Resource Economics:
Discovery and Production of Natural Gas in the USA

These exercises provide an opportunity to use system dynamics to study the life cycle of a non-renewable resource. Natural gas may be the most important source of energy in the United States today. It has many traditional uses in homes and industries; it may emerge as an important fuel for clean vehicles. Natural gas was also the most popular fuel for new power generation during the construction boom of 1999-2000. The exercise collection begins with some historical background on this important resource. Then we'll develop a simple model to help us understand its longevity.

Background on Natural Gas in the United States

Natural gas is a surprisingly important source of energy in the United States today. It has always enjoyed traditional uses in homes and industries. But it is now emerging as a potentially important fuel for clean vehicles (see chapter 16 on feebates),and it has already emerged as the most important fuel for new power generation. Today's interest in gas-fired power generation is quite surprising since power companies were prohibited from investing in gas fired generation three decades ago.

System dynamics was used by Roger Naill to simulate the life cycle in natural gas exploration. He published his results in 1973, the year in which the Arab oil embargo made the industrialized world aware of the "energy crisis." To some, the energy crisis was an "oil crisis" -- we were too dependent on imported oil. But many experts spoke of an "oil and gas crisis." They feared that the United States was running low on both oil and gas reserves. In the well-known "Harvard Energy Study," Stobaugh and Yergin (1979) described gas policy as a debate over "how to slice a shrinking pie." They cautioned that "it will be a challenge to find enough new gas reserves to maintain production at current levels." Naill (1973, 215) held a similar view.

*The natural gas industry seems to be facing the most imminent crisis of fossil fuel depletion.
Although it has been estimated that from 400 to 900 trillion cubic feet of natural gas
still remain undiscovered in the United States, proven reserves are falling rapidly.
The discovery rate, currently less than the production rate,
is decreasing, while the production of natural gas is rising at almost 7 percent per year.*

Naill (1973, 248) simulated gas production and exploration over a time period from 1900 to 2020. The simulations led him to conclude that:

*The normal behavior mode is an initial period of unrestricted growth in supply,
a transition period when growth is slowed, and finally a decline in supply.
This is a natural result of the assumption of a finite amount of initial unproven reserves
--at some point in time, growth will be limited by rising costs due to scarcity of the resource ...
the time of transition is remarkably insensitive to changes in these [parameter] values.
For example, an increase by a factor of two in the actual quantity of initial unproven reserves
results in postponing the transition in supply for only ten years*

The natural gas model was the first of many modeling contributions to support policy making in the US energy sector. Naill and his colleagues developed several models, including COAL2 (Naill 1977), FOSSIL2 (used in the 1991 National Energy Strategy), and IDEAS (AES 1993). The history of these projects is reported in two articles in the *System Dynamics Review* (Naill 1992A,B). The first article explains the models' use for policy analysis at the US Department of Energy. The second article describes the results of a simulation search for a cost effective combination of energy policies to mitigate the US contribution to global warming.

These exercises introduce you to dynamics of gas exploration and production in the simplest possible manner. The goal is to make you familiar with the power of exponential growth in the demand for a limited resource.

A Simple Model of Natural Gas Discovery and Production

Figure 1 shows a simple model to introduce the combination of stocks and flows to study the lifecycle of discovery and production. The model has two stocks and two flows. The stocks are measured in trillion cubic feet (TCF); the flows are measured in TCF/yr. Proven reserves refer to previously discovered gas that is available for production. Unproven reserves are a larger, more speculative quantity. It stands for total resources that might be discovered in the future.

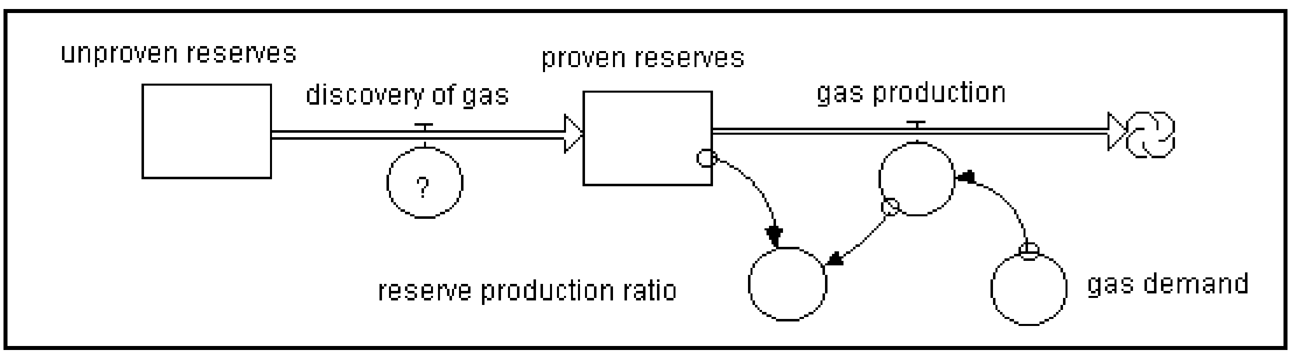

Figure 1. A simple model of natural gas production.

