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SYSTEM DYNAMICS MODEL FOR THE VALUATION OF REAL OPTIONS IN PUBLIC-PRIVATE PARTNERSHIPS

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Abstract: Public-private partnerships are increasingly being pursued for infrastructure procurement because of their ability to promote innovation, implement new technologies and alleviate pressure on government budgets. Public-private partnerships, however, inherently involves multiple stakeholders with different and sometimes opposing objectives. In addition, public-private partnerships often involve long-term contracts that need to account for future yet-to-be seen variables, which will potentially impact the financial feasibility of this procurement method. This is especially true when the public-private partnership exists within a portfolio of competing assets spanning across multiple types of infrastructure systems. The current research presents how a system dynamics model can be constructed to analyze the complexity of infrastructure found within such a portfolio. An illustrative case demonstrates how the system dynamic model captures discrete and continuous events that potentially impact the successful procurement of infrastructure within a portfolio of assets comprising regional water resources and an energy production infrastructure system. This paper contributes to the existing body of knowledge by showing how a system dynamics model can simulate the real world causal relationships that impact a public-private partnership within these interdependent systems. The simulation results from the system dynamics model can be used for the valuation of real options to enhance the financial feasibility and economic sustainability of infrastructure procured through a public-private partnership.

System Dynamics, Real Options, Sustainability

1. INTRODUCTION

The current investigation into the procurement processes for infrastructure found at the nexus between energy and water is a valuable research subject. The relationship between these two systems is far-reaching and requires industry leaders and concerned governments to strategically manage these interdependent resources in a joint fashion. A strategic goal of the U.S. Department of Energy (D.O.E.) is to promote energy security through reliable, clean and affordable energy. At the same time, the D.O.E. recognizes that energy and water are essential and interdependent resources. To maintain reliable energy and water supplies these two resources must be managed together as demand grows and limitations increase at the regional, national and global level. Furthermore, these systems inherently involve multiple stakeholders with different objectives. Therefore, an investigation into the system dynamics of jointly managing these resources must capture these sometimes opposing objectives. This current paper investigates and develops a SD model that captures the relationship between the unconventional natural gas (UNG) drilling (or *fracking*) industry, which is driven primarily by profit; and sustainable water resource management (WRM), which primarily aims to protect public health and the environment. While the current investigation focuses on the UNG drilling industry, a wider goal of this research is to develop a more holistic method for decision-making and to enhance private participation in the procurement of the infrastructure found at the nexus of water and energy.

The investigation of system dynamics and the simulation model presented in this paper represents the second part in a continuum of research divided into three phases. The research presented in this paper builds upon the first (1 of 3) phase presented in Fitch et al. (2016). In that work a methodology is presented for determining the appropriate level of abstraction for constructing a system dynamics (SD) model to simulate and analyze water usage and its treatment in the shale gas value chain. This paper represents the second (2 of 3) phase and a continuation of that research. This paper presents the resultant SD model. This paper also presents the results from simulation runs in order to demonstrate how the model can be used to forecast changes in water treatment as competing feedback occurs from market forces, information limitations, costs of entry and exit, and inflexibility of resources within the shale gas value chain. In addition, this paper investigates public-private partnership (P3) project agreements used for treating water and wastewater. Particular emphasis is placed on the key elements of the project-finance structure that are likely to be used for delivering the infrastructure required to transport and treat wastewater produced in the shale gas value chain. This paper concludes with an investigation of how the results of the SD model will be used for the valuation of real options that will be presented in the third (3 of 3) and final phase of this research. In the follow-up investigation the SD Model will be expanded so that it can be used effectively for the valuation of real options during a P3 procurement process. Taken as a whole, the three phases of this research aims to enhance the economic sustainability of infrastructure systems that will be required to transmit, treat and/or reuse the wastewater produced in the shale gas value chain.

