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Expanding Upon Naill's Natural Gas Model

Assessing the impacts of technological change on the dynamics of non renewable resource consumption

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We propose an expansion of Naill's Natural Gas model to incorporate the impacts of technological evolution over time. It is well documented that the costs associated with the production of new technologies gradually decrease over time as firms learn from their past experiences of design and implementation. Our model uses the ratio of the cost of natural gas to the cost of wind energy to determine the anticipated market share represented by the two technologies. Because natural gas is a non-renewable resource, we expect that its cost will increase over time as reserves become increasingly scarce. Alternatively, we expect that the relative cost of wind will decrease as there are increasing returns to learning from the cumulative installation of new wind power capacity. In this way, we hypothesize that our model will show that at some point in the future the market share of wind will overtake that of natural gas, constituting the dominant portion of the installed energy generation capacity in the United States.

Problem Statement

In 1972, Roger F. Naill, then a master's student in the Systems Dynamics Group at MIT's Sloan School of Management, published his thesis on the dynamics of the discovery and usage of natural gas in the United States. The core purpose of Naill's thesis was to evaluate the impacts of price regulation in the natural gas market on the rate's of discovery, production, and utilization of the resource over time. To simulate the effect of this market intervention Naill developed a systems dynamics model for the natural gas production system in the United States. This model, originally scripted in DYNAMO, a forerunner to modern systems dynamics programming languages, has since become a classic example of how the systems dynamics modeling approach can be applied to understand long term trends associated with the price, usage rate, and availability of a non renewable resource.

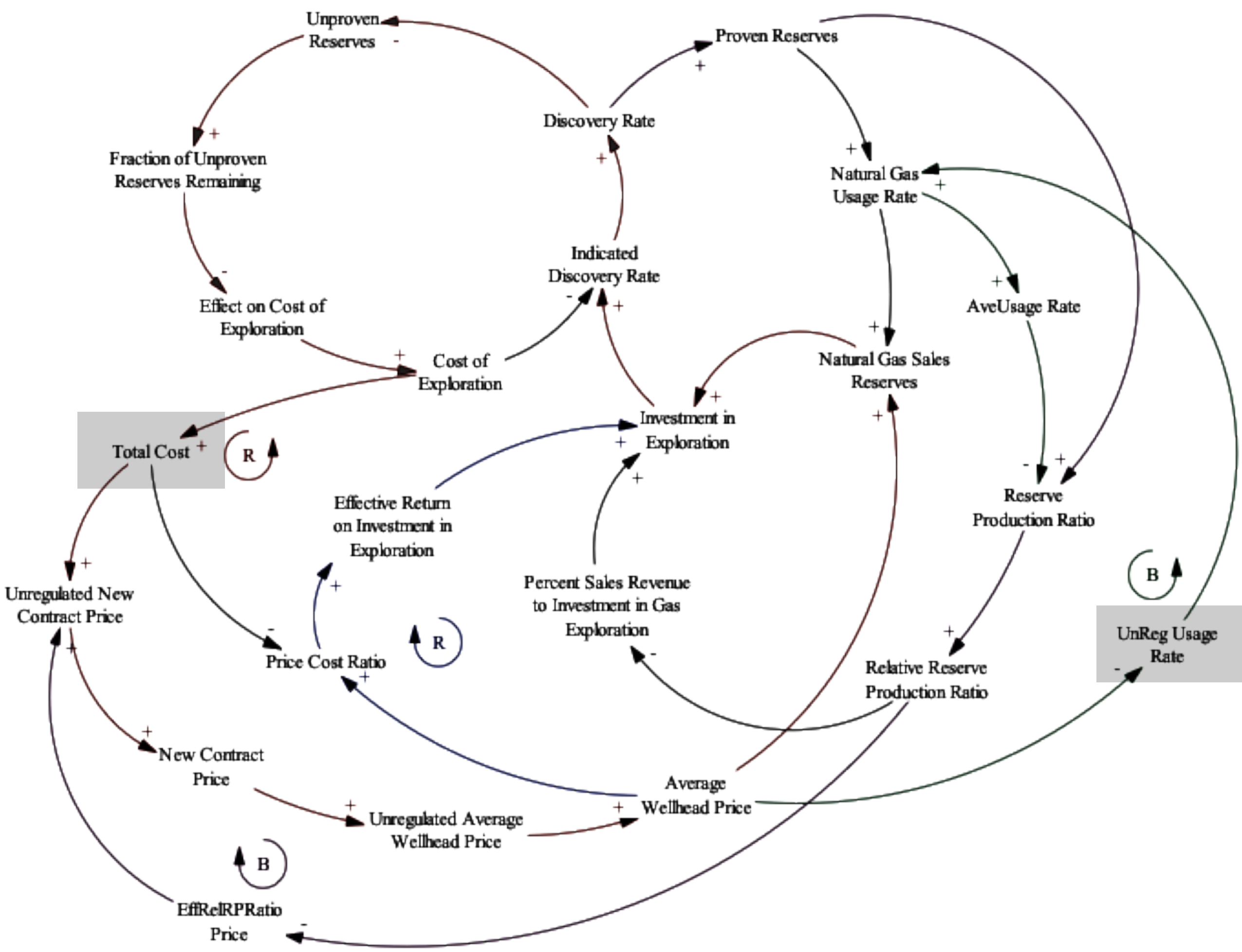
In Naill's thesis, he notes that over the long term there are likely to be significant impacts on the dynamics of the natural gas system associated with technological change and the development of substitute energy production and conversion technologies. However, because this issue is not explicitly related to his stated research question it is deliberately omitted from his model. In partial acknowledgement of this simplification he references the work of another student in his cohort in the Systems Dynamics Group, named William Behrens, whose master's thesis dealt explicitly with the role of technological change in the dynamics of non renewable resource consumption. Behrens' work treats, in the abstract, the various ways in which technological change could potentially impact natural resource utilization.

Our project seeks to use the structural relationships first hypothesized by Behrens to expand upon Naill's original model by further incorporating the effects of the introduction of a directly substitutable alternative energy technology on the dynamics of the natural gas system. For practical reasons of data availability, we have selected wind power as the single technological substitute which we are to model. However, it is important to understand that the modeling framework which we have developed could readily be used to investigate the impacts on the natural gas system from the introduction of any number of competing alternative energy technologies.

We hypothesize that as any substitute technology, in this case wind power, becomes increasingly cost competitive this will cause the usage rate of natural gas to decline more rapidly than in the original reference mode. Acceleration in the decline of the usage rate of natural gas will in turn cause the discovery rate of new natural gas reserves to decline, by reducing the level of investment in new exploration. These reductions, in both the rate of discovery and the usage rate of proven reserves, will therefore cause the stock of unproven reserves to be substantially larger in the presence of a cost competitive substitute technology.

Reference Modes

Causal Loop Diagram: Naill's Original 1972 Model

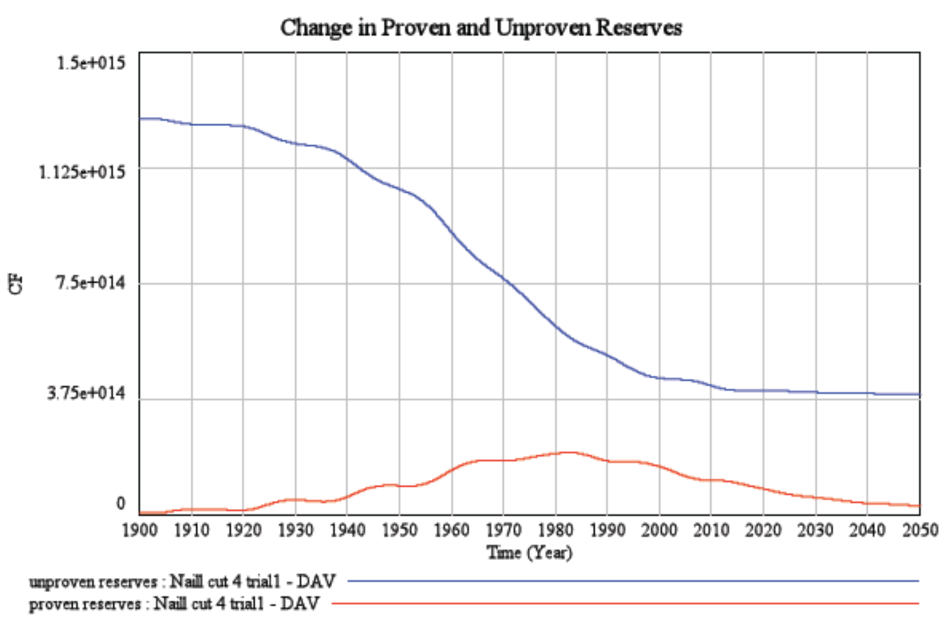


This figure illustrates the causal linkages between the various elements of Naill's 1972 model. The regions highlighted in gray reflect the locations at which our model expansion interacts with Naill's original model structure.

There are two important differences between this recreation of Naill's model and the model structure as published in his master's thesis.