The gas demand is a user specified variable which will grow over time. Near the start of the 20th century, gas demand was around 1 TCF/yr. Demand is satisfied by gas production which drains the stock of proven reserves. The reserve production ratio is used to measure the adequacy of proven reserves. If there were 20 TCF of reserves at the start of the century, for example, the ratio would have been 20 years. In other words, demand could be satisfied for 20 years even if there were no further discoveries.

To explain the discovery of gas, we need to know the industry rational for investing in exploration and the likelihood that the investments will lead to new discoveries. Naill assumed that the industry strives to keep the proven reserves at an adequate level, as measured by the reserve production ratio. He selected 20 years as the target value.

Figure 2 expands the introductory model to simulate the discovery of gas based on this target. Let's initialize the model with 20 TCF of proven reserves, 1,000 TCF of unproven reserves and a gas demand of 1 TCF/yr. The initial value of the reserve production ratio is 20 years, and the target ratio is 20 years.

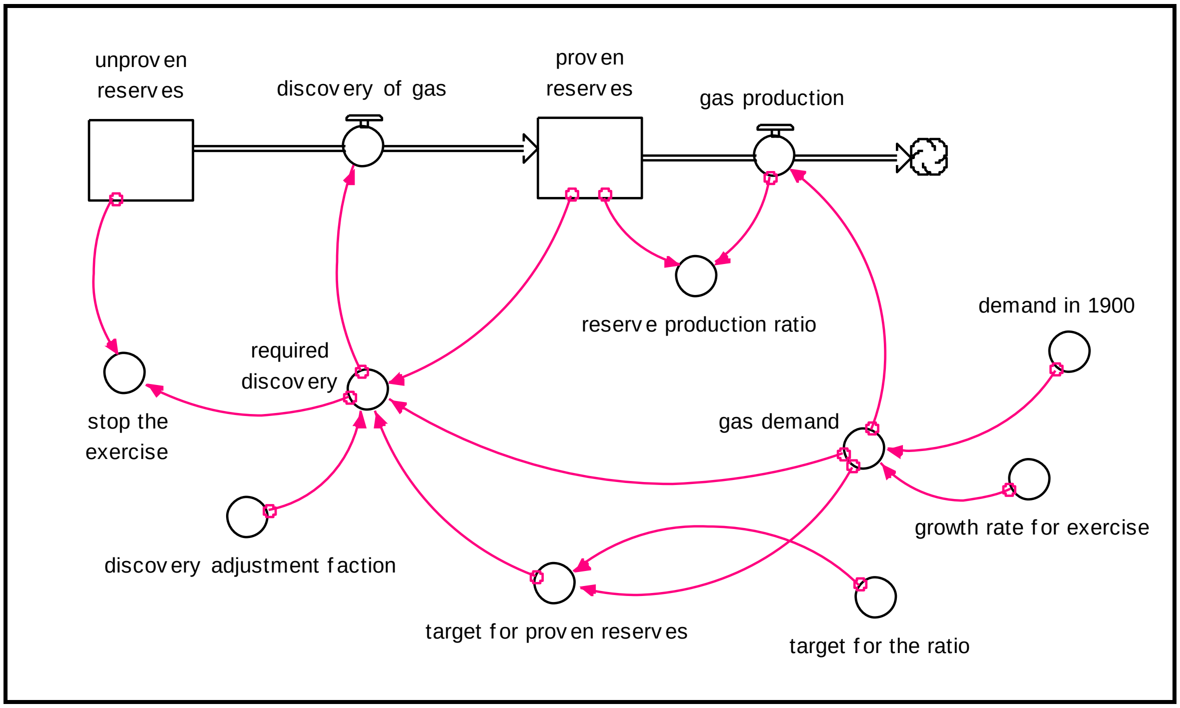

Figure 2. Simple model to experiment with a "thousand year supply" of natural gas.

The model assumes that the discovery of gas is identical to the discovery required to keep the proven reserves sufficiently large to provide "20 years of gas." If gas demand were to remain constant over time, the discovery of gas need only be 1 TCF/yr to replace gas production. With 1,000 TCF of unproven reserves, it appears that we are creating what might be called the

thousand year model.

That is, if demand were to remain constant, natural gas supplies would last for a thousand years!