2. RESEARCH METHODOLOGY

The primary objective of this research began with determining whether or not economic and environmental merits exist for employing a P3 procurement strategy for infrastructure that bridges the nexus between water and energy. The initial first phase in achieving this primary objective, began with an examination of the types of infrastructure found in the nexus of water and energy including:

1. The infrastructure required for the generation, transmission and distribution of power that will be required to transmit and treat water and/or wastewater; and

2. The infrastructure used to transmit and treat water and/or wastewater that will be produced and/or used during any of the processes required for the generation, transmission and distribution of power.

During the latter, this research focused on forecasted sources of energy through 2050 included in the U.S. Energy Information Administration's Annual Energy Outlook from 2015 through 2017. These forecast sources of energy are key indicators in determining what kinds of infrastructure will likely be required to transmit and treat water and/or wastewater that will be produced during any of the processes required for the generation, transmission and distribution of power. Forecast sources of energy provided by the U.S. Energy Information Administration indicate that UNG production, particularly from the Marcellus Shale Formation in the U.S. Commonwealth of Pennsylvania, will continue through 2040. As a result, the initial phase of research examined water resources used and/or impacted by shale gas drilling operations in the Marcellus Shale Formation. A review of existing literature surrounding the infrastructure used for the conveyance, treatment and/or reuse of wastewater produced in the Marcellus shale gas value chain shows that a further investigation is warranted into sustainable procurement practices. Empirical evidence suggests that given current regulations and ongoing trends, various types of infrastructure will increasingly be required to meet water treatment demands within Marcellus shale gas value chain through 2040.

The second phase of this research includes the selection of the appropriate level of abstraction to construct a simulation model to capture the dynamic relationship between water treatment processes and UNG production in the Marcellus Shale Formation (Fitch et al. 2016). This current investigation builds upon that previous work and takes into consideration the kinds of infrastructure that will be required in response to a variety of endogenous and exogenous drivers (e.g. regulatory constraints, market forces etc.). The primary focus of this paper is to present the resultant SD model that was constructed at the appropriate level of abstraction to show how the treatment of water within the Marcellus shale gas value chain may change over time within a portfolio of competing assets. The SD model presented in this paper represents a decision-support tool with mathematically embedded behaviors and is used to study the underlying physical and non-physical structure of interdependencies, feedback, accumulations, delays and other phenomena associated with the infrastructure systems used to treat water within the Marcellus shale gas value chain.

The third phase of this research, which begins in this paper, investigates how to raise the level of abstraction and link the SD model to a sustainable P3 procurement process. The current research recognizes that the central goal of the P3 procurement process is to alleviate government budgets by seeking capital from external financiers (Algarni et al., 2007). As such, in order to achieve this third and final objective, the current research investigates the theory of real options applied to project-finance structure of the P3 procurement process. The method of project-finance under a P3 project agreement is based on raising long-term debt against the cash flow generated from the project's revenue (Yescombe, 2014). Further, P3 projects are typically long-term contracts between a concerned government intended to satisfy public infrastructure needs and a consortium of private partners including equity sponsors and financial lenders who require a minimum attractive rate of return (MARR). Hence, the objective of the current research is to investigate how to enhance the abilities of a concerned government and private partners to achieve these competing goals using a SD model for the valuation of real options.

3. SYSTEM DYNAMICS

The current research constructs a SD model to analyze competing feedback effects on market forces, information limitations and costs of entry and exit. Forrester (1961) created the SD modeling method, defined as the feedback-based and object-oriented simulation process that can be used to model complex systems, including infrastructure portfolios. Sterman (2000) states that the purpose of system dynamics is to solve a particular problem and the SD model must have a clear and precise purpose. In order to accurately analyze how water and energy infrastructure systems interact and draw clear concise conclusions, all non-relevant factors are excluded from the problem to ensure the model is feasible and the results are timely. The current investigation recognizes that a problem statement must first be defined and used to construct the SD model at the appropriate level of abstraction. Consistent with Fitch et al. (2016) the problem statement for this research is as follows. *Sound public policy requires concurrent management of two monolithic systems: UNG production, which is primarily driven by economics; and sustainable WRM, which primarily aims to protect public health and the environment.*