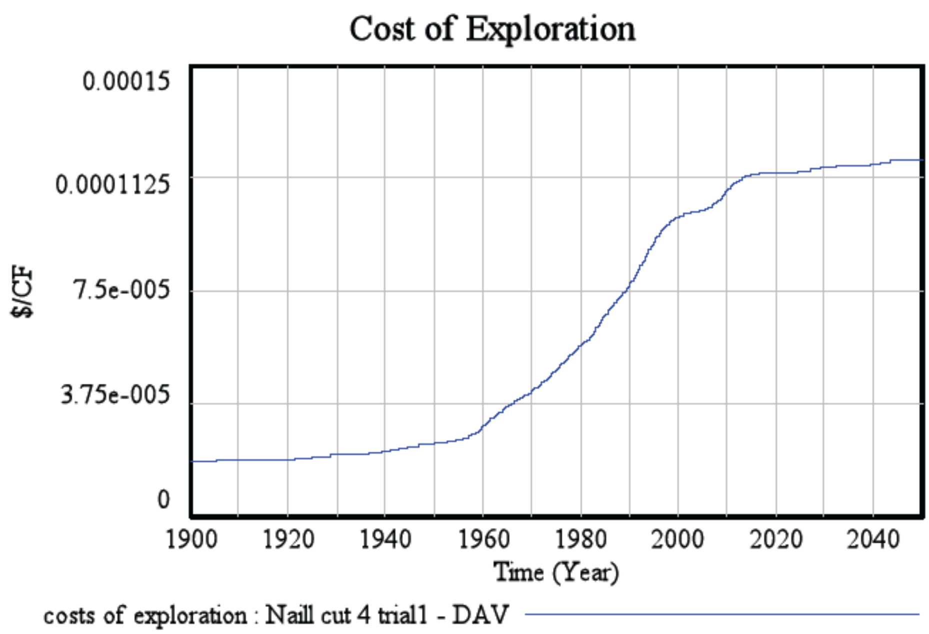
(1) The original model contained a series of switching elements which were included to facilitate comparison between the system's behavior in the presence versus the absence of price regulation. These switching elements have deliberately been omitted because they do not pertain to the question that we are attempting to answer through our model expansion.
(2) A second significant difference is the fact that in Naill's original model the price for natural gas was determined endogenously, permeating in the system's dynamics to the demand of natural gas. In this cut of the model, price for natural gas is specified as an exogenous lookup function based upon forecasted predictions for the future average wellhead price of natural gas. This difference has substantial implications for how the interaction between our expansion and the elements of Naill's original model may combine to reproduce the trends of the reference mode. Unfortunately however, despite its known limitations, we have been forced into using the model cut which relies on the exogenous price function because of the practical difficulties associated with reproducing Naill's original model from the documentation provided in the DYNAMO programming language.

Reference Modes for Naill's Original Model

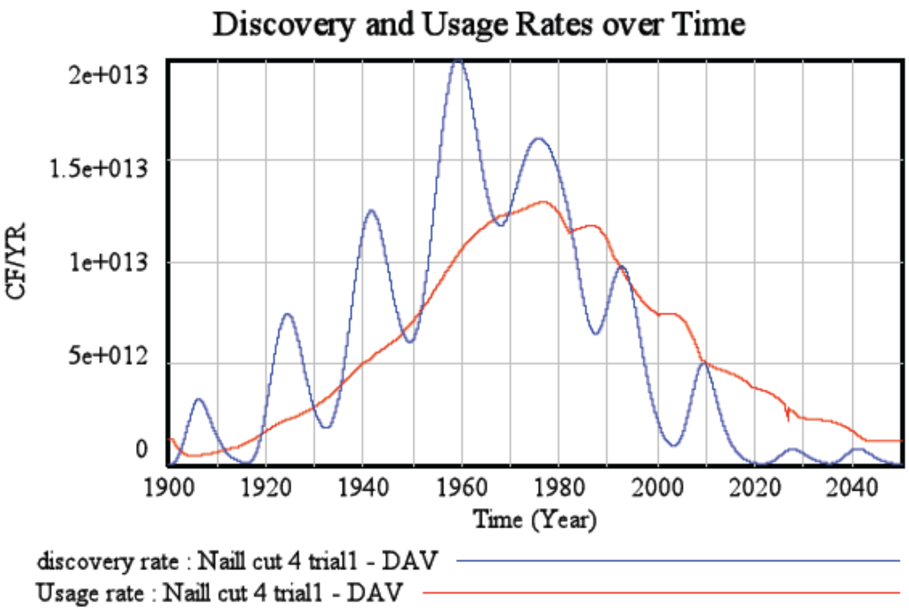


In Naill's original model the stock of unproven reserves is finite, reflecting the non-renewable nature of natural gas. The initial value of this stock is therefore equal to an estimate of the total amount of natural gas in existence on the planet. Unproven reserves are gradually converted to proven reserves through the process of resource discovery. Unproven reserves can only be discovered by engaging in exploration; a process requires continuous capital investment. The success rate of an exploratory effort is directly linked to the total quantity of unproven reserves still remaining at a given point in time and the return of investments in the natural gas industry. Thus, as the stock unproven reserves and the profit margin of natural gas gradually decline so too will the success rate of exploration as well as the net additions to the stock of proven reserves.

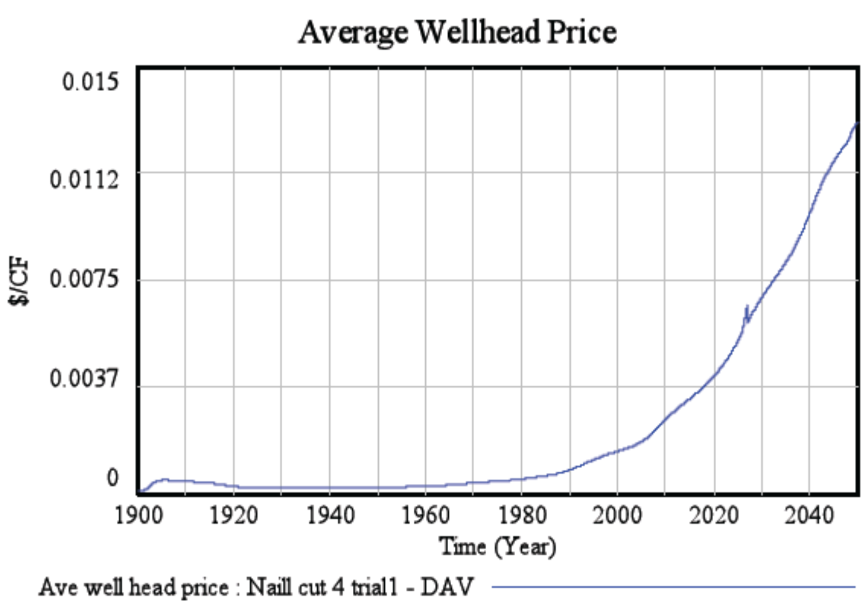
The figure above shows Naill's model predictions for the temporal change in the stocks of both proven and unproven reserves. In the early 1980's proven reserves are expected to peak and then gradually decrease as annual usage continues to deplete the stock and an increasing rate.



In Naill's original model the costs of exploration gradually increase because of a decrease in the fraction of remaining unproven reserves. This reflects an increasing scarcity of the resource.



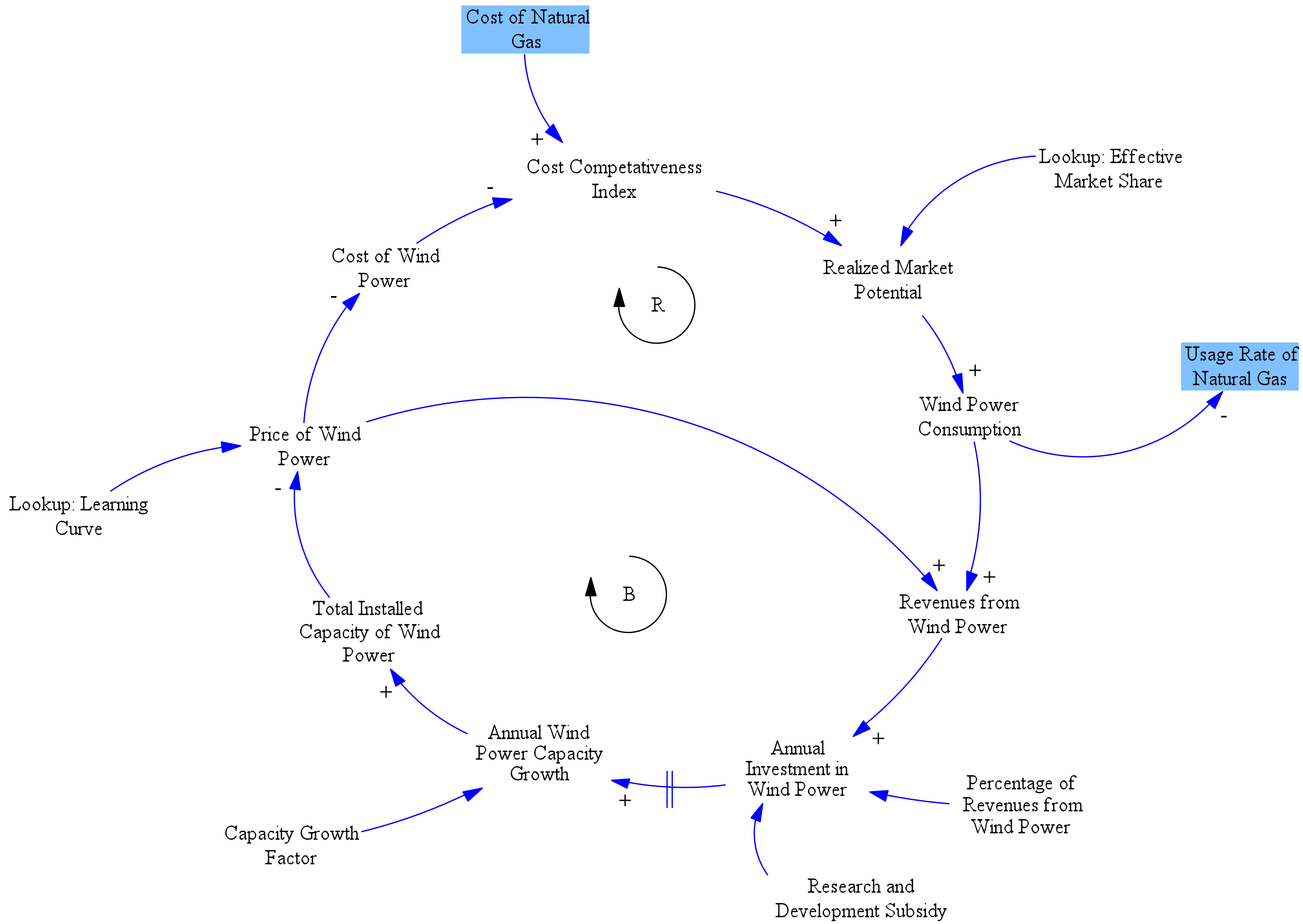
Here again this model illustrates Naill's model prediction that the usage rate (in red) of natural gas will increase until peaking in 1980 when increasing resource scarcity causes the wellhead price of natural gas to increase to uneconomical levels. The oscillation of the discovery rate (in blue) along the trend line established by the usage rate is caused by a delay between the indicated discovery rate and the actual discovery rate. Both the usage rate and the actual discovery rate of natural gas decline by 1980, reflecting the growing scarcity of natural gas.