Testing the Thousand Year Model

To test the simple model, let's set the gas demand to grow exponentially over time. The first test will be quite simple since the rate of growth is zero:

gas_demand = demand_in_1900*EXP(growth_rate_for_exercise*(time-1900))
growth_rate_for_exercise = .00

Then we set the gas production to serve the gas demand:

gas_production = gas_demand

And then we set the discovery of gas to match the required discovery:

discovery_of_gas = required_discovery

The equation for the target value of proven reserves is 20 years worth of demand:

target_for_proven_reserves = target_for_the_ratio*gas_demand
target_for_the_ratio = 20

The equation for the required discovery represents companies attempting to discover enough gas to compensate for the gas demand and to close the gap between the target for proven reserves and the actual proven reserves:

required discovery = gas_demand+
discovery_adjustment_faction*(target_for_proven_reserves-proven__reserves)

We will set the "discovery adjustment fraction" to 1/year which means companies are attempting to close the gap in one year. This is a long equation, so it is helpful to check the units. Recall the units for each of the variables:

required discovery (TCF/year)
gas demand (TCF/year)
discovery adjustment fraction (1/year)
target for proven reserves (TCF)
proven reserves (TCF)

The units check out as follows:

TCF/year = TCF/year + 1/year*(TCF – TCF) = TCF/year

Now, what results should we expect from the model in Figure 2? With a growth rate at zero, the simulations should show that discoveries will continually replenish the stock of proven reserves, and the reserve production ratio will be maintained near 20 years over the entire simulation.

But if you experiment with high growth rates (i.e., 50%/yr), we expect to see the stock of unproven reserves driven rapidly toward zero. When we reach a point where the rule for discoveries calls on more gas than remains in unproven reserves, the exercise is terminated.

Intentional Division by Zero: A Trick to Stop the Simulation

A simple trick to get the software to stop the simulation is to write an equation that forces division by zero:

stop_the_exercise = 1/MAX(0,unproven_reserves-required_discovery)

When unproven reserves are below the required discovery, the MAX function chooses 0 rather than the negative number. When Stella attempts to divide 1 by 0, the software will complain about the variable "stop_the_exercise." When we see this complaint, we will know the reason why Stella stopped the simulation.

What Is Your Expectation with 4% Annual Growth in Demand?

Let's now simulate the model with exponential growth in the demand for natural gas. An annual growth of 4% is a reasonable number for the historical period, so we can repeat the simulation with the growth rate at 0.04/yr.

Now, before looking ahead at the simulation results, you should guess how many years will pass before the model runs out of unproven reserves. What is your expectation --- will the simulation stop in a thousand years? in 500 years? in 250 years? Try to do the simulation in your head, (or by taking notes on a piece of paper). Then write your expectation for the longevity of the natural gas resource in the box below:

The simulation with 4% annual growth in demand will stop after ____________________ years.

Figure 3 shows the "thousand year model" in a simulation with 4%/yr growth in demand. Unproven reserves are at 1,000 TCF in 1900, and they decline slowly during the first 20 years of the simulation. The rate of decline accelerates, however, as growing demand forces higher and higher discoveries to replenish the stock of proven reserves. The decline is especially dramatic in the 1960s and 1970s. The exercise is terminated in the late 1970s because the remaining stock of unproven reserves is too small. Even if the industry were to discover the last cubic foot of gas, discoveries would not be sufficient to maintain the proven reserves at the target value.