In accordance with Sterman (2000), the logical sequence for constructing the SD model began with the identification of key variables and reference modes. These first steps help to define the problem statement and are predecessors to developing the casual loop diagrams (CLD) and the derivation of formulas and equations that constitute the mathematical representation within stock and flow diagrams. CLDs and stock and flow diagrams are developed in the current research in order to show how feedback relationships can impact the P3 procurement process. The SD model captures the dynamics of shifting loop dominance as competing alternatives are reduced or eliminated. The logical sequence for constructing the SD model in this research follows:

1. Define the problem statement and identify key variables;
2. Develop reference modes for key variables that are central to the problem;
3. Develop a causal map (i.e. CLDs) of the feedback processes responsible for the dynamics of the system; and
4. Create a stock and flow diagram that contains the mathematical representation of the systems.

3.1 SD Model architecture

For purposes of brevity this paper only presents the stock-and-flow diagram. The SD model and the stock-and-flow diagram presented within the current research was developed utilizing the computer software iThink 10.1.2® to simulate the complex relationships between water usage / treatment and the UNG drilling industry within the Marcellus Shale Formation. The SD model employs the industry-accepted general structure for stock-and-flow diagrams including stocks, flows, valves, and clouds (Figure 1). Stocks represented by rectangles signify both physical and non-physical accumulations and "traces" left by an activity. Flows represent activities or actions that transport quantities into or out of a stock instantaneously or over time. Inflows and outflows are represented by pipes or arrows pointing into (adding to) and out of (subtracting from) stocks, respectively. Unless there is a net value of zero, material stock exists at a given point in time and will remain even when the processes of inflows and outflows are complete. The nominal values, parameters and equations used for each of the model's sector frames are available upon request.

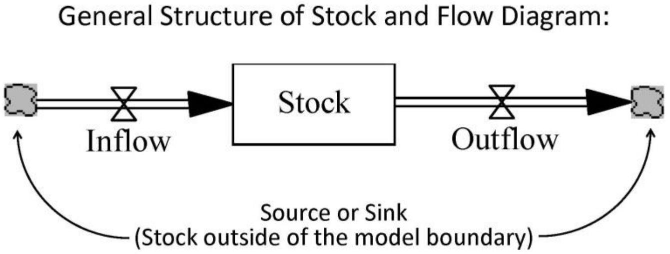

Figure 1 – General Structure for a Stock and Flow Diagram

Figure 2 shows the full structure of the System Dynamics model developed for simulating water management dynamics in shale gas production operations. As shown in Figure 2 the SD model includes the following eight sectors beginning from the top-left corner and moving clockwise:

1. Costs for Onsite Treatment and Recycle
2. Produced Water and Flowback Onsite Treatment and Recycle
3. Hydraulic Fracturing (HF) and Drilling Water Use
4. Shale Gas Production
5. Deep Well Disposal/Injection (DWI)
6. Central Water Treatment (CWT) and Reuse
7. Costs for Shale Gas Production, CWT, and DWI
8. Fresh Water Sourcing and Transport

Due to the complexity of the interconnections among these sectors, the use of sector frames in iThink was abandoned in favor of the color overlays as a means of communicating basic model structure. The model has 18 stocks (six of which are for computing cumulative costs in selected sectors) and includes several stochastic variables (modeled here with uniform distributions).

3.2 Case Study Simulations

The data for the variables in this model, including the estimated ranges for several of the stochastic variables, have been drawn from multiple sources, but particular weight was placed on data provided in Jiang et al. (2014) and Gao and You (2015). These studies addressed the multiobjective optimization problem for water infrastructure supporting shale gas production operations, with a particular emphasis on operations in the Marcelleus Shale. A summary of the stocks along with the equations and dependencies for all flow variables used in the model as show in Figure 2 are available upon request. The following cases studies demonstrate how the SD model can be used for analyzing how water treatment within the shale gas value chain changes over time and under various scenarios. The results of the simulation runs show how system dynamics can be used for structuring the parameters of a series of real options related to the procurement of infrastructure used to convey or treat wastewater produced in the shale gas value chain. On a concurrent basis the results of the simulation runs show how system dynamics can be used to account for various multipliers (i.e. costs and revenues associated with treatment processes) as well as the compounding effect of multiple types of real options existing within a P3 procurement process. For each of the simulation runs, the time horizon is set at 12 months, which is the time period when the shale gas well production is most substantial and dynamic with a time step of 0.125 months.