Naill's model forecasts that the average wellhead price for natural gas remains roughly constant for the first seventy years of the simulation. However, in the 1980's, following the peak in the proven reserves, the average wellhead price steadily increases reflecting the increasing scarcity of proven reserves of natural gas.

Main Feeback Loops

Causal Loop Diagram: Model Expansion



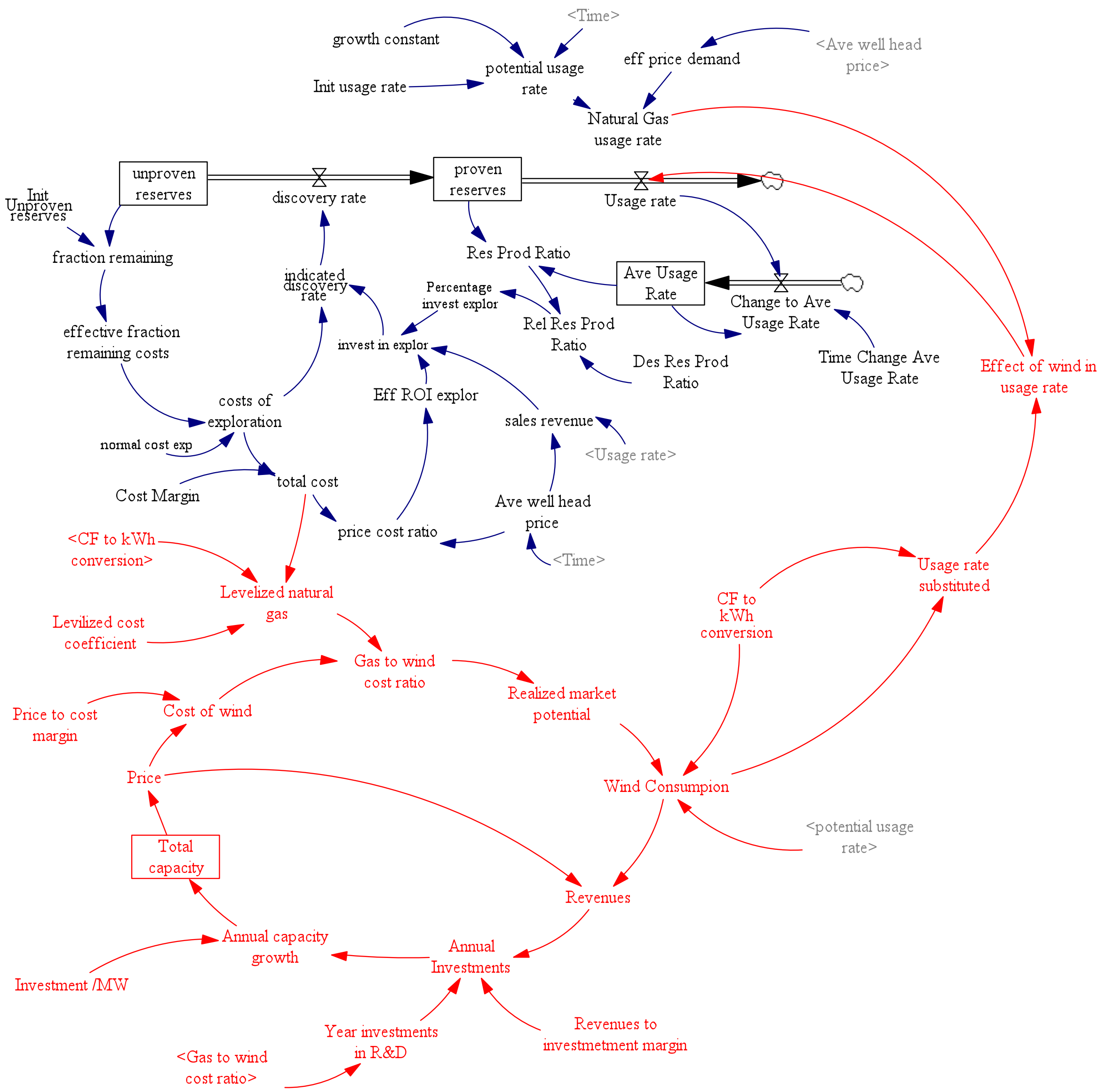
Overview of Model Expansion Causal Loop Dynamics

This causal loop diagram depicts the relationships between the important variables in our model expansion. The diagram contains two dynamic feedback loops: an inner balancing loop and an outer reinforcing loop.

- The outer reinforcing loop begins with the specification of the total cost for natural gas as an output of Naill's model.
- The cost of natural gas is divided by the cost of wind power to generate what we describe as a cost competitiveness index for the two technologies. This cost competitiveness index reflects the relative desirability of each energy production technology in terms of total cost.
- The cost competitiveness index is then used, via a lookup function, to determine the realized market potential (i.e. the fraction of the potential usage rate which can be satisfied by wind power). The realized market potential increases as the cost competitiveness of wind increases, reflecting the increased desirability of wind as a power generation technology relative to natural gas.
- The level of realized market potential then directly determines the quantity of wind power consumed as a fraction of the total market potential. This value is then linked to the usage rate of natural gas feeding back into the dynamics of Naill's model. As the quantity of wind power consumed increases, reflecting technological substitution, the usage rate of natural gas declines.
- The level of wind power consumption is then multiplied by the price of wind power to determine the quantity of revenues from the sale of wind power.
- The quantity of revenues is then related to the level of investment in wind power technology. In our model, investment in wind power technology takes on two general forms. The first reflects a constant annual subsidy for research and development in wind power presumably coming from government and private agencies. A secondary source of investment comes from the commercialization of wind power represented as a portion of the revenues obtained from the sale of wind power. The annual R & D is included in an effort to stimulate capacity growth during the nascent stage of technological development, when the cost competitiveness of wind power is relatively low.
- Annual investment in wind power translates into annual additions to installed wind generation capacity.
- These annual increases in wind generation capacity feed into the cumulative stock of wind generation capacity.
- The cumulative stock of wind generation capacity is then used to determine the price of wind power via a lookup function which represent the learning curve associated with the commercialization of wind power technology (a process described in the Parameter Estimates section)
- This price is used to determine both the annual revenues from wind power sales (closing the inner balancing loop) as well as to determine the cost of wind power via a price to cost ratio of 85%. This ratio reflects the proportion of the price of wind which constitutes the cost of production (i.e. the inverse of the profit margin).
- Finally, this cost of production is again feed back into the calculation of the cost competitiveness index closing the feedback loops.