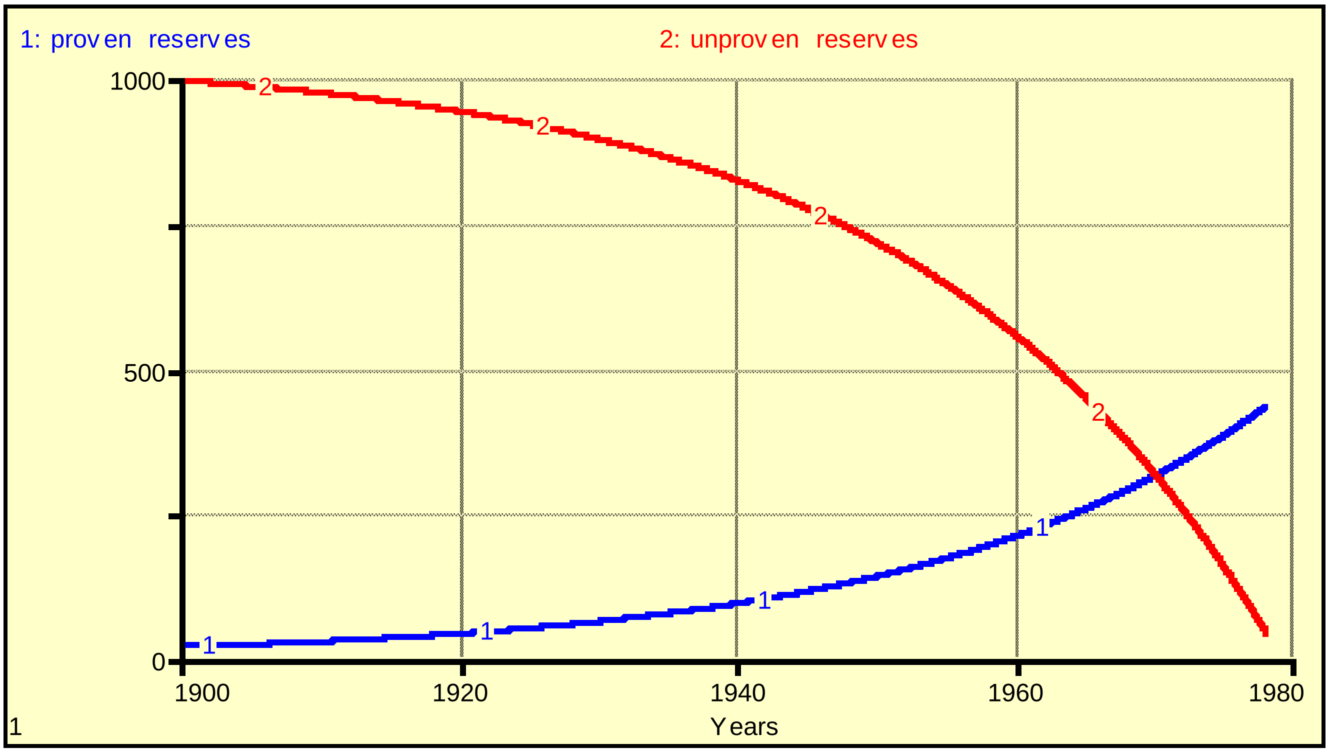

Figure 3. Simulated reserves with 4%/yr exponential growth in demand.
(Unproven reserves are far short of what is needed for a 1,000 years.
This experiment shows that the simulation is terminated in less than 80 years.)

Conclusion from the Simple Test

This experiment shows that an industry with a "thousand year resource" would find itself in serious trouble in less than 80 years. The simulation makes an important point about the discovery and production of a non-renewable resource like natural gas:

Exponential growth in demand is a powerful force
that will cause an industry to rapidly consume what appears to be a huge resource.

The simulation reveals that measuring resource adequacy based on current demand is terribly misleading in an exponentially growing system.[1]

Exercises

These exercises are provided for the student with an introductory interest in resources. They may be completed with the simple model used to study a “thousand year supply” of natural gas.

1. Build and Verify

Build the introductory model in Figure 2 and verify that it generates the results in Figure 3.

2. Simulate Cumulative Production

Add a stock to the model in Figure 2 to keep track of "cumulative production." Define a new converter named "total gas" as the sum of cumulative production, proven reserves and unproven reserves. Then simulate the model to verify that "total gas" remains constant over the simulation.

3. Double the Resource Base

Naill assumes that unproven gas reserves in 1900 were around 1,000 TCF based on the work by Hubbert (1969), but he cautions that other estimates have ranged as high as 2,000 TCF. Run the model in Figure 2 with 2,000 TCF of reserves. How much longer does the simulation run before termination?

Advanced Reading and Discussion Exercise

Naill describes a large range of uncertainty in the initial value assigned to the stock of unproven reserves. Review his explanation of why geologists arrive at such widely ranging estimates. Then review the work by Sterman and Richardson (1985) to simulate how geologists' estimates can change over time. Their model of the US petroleum industry is strikingly similar to Naill's model of natural gas, but their purpose is quite different. They wish to explain how geologists' estimates of a resource base change as more and more information becomes available.

To appreciate their purpose, we might imagine three possibilities:

- The geologists get the estimate right early in the life cycle.
- The estimates are too low in the early years, but the estimates gradually approach the correct value over time.
- The estimates start out too low, but the estimates increase rapidly as more information becomes available. Unfortunately, the estimates shoot past the correct amount, and downward corrections are needed later in the life cycle.

Review the 1985 article to learn which of the possible patterns is most characteristic of the nation's petroleum industry. Review the updated study (Davidsen 1990) to learn if they held the same view five years later. Do you agree with their characterization of oil resource estimation? Do you think their reasoning would apply to natural gas as well?

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End Note

[1] The problem with this measure of resource adequacy is explored in more detail by Behrens in a separate chapter of *Toward Global Equilibrium*. He provides a better measure of resource longevity.