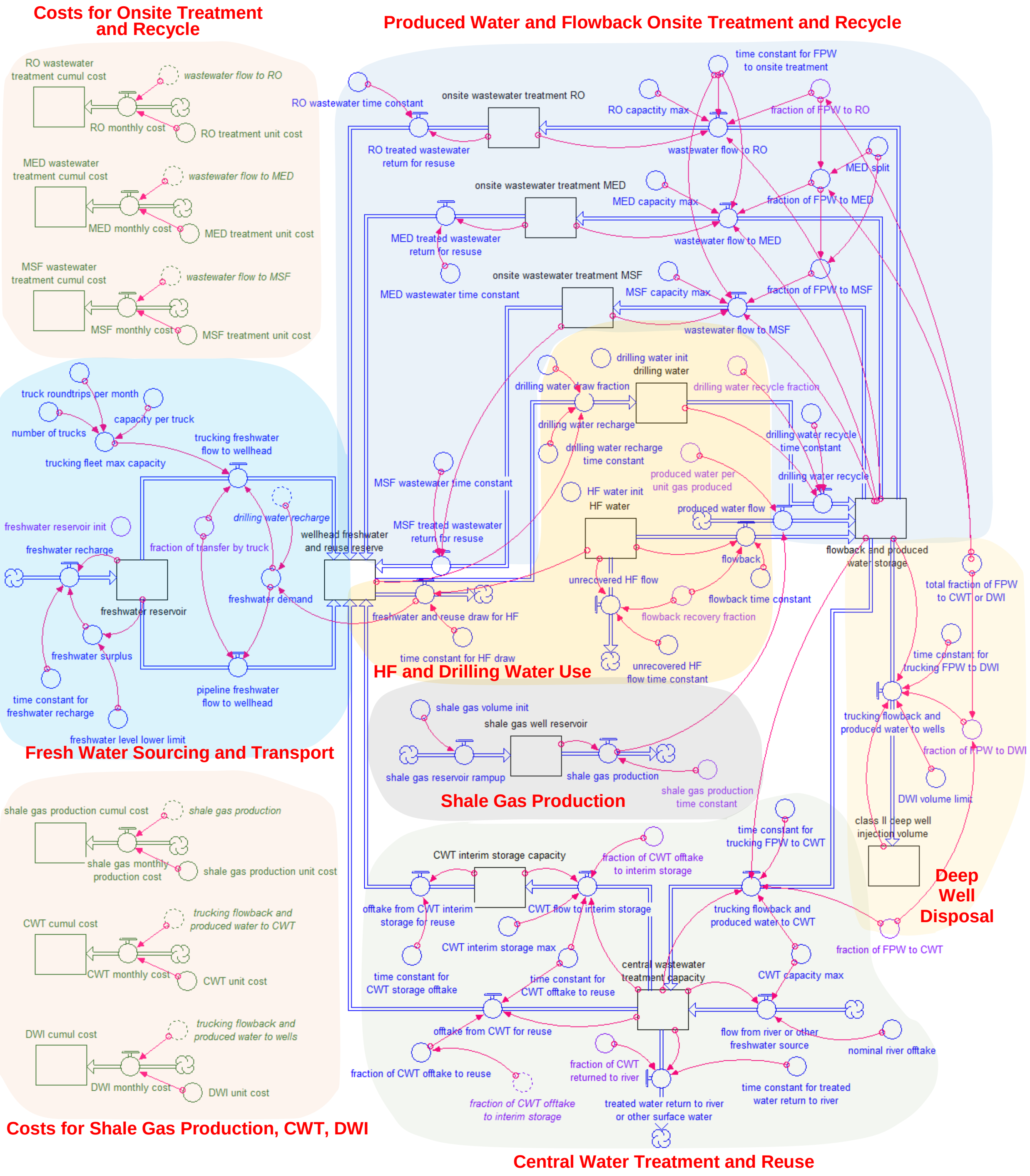

Figure 2 – Water-Shale Gas Nexus System Dynamic Model with Color-coded Sectors

3.2.1 Case A: Nominal Hydraulic Fracturing Water Requirement for Marcellus Shale Gas Well

In this simulation the requirement for hydraulic fracturing (HF) water per well is set at 15,000,000 liters. This is a nominal value as suggested by the study of Jiang et al. (2014) for a typical Marcellus shale well, with observed values ranging between 3,500,000 to 26,000,000 liters. The higher of these two values is explored in Case B.

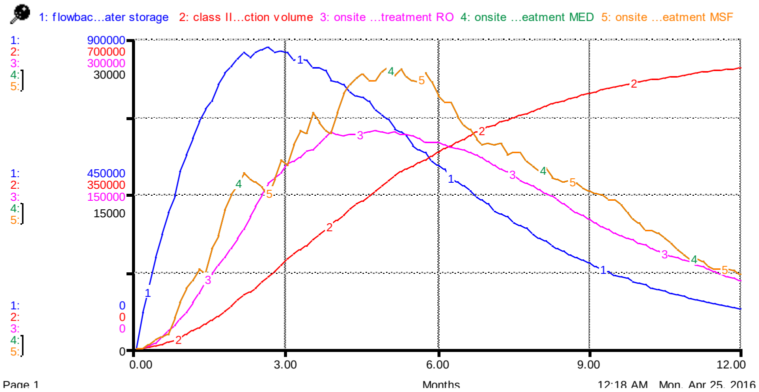

Figure 3 – Water Treatment Volumes under Nominal HF Volumes

Figure 3 shows that under nominal use of HF, the combined inventory of flowback and produced water (Line 1) surges, but subsequently declines. Onsite treatment (lines 4 and 5) lags but shows a similar time history as the initial surge volumes are treated for recycling. Treatment through