq/MWh.

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