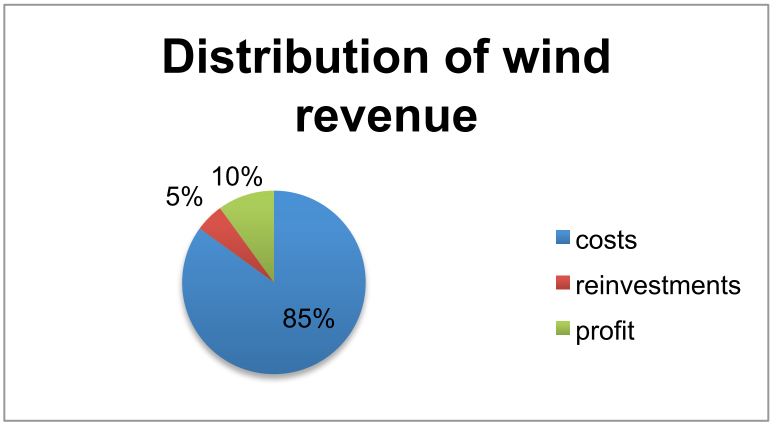
Model Structure

Vensim Diagram: Model Expansion



The figure presents our expanded version of Naill's model (colored in red) relative to Naill's original 1972 model (in blue). Our model expansion is connected to Naill's original model structure through following linkages:

(1) The dynamics of our substitute technology loop influence the Naill model by reducing the "Usage Rate of Natural Gas."
(2) Naill's model then influences the dynamics of our substitute technology loop via its specification of the "Total Cost of Natural Gas"

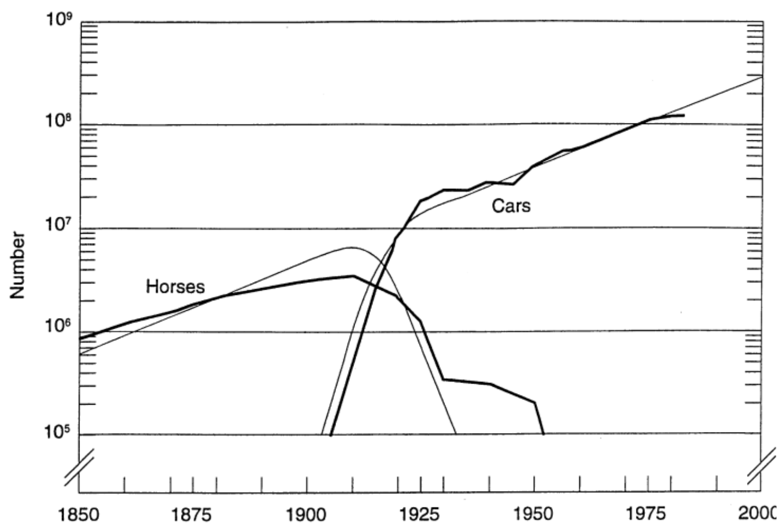


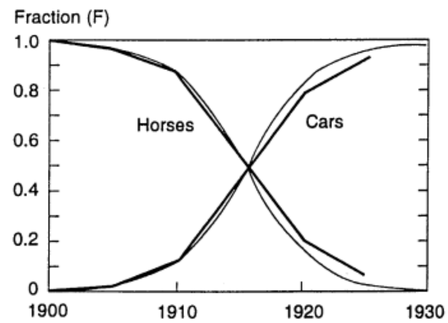
The margin of wind price to reinvestments and costs are based upon this distribution of revenue. In the sensitivity analysis we increase the percentage of revenues reinvested to 10% by reducing profit to 5%. We considers costs to be fixed to 85% of the revenues.

Parameter Estimates

Principles of Technological Substitution and the Effective Market Share Lookup Function

To illustrate the concept of technological substitution, consider the following historical case study of the evolution of personal transportation technologies: the substitution of horses to motor cars. In this simple example, one technological artifact, the automobile, replaced another transportation technology, the personal horse and carriage. In the two figures below, the one to the left plots both the number of cars and the number of horses over time. To the right, the relative fraction of the total number of road vehicles (cars + horses) is shown, illustrating the gradual conversion from one technology to the other over time.

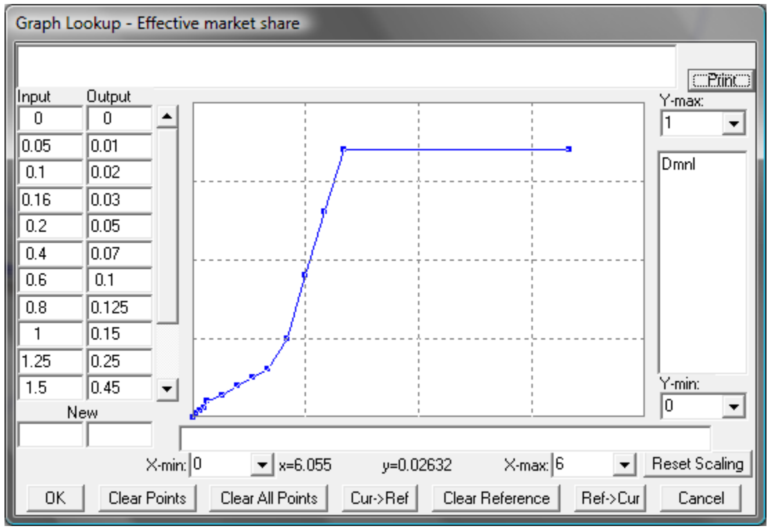




Source: Grubler, Nakicenovic, & Victor (1999)

This simple case of technological substitution illustrates the expected market behavior associated with the introduction of a product that is directly substitutable for another existing product. In the case of horses and cars, cars despite being more expensive were immediately recognized as the more competitive product because of their improved performance and expanded functionality.

Our expanded version of Naill's model treats wind power technology as a direct technological substitute for natural gas based power systems. However, it makes no claims about the relative performance of the two technologies. Rather, in our model, the only characteristic which determines the relative competitiveness of each product is their respective costs. As a result we maintain that the market share of wind power is based upon the ratio of the cost of natural gas to the cost of wind power. This relationship is incorporated into the following lookup function.

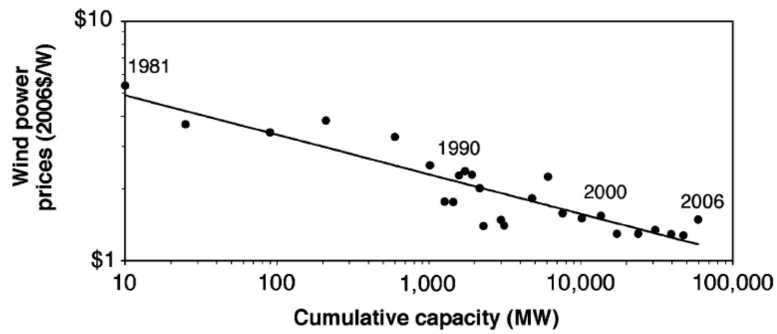


When natural gas costs are lower than those for wind, the ratio of the cost of natural gas to the cost of wind power (the cost competitiveness index) is lower. As the graph and table above illustrate, over this period the market share of wind power will increase, but only gradually, due to ongoing investments in the research and development of wind power technologies that are independent from their commercialization. However, as the cost competitiveness index begins to increase, meaning the cost of wind is becoming lower relative to that of natural gas, the market share allocated to wind power will increase more rapidly, reflecting the increased desirability of wind power as a substitute for natural gas.

Returns to Learning in the Evolution of Novell Technological Systems

The development of a completely new technological system capable of substituting for an existing commercialized one is a process characterized by high initial investment costs. At early phases in the technologies development, these high investment costs greatly limit the cost competitiveness of the new technology relative to its existing substitute. It has generally been observed however, that the cost competitiveness of a new technological system will tend to improve over time as firms engage in an iterative process of design innovation. Meaning, in the case of an energy production technology, that the unitary energy cost will decrease as the capacity of this technology expands. This phenomenon results from the ability of firms to learn from the shortcomings of previous product iterations and use this knowledge to incrementally improve the performance of their designs.

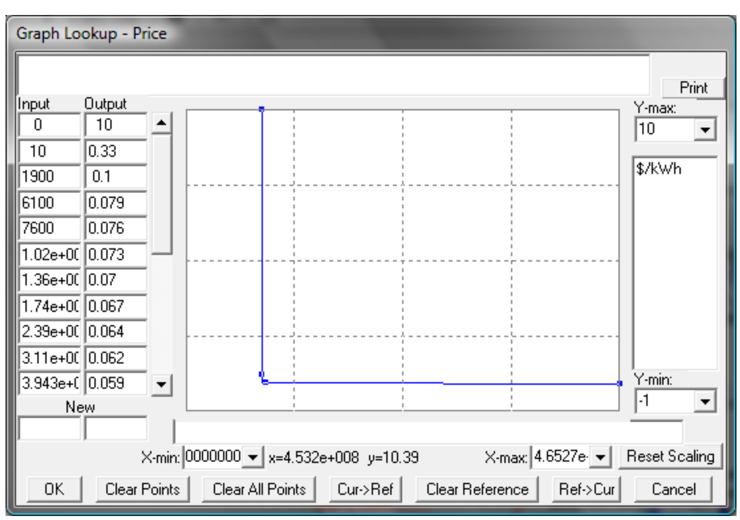
The returns to learning are well documented amongst energy production and conversion technologies as the impacts have been found to be quite drastic. Early in their research and development phase, the costs associated with a new energy system can be enormous. However, as the installed capacity of a new system increases a great deal is learned about how to improve their cost efficiency. This information is then disseminated throughout the industry decreasing average cost per unit energy output. The situation for the evolution of wind power systems is illustrated in the figure below.