reverse osmosis (line 3) is given priority as a result of more favorable costs. Deep well injection (line 2) is building over time but is approaching the specified limit for this case.

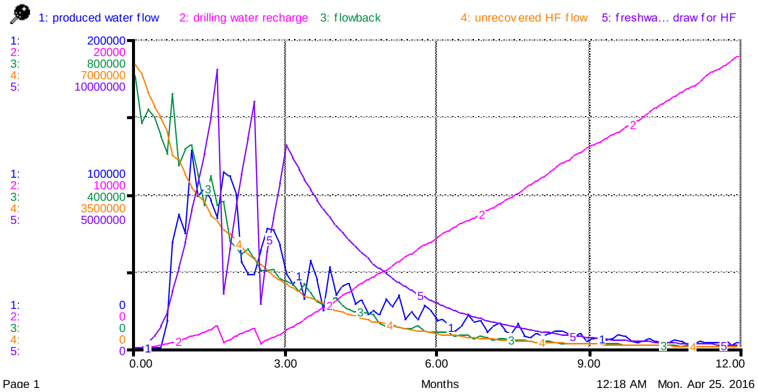

Figure 4 – Water Treatment Volumes under Nominal HF Volumes

Figure 4 shows flowback volume (line 3) declines exponentially while produced water volume (line 3) surges and then declines in a similar fashion. These results are consistent with the volumes observed in Marcellus wells. The transport of freshwater to the wellhead from the primary freshwater source (line 5) is highly variable due to limits imposed by the truck fleet size, which in the current SD model is set to 20 trucks with a capacity of 19,000 liters per truck. Also note that the transport of freshwater to the wellhead from the primary freshwater source (line 5) spikes at over 10,000,000 liters around month 2 compared with ~1,700,000 liters in Case C.

