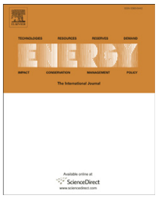
Energy 93 (2015) 1581–1594

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy



Optimal dynamic allocation of mobile plants to monetize associated or stranded natural gas, part I: Bakken shale play case study

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ARTICLE INFO

Article history:
Received 25 February 2015
Received in revised form
1 July 2015
Accepted 14 October 2015
Available online xxx

Keywords:
Natural gas monetization
Associated gas
Stranded gas
Mobile modular plants
Mixed-integer linear programming
Bakken shale play

ABSTRACT

Associated or stranded natural gas presents a challenge to monetize due to its low volume and lack of supporting infrastructure. Recent proposals for deploying mobile, modular plants, such as those which perform GTL (gas-to-liquids) conversion or produce LNG (liquefied natural gas) on a small scale, have been identified as possible attractive routes to gas monetization. However, such technologies are yet unproven in the marketplace. To assess their potential, we propose a multi-period optimization framework which determines the optimal dynamic allocation and operating decisions for a decision maker who utilizes mobile plants to monetize associated or stranded gas. We then apply this framework to a case study of the Bakken shale play. Our framework is implemented to determine the optimal NPV (net present value) which would be realized over a twenty-year time frame. Sensitivity studies on the technology costs and conversion inputs conclude that the profitability and viability of mobile technologies remain valid for a wide range of possible inputs.

1. Introduction

The discovery of large reserves of shale gas in many locations worldwide and the technological advances that have made it possible to exploit them have presented an unprecedented economic opportunity of a lifetime. According to the U.S. EIA (Energy Information Administration) [1], the growing abundance of natural gas in the United States is likely to increase the domestic use of natural gas for electricity generation and transportation and present expanded export opportunities. Rapid increases in natural gas production in recent years have also led to a depression of wellhead gas prices, and monetization strategies to convert the gas into more valuable liquid fuels in GTL (gas-to-liquids) processes or to produce LNG (liquefied natural gas) to be sold profitably in local or overseas markets are becoming increasingly attractive.

Traditionally, the oil and gas industry has been associated with large-scale infrastructure investments. Operating at larger scales allows operators to enjoy the benefits of economies of scale. The issue, however, is that the capital investments required for large-scale GTL and LNG plants are very high. A techno-economic study of these technologies by Patel [2] showed that these investments typically required billions of dollars. The large capital outlay and lengthy development times might pose significant risks for investors as there is considerable uncertainty in the future demand, supply and prices at the time at which an investment decision is being made.

In addition, large upfront investments preclude the tapping of stranded gas reserves, which are reserves that are either too small or too physically inaccessible to be economically exploitable. A recent survey of the gas fields in the world excluding the U.S. by Attanasi and Freeman [3] estimated that only around 12.2% of the gas fields were larger than 1.54 tcf in size. In contrast, as indicated by Velocys [4], the remaining fields which would be considered too small to monetize by traditional large-scale technologies might be accessible to medium- to small-scale technologies.

Stranded gas can also arise from the lack of infrastructure access despite the field having a large size. A pertinent example in the United States is the gas associated with the production of shale oil at liquids-rich fields, such as the Bakken shale field in North Dakota. In 2013, Ford and Davis [5] estimated that 33% of the natural gas produced at the Bakken was not marketed, where most gas not marketed was flared.

Recent concepts for implementing GTL and LNG technology at a small-scale and modular level have the game-changing potential to shift the paradigm away from large capital expenditures and one fixed location. These proposed plants are currently in the early

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http://dx.doi.org/10.1016/j.energy.2015.10.043
0360-5442/

stages of commercialization by several companies, including GE Oil & Gas [6], CompactGTL [7] and Velocys [8]. Essentially, these technologies involve pre-manufacturing each process unit as compartmentalized, individual modules which can then be shipped to the site of interest and assembled together in minimal time to form the entire plant. Additionally, plants can be quickly disassembled into their individual modules and redeployed at other sites, affording them the benefit of mobility. This mobility will allow them to respond quickly to changes in conditions that might affect their profitability. This could include economic factors such as large changes in the price of both the raw gas and its associated products, and supply shocks arising from the steep decline curves typically observed with unconventional sources of gas. For example, a study by Hughes in 2013 [9] concluded that wells in the top five U.S. shale plays typically produced 80–95% less gas after three years. Although the commercial availability of modular plants is limited at the time of writing, there has been a growing interest in evaluating them for purposes of monetizing stranded or associated gas from both conventional and nonconventional sources.

In view of these promising claims, it would be both useful and informative for industry players to have access to a framework that optimally utilizes these small-scale, mobile technologies to monetize stranded or associated gas. To this aim, we develop a multi-period strategy for the optimal allocation of these technologies under time-varying supplies of gas in locations where stranded or associated gas is present and time-varying prices of and demand for the various products in their respective markets.