Source: Nemet (2007)

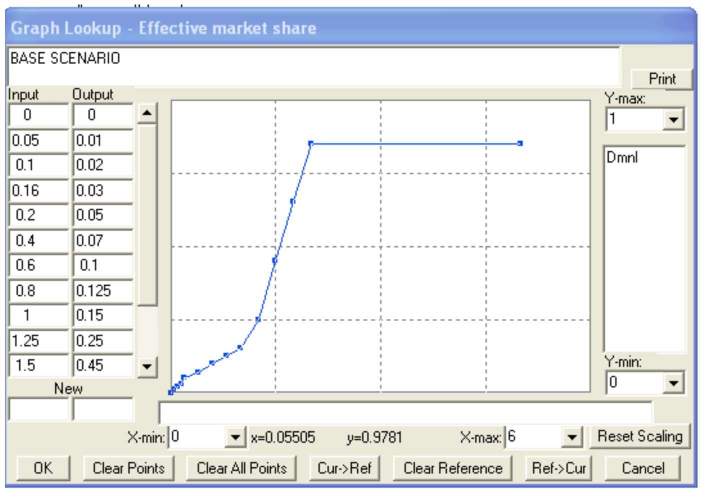
As the figure illustrates, the early 1980's constitute a nascent phase in the development of commercial wind power technologies. At this time the total cumulative capacity installed only amounted to a mere 10 MW. However, within ten years the cumulative capacity installed had increased by two orders of magnitude (note the logarithmic scale); this, despite the relatively high cost of wind power relative to other commercial energy technologies at the time. The early growth of wind power capacity can thus be attributed to a continuous stream of research and development subsidies provided by governments and private agencies.

Our expanded version of Naill's model incorporates the cost reductions associated with this learning process in the form of a lookup function which determines the cost of wind power on the basis of the cumulative capacity installed. As the cumulative capacity of installed wind power gradually increases during the early stages of the process of technological evolution the returns to learning in terms of increased cost efficiency are immense. With the passage of time the magnitude of the cost reduction, which can be achieved via this learning process, gradually decreases, reflecting an increasingly refined product design. In our lookup function, this progressive decrease is manifest as a fixed lower limit to the cost of wind power which occurs at the asymptote of the learning curve. Our learning curve was calibrated to reflect historical data of wind cost abatement through capacity building (Nemet, 2007) and reflects the fact that by 2006 the 74,000MW of wind capacity had been built was selling at an average price of $0.05/Kwh.



(Note: The figure appears distorted because of the inability to specific a logarithmic scale on the axes of a lookup function graph within Vensim)

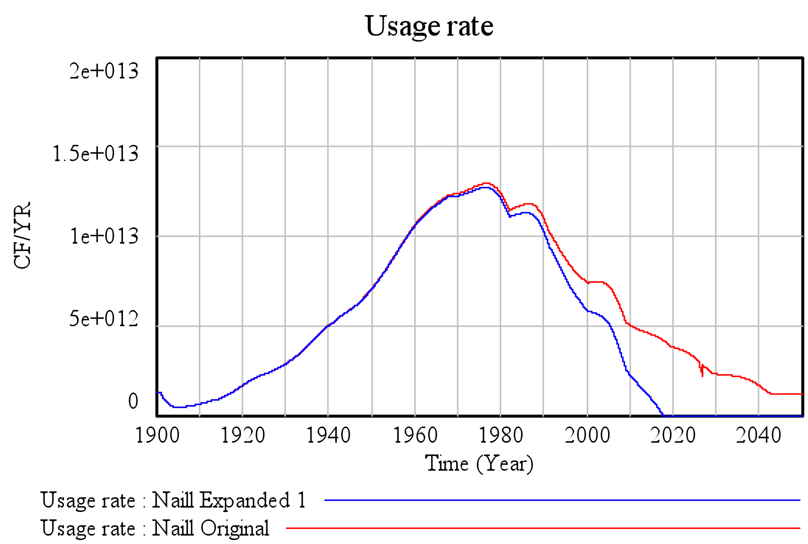
Another look up function assessed the competitiveness fraction on the realized market potential. This function was calibrated to fit historical assimilation of wind-generated electricity and the fact that by 2006 wind had only 3% of the market share relative to natural gas. As wind becomes more competitive the market will quickly assimilate the technology. Until at a point in time wind wind will satisfy most of the demand, it will saturate the market, and its growth will level down. These S-shaped curves, as the one presented in our look up function below, are a typical behavior in new technology assimilations.



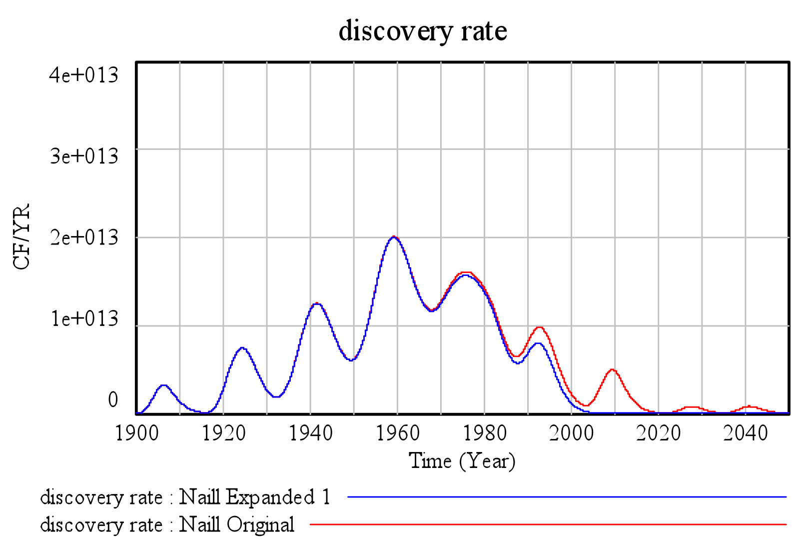
Analysis of Reference Modes

Our results show that wind power, the competing technology, will eventually impact the natural gas average usage rate accelerating its decline following the 1980 peak. The reference mode usage rate is primarily determined by the shrinking effective demand, which is in turn a result of the exponential increase in natural gas price (determined by an exogenous forecast). Thus, the resulting bell shaped curved doesn't change between the reference and the expanded models.

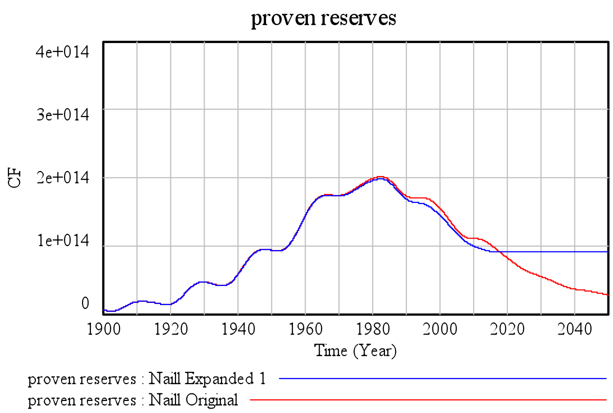
However, as the usage rate reaches its peak and becomes more expensive, wind starts affecting the decline of the usage rate making it sharper until it finally makes the usage rate drop down to zero by 2015. At this point in time, wind can fully satisfy the demand for natural gas and thus the technology takes over the demand in the system.

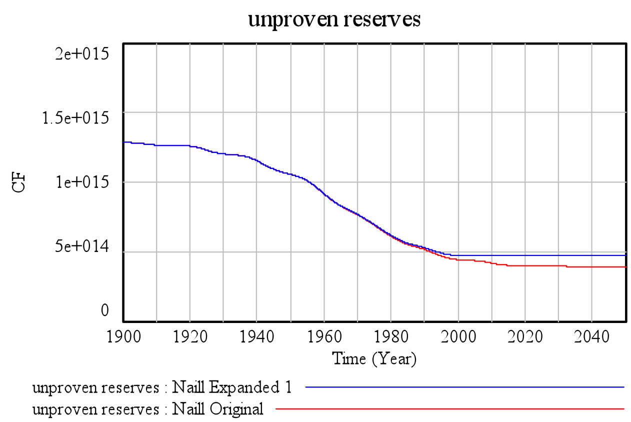


The decline in the discovery rate in our expanded model also accelerates. The competitiveness of wind reduces the investments in exploration, which makes sharper decaying oscillations in the discovery rate until, by 2000, no discoveries are further made. The reason for this is that there is no need on more discovery rates to fill a demand when the demand is being satisfied by a substitute technology.



Our model is therefore consistent with the hypothesized behavior of the unproven and proven stocks. Decreased rates in the discovery and usage outflow rates will reduce the deployment of both the unproven and proven reserves. As stocks stabilize, the level of natural gas remaining in both reserves will be significantly higher in our expanded model that in the reference mode.



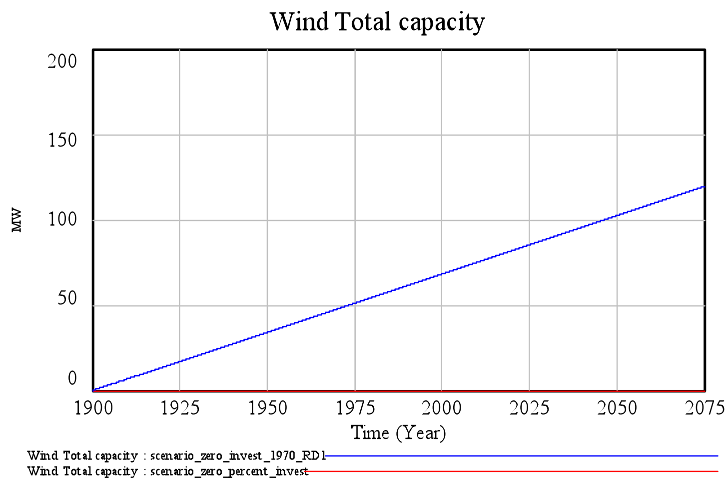


Scenario Analysis

Three key parameters of the new model were tested for their impact on the overall results of the simulation. The parameters tested were: the type and size of investment in increased capacity; the relationship between the competitiveness index and the realized market potential (i.e.: the shape of the lookup function governing realized market potential); and the relationship between total capacity of wind and price of wind (i.e.: the shape of the lookup function which describes the "learning rate").