3.2.2 Case B: High HF Water Requirement for Marcellus Shale Gas Well

In this simulation there is a requirement for “high HF volume” excursion relative to the nominal HF case presented in Case A. Specifically for this case, the HF water requirement for the shale gas well was set at 26,000,000 liters. All other parameters remained as set for Case A. The results for Case B are qualitatively similar to those in Case A, with amplitudes shifted to higher levels across most variables.

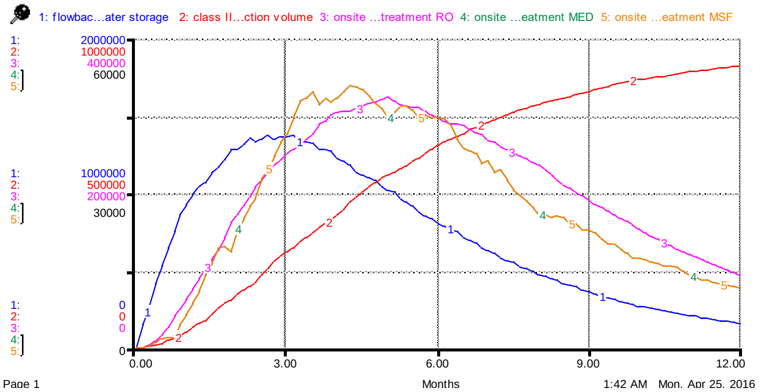

Figure 5 – Water Treatment Volumes under High HF Volumes

Figure 5 shows that water treatment volumes go up as a result of the much larger level of HF as compared with Case A (See Figure 3). In this simulation, the SD model shows that deep well disposal is approaching its specified volume limit (indicated by line no. 2), which when it occurs would result in greater volume be directed to both CWT facilities and onsite wastewater treatment. This in turn would increase their cost of operation of these facilities.

3.2.3 Case C: Interruption of Primary Freshwater Resource

In this simulation it is assumed that the primary freshwater source is interrupted or severely restricted *but only after* the 15,000,000 liter water inventory is already at the wellhead and available for hydraulic fracturing. This theoretical situation could result from regulatory or other legal intervention, a transportation interruption, or significant equipment failure. There is still a small flow of freshwater through the CWT facility, but this is small in comparison with the primary freshwater resource which is being interrupted.

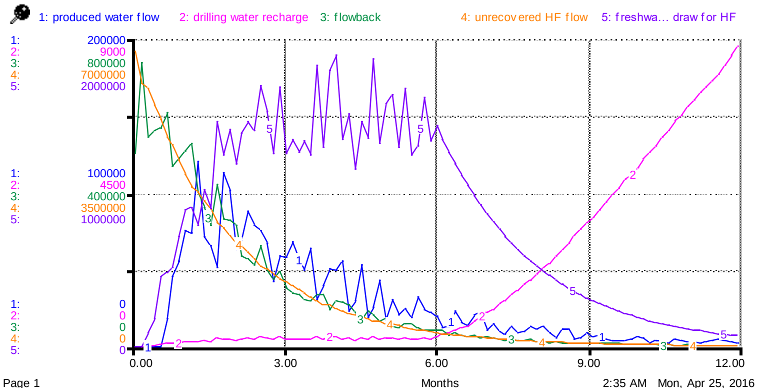

Figure 6 – Water Treatment Volumes under High HF Volumes

This result is dramatically different from what is observed in Case A (See Figure 4). The demand on freshwater driven by the hydraulic fracturing now has to be shifted to the co-mingled recycled and freshwater volumes at the wellhead. Note the “freshwater draw for HF” (line 5) is now shifted significantly lower and fluctuates around 1,500,000 liters with a flattened profile for months 1 – 6. Hence, under this simulation the demand for water now depends more heavily on recycled sources.