The application of optimization techniques to solve problems in the energy field has a rich literature. Here, we mention several examples which have appeared in *Energy* in recent years. Ashouri et al. [10] studied the optimal selection and sizing of a smart building system. Cristóbal et al. [11] determined optimal investment and operational decisions for a CO_2 capture system in a coal fired power plant. Madzharov et al. [12] presented an optimization framework to analyze the impact of electric vehicles on electricity generation systems. Pousinho et al. [13] optimized the self-scheduling of wind power plants with concentrated solar power plants having thermal energy storage. Mitra et al. [14], Bischi et al. [15], and Kim and Edgar [16] studied the optimal scheduling and operation of CHP (combined heat and power) or CCHP (combined cooling, heat and power) plants. Ommen et al. [17] and Rieder et al. [18] studied the optimization of systems for energy distribution. In these studies, the optimization techniques included LP (linear programming), NLP (non-linear programming), MILP (mixed-integer linear programming) and MINLP (mixed-integer non-linear programming), with MILP being the most commonly used method.

Concurrently, several papers which studied the problems and opportunities associated with shale gas have been published in *Energy*. The profitabilities of shale gas wells in the Haynesville, Barnett and Fayetteville shale plays were studied by Kaiser [19], Gülen et al. [20] and Ikonnikova et al. [21] respectively. The specific application of optimization techniques to problems related to shale gas is still relatively new. Martín and Grossmann [22] presented a superstructure optimization approach to produce liquid fuels and hydrogen from switchgrass and shale gas in a facility. Knudsen et al. [23] formulated an optimization framework to schedule the supply of shale gas for electric power production.

2. Problem description and challenges

We will assume the role of a decision maker whose primary concern is to monetize natural gas in stranded fields or associated with the production of oil. When making decisions, the decision maker would have to consider the production characteristics unique to the field and choose among several technology options. These technologies convert natural gas into either higher-value products or a more transportable form, or both. Among the technology options available, two which have garnered the most interest due to their relative maturity are the GTL (gas-to-liquids) and LNG (liquefied natural gas) technologies.

GTL has recently gained attention due to the increased spread between the price of oil and natural gas, as noted by Hobbs and Adair [24] and Salehi et al. [25]. The GTL process converts natural gas into liquid fuel. There are three main parts to this process: 1) syngas generation, 2) FT (Fischer–Tropsch) synthesis, and 3) refining and upgrading.

In syngas generation, natural gas is first cleaned and then converted into syngas, which is a mixture of hydrogen and carbon monoxide. After the syngas has been generated, it undergoes FT synthesis where it is converted into longer chain hydrocarbons. Finally, after the FT synthesis step, the product is sent for refining and upgrading to meet final specifications.

GTL products are attractive not only because they are liquid fuels and can be easily transported, but also because they are virtually sulfur-free, as mentioned in studies by Wood et al. [26] and Salehi et al. [25]. The most promising product from the GTL process is GTL diesel. Also high in cetane number, it is ideal as a blendstock for refineries to adjust conventional diesel in production to meet specifications.

LNG technology is considered mature and proven. The process involves liquefaction of gas by cooling to cryogenic temperatures. Prior to cooling, the feed gas undergoes several treatment steps, such as filtration and removal of carbon dioxide, sulfur, mercury and water.

The value of LNG is that it significantly increases the energy density of natural gas, allowing it to be transportable for sale in distant markets. In the U.S., the most promising market for LNG is fuel for heavy-duty trucks or freight rail, as documented in a study by TIAX [27].

In addition, depending on the source of natural gas, there may be a significant presence of NGLs (natural gas liquids) mixed in the wellhead gas. Such gas is termed “wet gas”, and the NGLs are usually separated from the mixture because they possess substantial economic value. NGLs primarily serve as feedstock for the petrochemical industry or as fuel for heating and transportation purposes, as noted by Platts Price Group [28]. Therefore, GTL and LNG technologies which take in wet gas as their feedstock should necessarily have a NGL separation unit.

Applying these technologies to monetize stranded or associated gas poses a challenge. First, the technologies have to be designed to be mobile, since the supply of gas at any fixed location would not last for very long. The mobility of the plants adds a dimension of complexity to the decision-making process. Although the idea of mobility generally allows plants to be more agile and thus suitable for capturing stranded gas, start-up and shut-down costs would be incurred every time a move is made. Thus, the company has to weigh the costs and benefits of continuing operations at a certain location versus redeployment in the context of how the supply profile and the demands of its customers evolve over time. Second, because of the dynamic nature of gas supply and well availability, it is a challenge to determine the optimal number of mobile plants of each technology type to be purchased or sold at each time point of the time horizon that would maximize profits.

Fig. 1 portrays a simplified illustration of the decision framework under consideration. In this example, there are three time stages, three gas sources, two technologies for mobile plants (GTL and LNG) and two markets. Depending on the time period, the gas