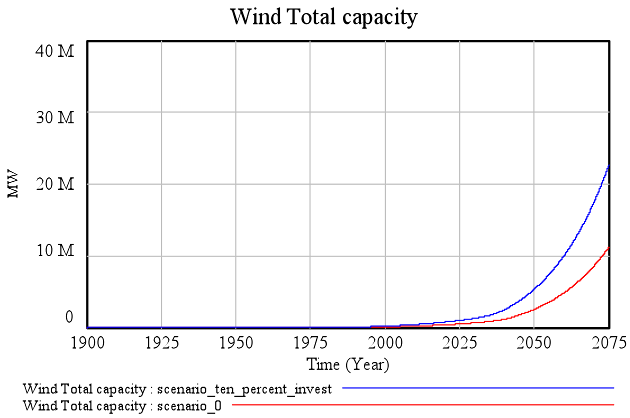
Investment

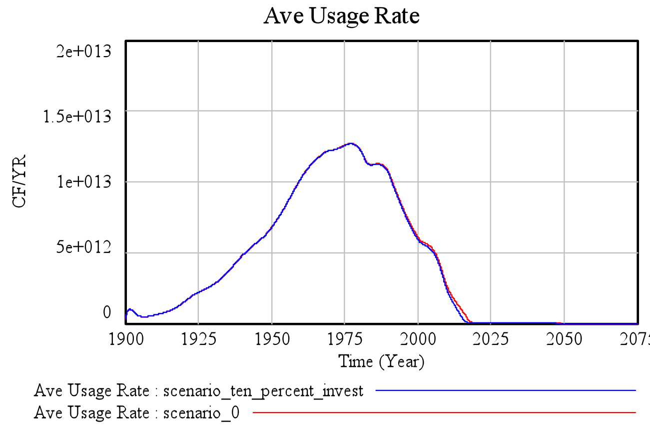
Our model contains two sources of investment which can lead to increases in capacity of wind power: 1) Yearly investments in research and development which represent non-commercial investments in wind power which occur irrespective of its commercial viability; 2) Investments which result from a portion of business revenues from generation of wind power being applied to creation of new capacity. We studied the relative importance of these two forms of investment in effecting the total capacity of wind power and the usage rate of natural gas.



The figure above shows the growth in total wind capacity that results from a scenario in which the only source of investment in new capacity is a yearly infusion of $1 million in Research and Development. There is no investment resulting from commercial revenue. Note the modest linear growth in capacity, culminating in a wind capacity of c. 125 MW. We can see the insignificance of this type of investment when we compare it to the values achieved under a scenario where commercial re-investment does occur.

When investment in capacity also includes a portion of yearly revenues from wind power, the values for total wind capacity are drastically higher. The graphs below show the large impact of revenue reinvestment relative to small yearly subsidies, as well as the effect of changing the rate of reinvestment. Higher rates of investment lead to higher total capacity, and also to slightly faster drop in the usage rate of natural gas.

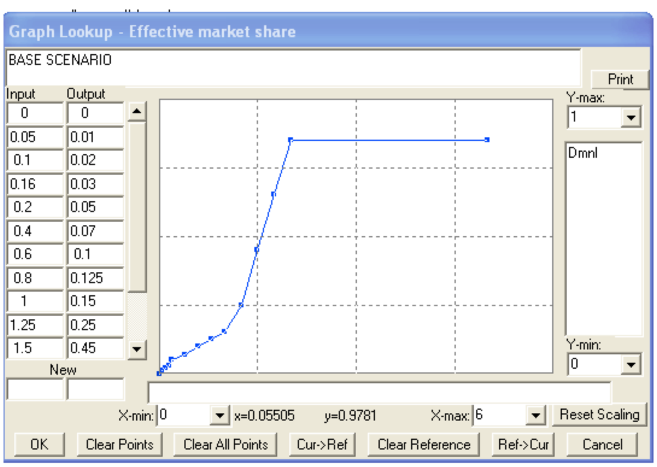


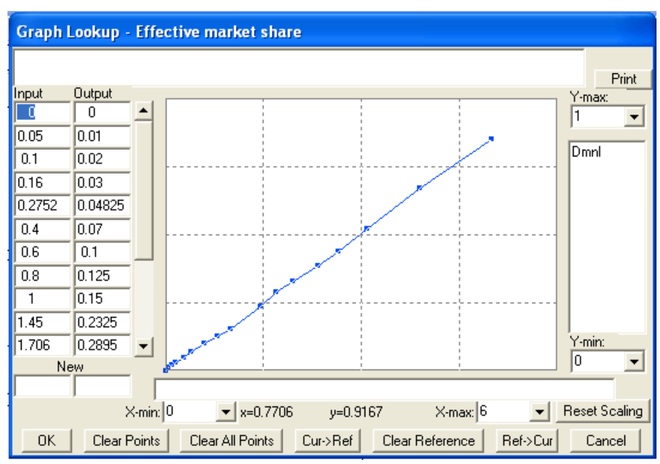


Red: 5% of yearly revenues from wind power are re-invested in capacity building
Blue: 10% of yearly revenues from wind power are re-invested in capacity building

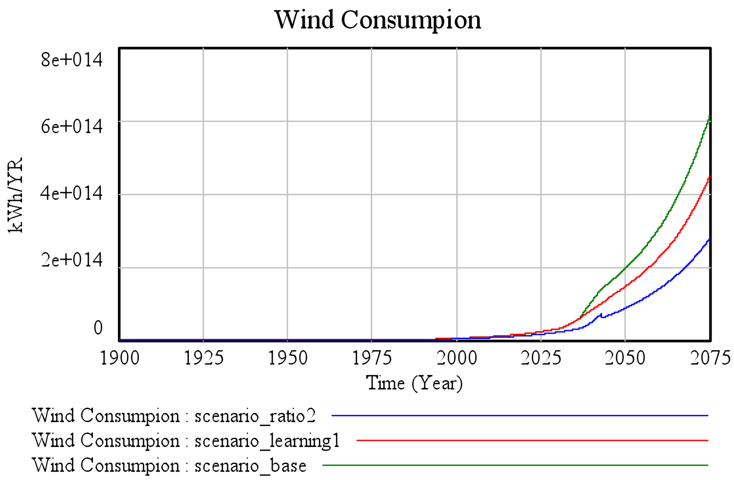
Realized market potential

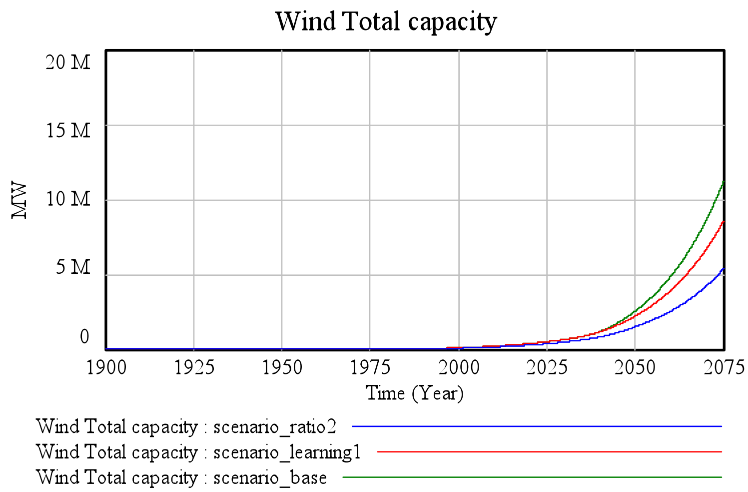
One area of significant uncertainty in the parameterization of the model was the effect of the competitiveness fraction on the realized market potential of wind. Therefore, in addition to the base scenario, we explored two alternative scenarios in which the lookup function takes a different form. The alternative lookup graphs reflect less optimistic outlooks on the influence of wind's cost competitiveness on its realized market potential.