3.3 Simulations Results and Valuation of Real Options

These case studies show how the SD model can be used to forecast how the volumes of water usage and water requiring various treatment processes may change as parameters are altered due to limitations of resources, regulatory constraints etc. There exists a corollary between the results of these simulation runs and the valuation of real options related to the infrastructure required for transporting and treating wastewater produced in the shale gas value chain. To illustrate, take for example the simulation results in Case B where greater volumes of HF result in greater amounts of water requiring treatment at CWT facilities**.** Under this scenario, investment by private equity sponsors and commercial lenders in the procurement of CWT facilities would alleviate government budgets while preserving best management practices related to water resource management. The risk of financial loss to these investors could be hedged with minimum revenue guarantees (MRGs) provided by the concerned government. The value of these MRGs would be based on a prescribed unit cost and the model's forecasted volume of wastewater requiring treatment.

Under Case C, more stable but lower volumes of freshwater shipped to wellheads relative to Case A supports lesser amounts of financial investment in infrastructure required for conveyance (i.e. trucks, roads, pipelines etc.) and vice versa. Again, the forecasted volumes provided by the SD model are the basis for the valuation of real options related to those kinds of infrastructure delivered through a P3 procurement process. The following section describes the basic structure of the P3 agreement with particular emphasis on the key elements of the project-finance structure that are required for the valuation of real options within this procurement strategy. This section is followed in-turn by a discussion of the types and structure of real options that will likely be included under such a P3 procurement strategy.

4. PUBLIC PRIVATE PARTNERSHIPS

Under the term "public-private partnership" a private equity sponsor finances the design, construction, maintenance and operation of a public project for a specified duration, with anticipation of recouping its costs and achieving profits (Algarni et al. 2007). The P3 procurement process has historically been used in successive waves and during that time project agreements and project-finance structures have evolved into various forms in order to meet the needs and characteristics that are unique to the different types of infrastructure. To varying degrees the dividing lines between these types of project agreements and project-finance structures are inexact, but Yescombe (2014) categorizes project finance structures into three general types of agreements: 1. Process-plant Agreements, 2. Concession Agreements and 3. The Private Finance Initiative Model. While the use of a SD model for the valuation of real options can be applied to any variation of these types of P3 agreements, this paper presents a process-plant agreement.

4.2 P3 Process-plant Project Delivery

In order to effectively value real options, the SD model must capture the relevant elements of the project-finance structure. These elements include the concerned government or contracting authority, equity sponsors, commercial lenders, the project company and its subcontracts. Under this type of project agreement there is an input (wastewater) at one end of the project, which goes through a process within the project, and emerges as an output (i.e. treated water and by-products). The process-plant project typically includes as sub-contracts: 1. Engineer-procure-construct (EPC) contract; 2. Treatment contract; and 3. Operations and maintenance contract for the duration of the project operating term (Yescombe, 2014).

4.3 P3 Process-plant Project Finance Structure

A discussion of overall project-finance structure is beyond the breadth of this paper, but two significant factors that are critical for achieving the primary research objective include the debt: equity ratio and the MARR required by the project's equity sponsors and commercial lenders. The debt: equity ratio is a function of the risks perceived by the financiers (i.e. equity sponsors and commercial lenders) and projects with greater risk have less financial leverage or lower debt: equity ratios. The theoretical MARR along with the typical debt: equity ratio will be the factors used for calculating a weighted average cost of capital (WACC). Yescombe, 2014 states that a process-plant project has a typical a debt: equity ratio of 85: 15. This theoretical WACC will be used for financing the P3 project. The follow-on investigation will use this theoretical WACC as the discount rate during a series of net present value analyses for the valuation of real options.

5. REAL OPTIONS

The final phase of this research shall demonstrate how the P3 process can be sustained by hedging the risk of financial loss with the application of real options. This phase of research, which has yet-to-be completed, will be consistent with Wang and Neufville (2005) and shall consider real options in terms of being either “in” or “on” projects. In these terms, a real option “in” an infrastructure asset used to treat water is an option created by changing the actual technical design. In contrast, a real option “on” a project is a financial option attached to a “thing.” Consistent with these definitions, real options “in” infrastructure used to treat water would be concerned with actual design and would require an in-depth understanding of the physical characteristics of the asset(s) related to the design criteria and performance. In this regard, real options “in” water treatment within the Marcellus shale gas value chain would include future options to upgrade or expand capacity of the infrastructure as demand for its use ramps up and as technology evolves. This current second (2 of 3) phase of the research constructs the SD model presented in this paper so that it can be used for the valuation of real options both “in” and “on” the P3 project agreement. While a full discussion of the valuation for all types of real options is beyond the breadth of this paper, the following section discusses how the existing SD model will be expanded to include new sectors with mathematically embedded equations for the valuation of real options.

