SHALE GAS PRODUCTION: INFRASTRUCTURE DESIGN, WATER MANAGEMENT, AND IMPACT ON ELECTRIC POWER GENERATION AND NEW CHEMICAL PROCESSES

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Natural gas is an abundant energy source and the cleanest-burning fossil fuel. Gas extracted from dense shale rock formations has become the fastest-growing fuel in the U.S. and could become a significant new global energy source. In addition, shale gas contains significant amounts of light hydrocarbons (e.g. ethane) providing lower cost raw materials to the U.S. chemical industry (Siirola, 2014). Over the past decade, the combination of horizontal drilling and hydraulic fracturing has allowed access to large volumes of shale gas that were previously uneconomical to produce. This has reinvigorated the natural gas and chemical industries in the U.S. It has also been used to replace coal for electric power generation which has lead to significant CO_2 emissions. Shale gas production is expected to grow from 23% to almost 50% of the total gas production in the next 25 years (EIA, 2012). Regarding both economic and environmental impacts, the long-term planning of the shale gas supply chain network is a very relevant problem, since virtually all portions of the shale gas value chain need new, expanded, and/or upgraded infrastructure (Goellner, 2012). However, to the best of our knowledge, it has not been addressed before in the literature through the use of optimization models and tools. In this presentation we describe optimization models that have been developed for infrastructure design and planning, water management, long term planning of electric power generation, and design of new chemical processes based on C_1 and C_2 chemistries.

MINLP MODELS FOR INFRASTRUCTURE DESIGN AND PLANNING

The problem we have addressed in this area is as follows (Drouven and Grossmann, 2016). Within a potential shale gas development area there are a set of candidate well pads from which shale gas may or may not be extracted. One would like to sell extracted gas at a set of downstream delivery nodes which are typically located along interstate transmission pipelines. For this purpose a gathering system superstructure has been identified that specifies all feasible alternative options for laying out gathering pipelines to connect candidate well pads with the given set of delivery nodes. In addition, the superstructure indicates candidate locations for compressor stations as well as the location of existing processing plants.

The long-term shale gas development problem involves planning, design and strategic decisions: a) where, when and how many wells to drill at every candidate well pad, b) whether selected wells should be shut-in and, if so, for how long, and c) how to allocate drilling rigs over time. The design decisions involve a) where to lay out gathering pipelines, b) what size pipelines to install, c) where to construct compressor stations, and d) how much compression power to provide. We also consider strategic decisions that include a) the selection of preferred downstream delivery nodes, b) the arrangement of delivery agreements, and c) the procurement of take-away capacity. The objective is to determine optimal planning, design and strategic decisions such that the net present value is maximized.

We present a model based on Generalized Disjunctive Programming (GDP) that is transformed into an MINLP for which a special solution strategy is developed. The proposed model has been applied to a set of real-world case studies based on historic development data provided by one of the largest upstream operators in the Marcellus Shale region. The results demonstrate that previous, uncoordinated development strategies led to over-sized gathering systems that were heavily under-utilized at times. Moreover, the case studies allow to quantify the economic value of advanced, computational tools in this domain.

Long- and Short-Term Optimization Model for Shale Gas Water Management

Since water use is associated with each step of the drilling and production process, it is an important aspect in shale gas development. The challenge with water management is that a large volume of it is required in a short-period of time. Water sources can be described as interruptible and non-interruptible sources. Whereas withdrawal from a non-interruptible source remains constant, withdrawal from an interruptible source can be affected by seasonal variation in water availability. As a result, even in water-rich regions, water use can be under strain due to the high demand. To this end, impoundments can be installed close to the water sources in order to serve as buffer tanks to store water when there is high freshwater supply in the sources. In order to avoid hauling freshwater to shale gas wellpads through trucks, overland or buried pipeline could be installed to transport freshwater from water sources to the wellpads. While permanent pipeline can be buried underground when the operators set up gas pipelines, overland pipelines are temporary and can be rented. Flowback water can be reused at the next frac through adequate treatment and blending with freshwater. Thus, based on the flowback water composition, different treatment techniques can be adopted.

We describe a mixed-integer linear programming (MILP) models (Yang et al., 2004) for optimizing daily and long-term decisions in water use through a discrete-time representation of the State-Task Network. In order to include capital investment decisions we develop a model that minimizes the overall cost including capital cost of impoundment, piping, and treatment facility, and operating cost including freshwater, pumping, and treatment. Given are the potential freshwater source location and withdrawal data, potential impoundment location, wellpad storage, location, and total number of stages, treatment unit capability and location, and the number of frac crews available. The goal is to determine the location and capacity of impoundment, the type of piping, treatment facility locations and removal capability, as well as the frac schedule, and the water sources to obtain freshwater. In addition, we examine the impact truck hauling restriction has on the overall cost and frac schedule. The problem is optimized over a long planning horizon. A real-world case study in the Utica Shale was optimized to illustrate the application of the proposed formulation.

OPTIMAL PLANNING OF ELECTRIC POWER INFRASTRUCTURES

We describe an optimization modeling framework to evaluate the changes in generation and transmission infrastructure required to meet the projected demand for electricity over the next few decades while taking into account detailed operational constraints (e.g. unit commitment) and the variability and intermittency of renewable generation sources (Lara et al, 2017). The modeling framework, which is based on mixed-integer linear programming (MILP), takes the viewpoint of a central planning entity whose goal is to identify the source (nuclear, coal, natural gas, wind and solar), type, location and capacity of future power generation technologies and transmission infrastructure that can meet the projected electricity demand while minimizing the amortized capital investment of all new generating units and transmission lines, the operating and maintenance costs of both new and existing units, and suitable environmental costs (e.g. carbon tax). In order to optimize large instances, we propose a decomposition algorithm based on Nested Benders Decomposition for mixed-integer problems.

The proposed formulation is applied to a case study in the region managed by the Electric Reliability Council of Texas (ERCOT) for a 30 year planning horizon, resulting in a large-scale MILP model with more than 100,000 discrete variables and constraints. Through a combination of judicious model formulation strategies such as time sampling and generator clustering as well as the use of specialized decomposition strategies, this work demonstrates that these large-scale MILP problems can be solved in a reasonable amount of time. The results for hourly and sub-hourly level of information are compared and, in both cases, it shows that the future growth will be met by a portfolio of different generation technologies.

Specifically, the model predicts According to these results, the optimal planning considers a 59-fold increase of the photo-voltaic solar capacity, 33% increase in natural gas, while there is a 5% decrease of wind capacity. In this way the renewable generation capacity is predicted to be 40% in 2045.

DESIGN OF NEW CHEMICAL PROCESSES BASED ON C_1 AND C_2 CHEMISTRIES

Finally, we describe several design projects that we have undertaken in the last few years at Carnegie Mellon that exploit the availability of methane and ethane from shale gas in the Marcellus. These projects include production of aromatics (benzene, toluene and xylene) from methane and ethane, production of propylene from methane vs. propane dehydrogenation, production of ethylene from ethane vs. partial oxidation, and production of fuel grade ethanol from ethylene. Some of these flowsheets have not been reported in the literature, which has given the opportunity to students to invent new process flowsheets by applying concepts and tools of process synthesis and process integration.

Given the controversy with shale gas, we close the presentation by briefly listing advantages and disadvantages in terms of energy and feedstocks, and in terms of economics and environmental impact.

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