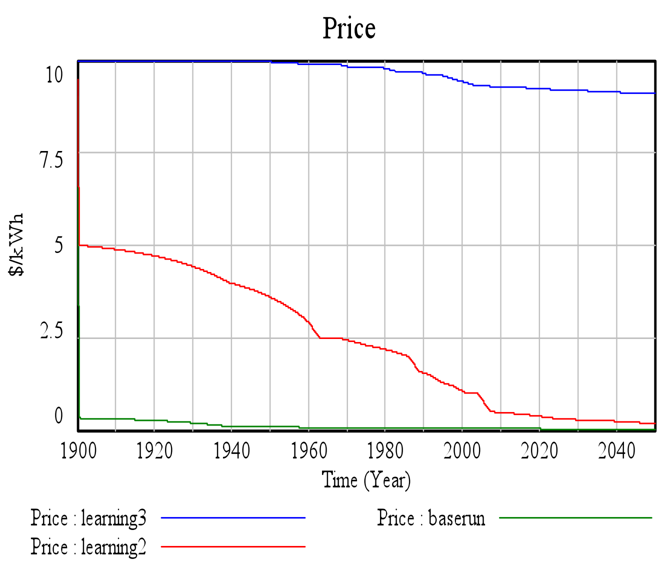
Compared to the base scenario in the upper left of the figure above, the two alternative scenarios show a less significant response of market capture by wind to improvements in the competitiveness of wind power over natural gas. The two figures below shows the sensitivity of wind consumption and total wind capacity to differing scenarios for the effect of the competitiveness index. Clearly, this parameter has a significant influence on the eventual outcome of the model, and should therefore be treated carefully.

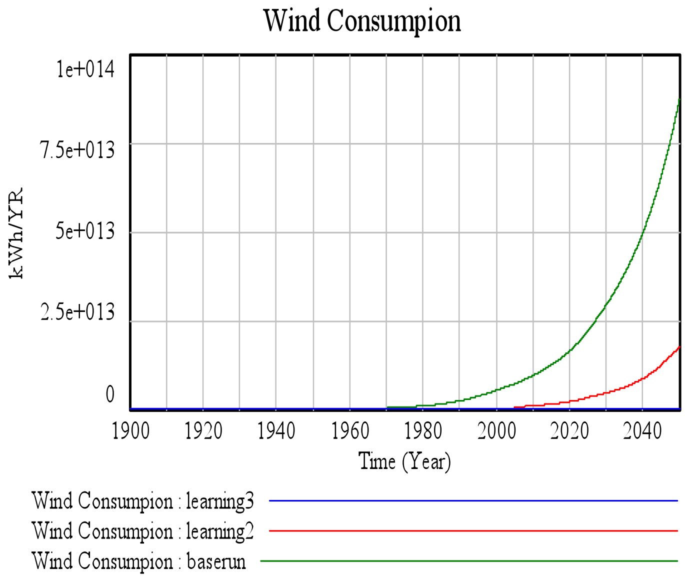


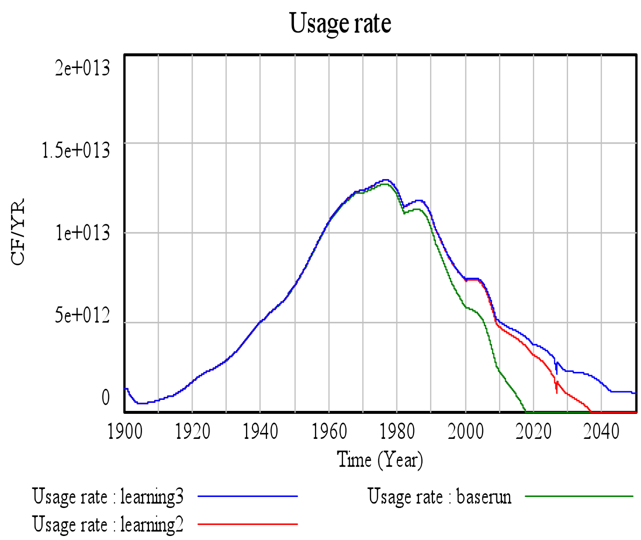


Learning Curve

The learning curve is a lookup function in our model which controls the rate at which price of wind power decreases as capacity increases. We conducted a sensitivity analysis to determine how much this parameter affected the simulation results. As can be seen in the figure below, the three different learning curves lead to three significantly different scenarios for the evolution of the price of wind power. The importance of changes in wind price can be seen in the two following graphs that compare wind consumption and natural gas usage across the different learning curve scenario options.



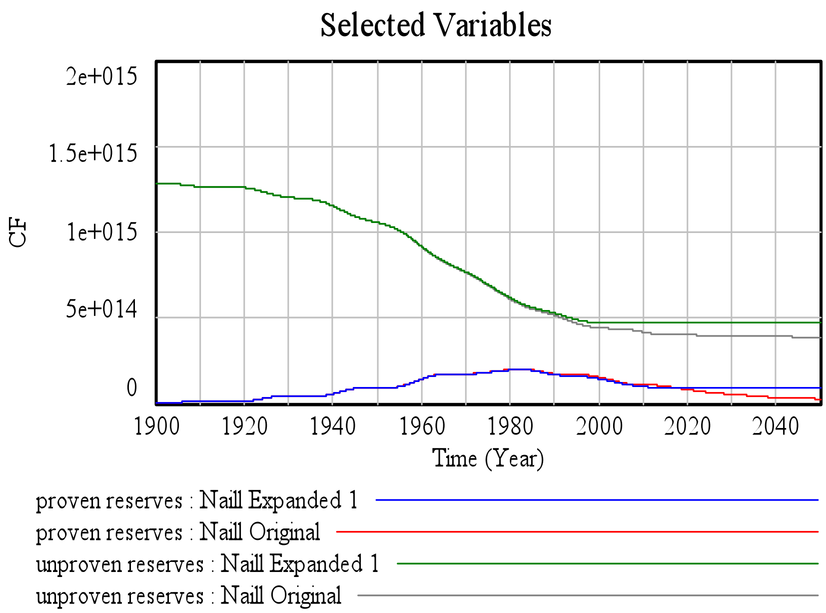

Wind Consumpion
1e+014
7.5e+013
5e+013
2.5e+013
0
kWh/YR
1900
1920
1940
1960
1980
2000
2020
2040
Time (Year)
Wind Consumpion : learning3
Wind Consumpion : learning2
Wind Consumpion : baserun


Usage rate
2e+013
1.5e+013
1e+013
5e+012
0
CF/YR
1900
1920
1940
1960
1980
2000
2020
2040
Time (Year)
Usage rate : learning3
Usage rate : learning2
Usage rate : baserun

Policy Insights

Accelerating the Transition towards a Low Carbon Economy

The following figure plots the levels of proven and unproven reserves predicted by Naill's original model as well as the predictions from our expanded model which incorporates the effects of increasing cost competitiveness of a substitution technology.



In our expanded model the final level of both proven and unproven reserves are significantly higher than the levels predicted by Naill's model. This essentially means that the decline in the usage rate of natural gas caused by the transition to a more cost competitive substitute technology results in less consumption of the non-renewable resource. In the context of the climate change debate, this means that the transition to a low carbon economy can be accelerated by taking measures to increase the cost competitiveness of low carbon substitute technologies.

Increasing Research and Development Funding vs. Stimulating Commercialization

Our sensitivity analysis shows that total wind capacity is hardly responsive to direct R&D investments, whereas it is highly responsive to an increased margin of private reinvestments into the industry. A clear policy implication is that the government can have a much greater impact by giving preference to initiatives that accelerates this private reinvestment margin rather than investing public monies directly into the industry. We suggest two government incentives in line with this logic:

- Tax breaks on private investments in wind developments. This policy tool will credit wind developmers a certain percentage of their investments in their tax balances.

– Feed in tariffs that capture the externalities associated with fossil fuels (green house gas emissions and other pollutants) and by doing so will give a premium to the price of electricity generated by non-carbon emitting fuels. A feed in tariff will make investments in wind more attractive due not only to this premium but also by reducing the risks in their revenues due to the volatility of competing fossil fuel prices.

Both of these policies will have the most impact in promoting a virtuous cycle towards more wind capacity.

Effecting the Learning Curve

Our sensitivity analysis also shows that the learning curve highly determines prices and directly permeates into winds' competitiveness. To make the learning curve steeper we need to foster an integrated wind industry. Policy initiatives that enhance information sharing, training and technology transfers will promote this wind's industry integration.

REFERENCES

Gregory F Nemet, 2009 . Interim monitoring of cost dynamics for publicly supported energy technologies. *Energy Policy* 37 (2009) 825-835

Arnul Grubler, Nebojsa Nackic Henovich, David G. Victor, 1999. Dynamics of energy technology and global change*. Energy Policy* 27 (1999) 247-280

Beherens Williams, 1972. The dynamics of natural resource utilization. *Simulation*, 1972; 19; 91

Roger F. Naill, 1972. Managing the discovery lifecycle of a finite resource: A case study of U.S. Natural Gas. Massachusetts Institute of Technology Master Thesis.

Roger F. Naill and Sharon D. Belanger. A systems dynamics model for national energy policy planning.