5.1 Valuation of Real Options

The existing SD model presented in this paper includes a sector capturing the costs for onsite treatment and recycling wastewater at the wellhead. This sector and the model as a whole will be expanded to include new sectors for the valuation of real options related to the various other methods of conveyance, treatment and disposal processes (i.e. trucking, pipelines, CWT facilities and deep well injection etc.). The new model sectors will draw on three stocks representing the NPV of cash outflow including debt repayment, operations and maintenance (O&M) costs, and treatment costs for each process. Each of the new sectors will also draw on a single stock representing the NPV of the prescribed revenue per the terms of a theoretical process-plant agreement for wastewater conveyance and treatment. The sum of these NPV stocks is equivalent to the value of the real option “in” the infrastructure used to convey and treat wastewater in the shale gas value chain.

Two additional sectors will be added to show how the value of real options “on” a project related to a particular process can be calculated. These real options “on” a project related to a particular project include MRGs and the right to abandon (AO). For example the AO grants the concessionaire the option (but not the obligation) to abandon the project no later than the start date for construction. The AO provides an incentive (granted by the concerned government or contracting authority) for the private equity sponsors and commercial lenders to engage in a joint venture for the development of critical infrastructure. The formulation for this real option is based on the work of Huang and Chou (2006), which was applied in their case to rail infrastructure development. The maturity for this option will be equal to the duration beginning at the inception of the design effort to start of construction. The “strike” of this option is the sum of the fixed and variable costs, which represents the debt repayments, O&M as well as treatment costs. Consistent with Black-Scholes (1973) the price for this European-style put option (i.e. exercisable only at maturity) is expressed as:

$$f = P^0[N(k_1) - 1] - I^0[N(k_2) - 1] = \\ I^0 N(-k_2) - P^0 N(-k_1)$$

Where P^0 equals the present value of operating revenues, I^0 equals the present value of the total investment costs at t=0 and $N(\cdot)$ is a cumulative normal distribution function. The parameters k_1 and k_2 equal:

$$k_1 = \frac{\ln\left(P^0/I^0\right) + \left(\sigma^2/2\right)t_B}{\sigma\sqrt{t_B}} \text{ and}$$

$$k_2 = \frac{\ln\left(P^0/I^0\right) - \left(\sigma^2/2\right)t_B}{\sigma\sqrt{t_B}} = k_1 - \sigma\sqrt{t_B}$$

Where σ^2 is the variance and t_B is the time to maturity of the option. Similarly, the model will expanded to include a sector for the valuation of a MRG that can be set at a level less than the total amount of expenditures. Again the model will draw on a similar Black-Scholes option pricing framework as for the AO. In the case of the MRG, however, a series (or "strip") of put options will give the concessionaire the ability to exercise a MRG, if and when, a revenue falls below the total costs for project delivery and its operations.

6. CONCLUSION AND FURTHER RESEARCH

The current research contributes to the existing body of knowledge by demonstrating how a SD model can simulate the real world causal relationships used to forecast changes in the volumes of wastewater treated through various processes within the shale gas value chain. This paper also investigates the P3 procurement process with particular emphasis placed on the key elements of the project-finance structure that are likely to be used for delivering the infrastructure required to transport and treat wastewater produced in the shale gas value chain. This paper concludes with a narrative of how those aspects from the P3 finance structure will be used in conjunction with an extended version of the SD model for the valuation of real options. The SD model presented in this current paper serves as a springboard for that follow-on investigation that will presented in the third and final phase of this research effort.

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