Appendix 1: Equations in the Expanded Version of Naill's Model

(01) Annual capacity growth= DELAY1((Annual Investments*"Investment /MW"), 3)
Units: MW

(02) Annual Investments= Revenues*Revenues to investmetment margin+"Year investments in R&D"
Units: $/kWh

(03) Ave Usage Rate= INTEG (Change to Ave Usage Rate, 3.2e+011)
Units: CF/YR

(04) Ave well head price = WITH LOOKUP (Time, ([(1889,0)-(2051,0.02)],(1900,8e-005),(1901,8.25e-005),(1902,0.000162), (1903,0.000335), (1904,0.000431), (1905,0.000458),(1906,0.000461),(1907,0.000455),(1908,0.000446),(1909,0.000436),(1910,0.000425),(1911,0.000412),(1912,0.000399),(1913,0.000383),(1914,0.000383),(1915,0.000366),(1916,0.000346),(1917,0.000323),(1918,0.000297),(1919,0.00027),(1920,0.000245),(1921,0.000226),(1922,0.000214),(1923,0.000208),(1924,0.000207),(1925,0.000209),(1926,0.000211),(1927,0.000213),(1928,0.000213),(1929,0.000213),(1930,0.000212),(1931,0.000209),(1932,0.000205),(1933,0.000201),(1934,0.000196),(1935,0.000191),(1936,0.000186),(1937,0.000182),(1938,0.000179),(1939,0.000178),(1940,0.000179),(1941,0.000185),(1942,0.000185),(1943,0.00019),(1944,0.000196),(1945,0.000202),(1946,0.000207),(1947,0.000217),(1948,0.000216),(1949,0.000219),(1950,0.000221),(1951,0.000223),(1952,0.000224),(1953,0.000225),(1954,0.000226),(1955,0.000226),(1956,0.000228),(1957,0.00023),(1958,0.000233),(1959,0.000237),(1960,0.000243),(1961,0.00025),(1962,0.000259),(1963,0.00027),(1964,0.000281),(1965,0.000294),(1966,0.000307),(1967,0.000321),(1968,0.000334),(1969,0.000348),(1970,0.000362),(1971,0.000375),(1972,0.000387),(1973,0.000399),(1974,0.00041),(1975,0.000422),(1976,0.000434),(1977,0.000447),(1978,0.000463),(1979,0.00048),(1980,0.000499),(1981,0.000521),(1982,0.000545),(1983,0.000569),(1984,0.000593),(1985,0.000619),(1986,0.000646),(1987,0.000677),(1988,0.000714),(1989,0.00076),(1990,0.000815),(1991,0.000881),(1992,0.000952),(1993,0.001027),(1994,0.001103),(1995,0.001177),(1996,0.001246),(1997,0.00131),(1998,0.001369),(1999,0.001423),(2000,0.001476),(2001,0.001529),(2002,0.001585),(2003,0.001649),(2004,0.001723),(2005,0.001815),(2006,0.001931),(2007,0.002074),(2008,0.002241),(2009,0.00242),(2010,0.002594),(2011,0.002757),(2012,0.002909),(2013,0.003051),(2014,0.003186),(2015,0.003319),(2016,0.003455),(2017,0.003597),(2018,0.003751),(2019,0.003918),(2020,0.004101),(2021,0.0043),(2022,0.004519),(2023,0.004761),(2024,0.00503),(2025,0.005327),(2026,0.005646),(2027,0.006593),(2027,0.005974),(2028,0.006294),(2029,0.006593),(2030,0.006867),(2031,0.007122),(2032,0.007365),(2033,0.007602),(2034,0.007842),(2035,0.008093),(2036,0.008367),(2037,0.008673),(2038,0.009018),(2039,0.009406),(2040,0.009828),(2041,0.010258),(2042,0.010669),(2043,0.011039),(2044,0.011362),(2045,0.011652),(2046,0.011916),(2047,0.012156),(2048,0.012375),(2049,0.012791),(2050,0.013028)))
Units: $/CF

(05) CF to kWh conversion=1/0.29
Units: kWh/YR

(06) Change to Ave Usage Rate=(Usage rate-Ave Usage Rate)/Time Change Ave Usage Rate
Units: CF/YR/YR

(07) Cost Margin=0.967118
Units: Dmnl

(08) Cost of wind=Price*Price to cost margin
Units: $/kWh

(09) costs of exploration=normal cost exp*effective fraction remaining costs
Units: $/CF

(10) Des Res Prod Ratio=10.5132

Units: YR

(11) discovery rate=DELAY3I(indicated discovery rate, 4.5, 3)
Units: CF/ YR

(12) eff price demand = WITH LOOKUP (LN(Ave well head price*100000),
([(0,0)(10,2.2)],(1,2.1),(1.5,1.59),(2,1.21),(2.5,0.9),(3,0.69),(3.5,0.5),(4,0.24),(4.5,0.14),(5,0.067),(5.5,0.031),(6,0.014),
(6.5,0.0055),(7,0.0015),(7.5,0.0002),(8,1.7e-005)))
Units: Dmnl

(13) Eff ROI explor = WITH LOOKUP (price cost ratio,([(0,0)
(2.4,1.1)],(0,0),(0.2,0.08),(0.4,0.25),(0.6,0.44),(0.8,0.55),(1,0.67),(1.2,0.76),(1.4,0.82),(1.6,0.88),(1.8,0.92),(2,0.96),(2.2,
1)))
Units: Dmnl

(14) Effect of wind in usage rate=IF THEN ELSE(Usage rate substituted>Usage rate of natural gas, 0 , Usage rate of natural gas-Usage rate substituted)
Units: CF/YR

(15) effective fraction remaining costs = WITH LOOKUP (LN(10*fraction remaining),([(-5,0)-(5,14000)],(-
3.5,13000),(-3,6000),(-2.5,2700),(-2,1000),(-1.5,545),(-1,245),(-
0.5,110),(0,50),(0.5,22),(1,9.98),(1.5,4.48),(2,2.02),(2.5,0.91)))
Units: Dmnl

(16) Effective market share = WITH LOOKUP (Gas to wind cost ratio,
([(0,0)-(6,1)],(0,0),(0.05,0.01),(0.1,0.02),(0.16,0.03),(0.2,0.05),(0.4,
0.07),(0.6,0.1),(0.8,0.125),(1,0.15),(1.25,0.25),(1.5,0.45),(1.75,0.65),(2,0.85),(5,0.85)))
Units: Dmnl

(17) FINAL TIME = 2050
Units: Year
The final time for the simulation.

(18) fraction remaining=unproven reserves/Init Unproven reserves
Units: Dmnl

(19) Gas to wind cost ratio=Levelized natural gas/Cost of wind
Units: Dmnl

(20) growth constant=0.0463497
Units: 1/YR

(21) indicated discovery rate=invest in explor/costs of exploration
Units: CF/YR

(22) Init Unproven reserves=1.28434e+015
Units: CF

(23) Init usage rate=1.06331e+012
Units: CF/YR

(24) INITIAL TIME = 1900
Units: Year
The initial time for the simulation.

(25) invest in explor=sales revenue*Percentage invest explor*Eff ROI explor
Units: $/YR

(26) "Investment /MW"=1/1.5e+006
Units: MW/$

(27) Levelized natural gas=total cost*CF to kWh conversion*Levilized cost coefficient
Units: $/kWh

(28) Levilized cost coefficient=10
Units: Dmnl

(29) normal cost exp=1.34775e-005
Units: $/CF

(30) Percentage invest explor = WITH LOOKUP (Rel Res Prod Ratio,([(0,0)-(2,1)],(0.2,0.5),(0.4,0.5),(0.6,0.5),(0.8,0.48),(1,0.39),(1.2,0.24),(1.4,0.12),(1.6,0.05),(1.8,0.01),(2,0)))
Units: Dmnl

(31) potential usage rate=Init usage rate*EXP(growth constant*(Time-1900))
Units: CF/YR

(32) Price = WITH LOOKUP (Total capacity, ([(0,0)
(4.6527e+008,10)],(0,10),(10,0.33),(1900,0.1),(6100,0.079),(7600,0.076),(10200,0.073),(13600,0.07),(17400,0.067),(23900,0.064),(31100,0.062),(39431,0.059),(47620,0.057),(59091,0.055),(74052,0.053),(93823,0.051),(120791,0.048),(150988,0.047),(188735,0.045),(575976,0.037),(1.75774e+006,0.03),(4.99579e+006,0.032),(4.6527e+008,0.011)
))
Units: $/kWh

(33) price cost ratio=Ave well head price/total cost
Units: Dmnl

(34) Price to cost margin=0.85
Units: Dmnl

(35) proven reserves= INTEG (discovery rate-Usage rate,6.4e+012)
Units: CF

(36) Rel Res Prod Ratio=Res Prod Ratio/Des Res Prod Ratio
Units: Dmnl

(37) Res Prod Ratio=proven reserves/Ave Usage Rate
Units: YR

(38) Revenues=Price*Wind Consumption
Units: $

(39) Revenues to investment margin=0.05
Units: Dmnl

(40) sales revenue=Usage rate*Ave well head price
Units: $/YR

(41) SAVEPER = TIME STEP
Units: Year [0,2050]

The frequency with which output is stored.

(42) Time Change Ave Usage Rate=1
Units: YR

(43) TIME STEP = 0.002
Units: Year [0,2050]
The time step for the simulation.

(44) Total capacity= INTEG (+Annual capacity growth,1)
Units: MW

(45) total cost=costs of exploration*Cost Margin
Units: $/CF

(46) unproven reserves= INTEG (-discovery rate,1.28434e+015)
Units: CF

(47) Usage rate=Effect of wind in usage rate
Units: CF/YR

(48) Usage rate of natural gas=eff price demand*potential usage rate
Units: CF/YR

(49) Usage rate substituted=Wind Consumpion/CF to kWh conversion
Units: CF/YR

(50) Wind Consumpion=Effective market share*((potential usage rate)*CF to kWh conversion)
Units: kWh/YR

(51) "Year investments in R&D"=IF THEN ELSE(Gas to wind cost ratio<1, 1e+006, 0)
Units: