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How Abundant? Assessing the Estimates of Natural Gas Supply

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I. Introduction and Summary

One of the principal challenges of solving urban air pollution problems is to reduce the emissions created by electric power generation. Because electric power is generated 56% by coal and only 10% by natural gas, which has significantly fewer emissions, major reductions could potentially be achieved by shifting from coal to gas as a fuel source. The Environmental Law Institute (ELI) is therefore analyzing legal and economic factors, including an assessment of the cost and benefits, associated with increasing the use of natural gas for electric generation.

An important preliminary issue is whether an adequate supply of natural gas is available to make such a transition. Government data show that the United States has only nine years of "proved reserves" of natural gas and 60 years of "potential resources" at current usage rates. These figures have been advanced in policy debates to support the argument that - even if desirable - there is an inadequate supply of natural gas to allow its increased use for energy generation.

Because of the importance of this issue to the policy debate, ELI has reviewed the published government and industry reports to examine these figures and the assumptions behind them. ELI's review relies upon the data used by industry and government, but allows for more varied assumptions about the rate of technological advance. Five scenarios of future natural gas supply are presented below, based upon similar data, but differing assumptions of the rate of technical progress or price changes. Several of these scenarios indicate that in reality there are likely to be significantly greater supplies of natural gas than current projections.

The first three scenarios are based upon current trends and prices of natural gas, but differing assumptions of future technological progress. Scenario 1 limits technological advance to what is currently foreseeable, and Scenarios 2 and 3 are based on assumptions of continued technological progress coupled with growing geological information. Scenarios 2 and 3 also rely on government data that reveals very large in-place gas resources in tight sands and other "unconventional" sources. An examination of this data is highly relevant to future estimates of potential supply if robust technological progress is assumed, although it plays very little part in current government and industry estimates.

Table 1.
Current Estimates of Recoverable and Total Natural Gas Resources (1997; Tcf)

	US	Canada	World
Current annual consumption	23	3	43
Current proved reserves	160	113	5,086
Estimated recoverable resources	1,331*	888*	
Total coalbed methane	300**	3,500	
Total tight sands	6,600**	2,600	
Deep gas deposits	3,200	not est.	
Geopressurized aquifers	5,700	not est.	
Methane hydrates	200,000	not est.	

Sources: EIA 1998b, EIA 1998d; NPC 1992; NRC 1996; and tables below (*partial).

In addition to these scenarios based on estimations of future technological advance, predictions of future supply also need to take into account the price of gas and competing fuels. Although technological progress can result in lower costs and price, prices are also affected by demand and other public and economic policies. Two additional scenarios are therefore presented: one for lower gas prices due to lowered demand that restricts supply; and another for higher prices that would unlock additional domestic and international supplies of gas.

Finally, public and economic policy may also significantly affect gas supply issues. These range from issues such as decisions to close or open access to federal lands and waters, to tax treatment of exploration expenses, to new environmental laws that may create a preference for the use of gas or other low-emissions technologies for electric generation.

Scenario 1 (Official Estimates) represents a limited vision of technological growth as currently used in government and industry estimates. These forecasts are based on existing geological evidence and only the foreseeable extension of current technologies, generally to 2010 or so. These estimations of recoverable natural gas resources total 1,331 trillion cubic feet (Tcf) for the U.S. and 888 Tcf for Canada. Excluding the gas from Alaska and other frontier areas which is not yet marketable, these estimates indicate 60 years of supply at current rates. As these official estimates are based on limiting assumptions, they can be expected to grow in the future as more geologic information is gathered and as technology progresses.

Scenario 2 (Historical Trends) is an intermediate projection of technological progress based upon historical trends. As described below in Section III, official predictions of potential gas resources have gradually grown over the past decades, as additional geologic information and technological progress allow more gas to be deemed recoverable at current prices. Over the past thirty years, such growth has offset or made up for about 75% of the gas produced, and in the past decade has offset 100% as technology has progressed faster than the resource has been depleted. This scenario projects forward expected appreciation in resource estimates based on these historical trends, adding another 100 years to the potential supply.

Scenario 3 (Rapid Technology Growth) is based on a view that exploration and technology should be expected to advance at a reasonably rapid rate, as they have in the past decade. In this scenario, technological advance would be expected to gradually unlock the truly enormous gas resources that are known to exist in tight sands, coalbed methane and other unconventional sources, but are currently considered economically unrecoverable. As shown in Table 1, these resources are so large that they could be expected to allow natural gas to be used as an abundant energy source for centuries, provided either advances in technology or a rise in price allow their economic exploitation.

Scenario 4 (Low Prices): Significantly lower demand for gas leading to lower prices would not only restrict current supply, leading to the permanent plugging of wells, but could also restrain the geological exploration, drilling and technological advance needed to develop future supplies. Lower demand for gas could occur if environmental policies fail to reward low-emission fuels, and if prices from competing fuels continue to fall. If lower demand, or increased costs, leads to wellhead prices significantly lower than the current $2 per thousand cubic feet (Mcf), technology advance will be slowed, and supply may not even attain the levels referred to in Scenario 1.

Scenario 5 (High Prices): A rise in the price of delivered gas from the current $2 to $4 per Mcf would trigger major new supplies, both domestically and internationally. A price at or above $4 per Mcf would cover the production and transportation costs to allow liquefied natural gas to enter U.S. coastal markets, making accessible the large international reserves of gas (NPC 1992 at 215). In addition, the Department of Energy’s Energy Information Agency (EIA) estimates a $3.89 price would support development of the proposed Alaska Natural Gas Transportation System, making Alaskan reserves marketable (EIA 1998d at 228). Implementing this scenario would, however, require significant new investment to augment the existing receiving terminals for liquified gas, with a current capacity of 0.8 Tcf per year. In the long term, the availability of this international option places an upper bound on the price needed to assure a continuous supply of gas to U.S. sources for the next century.

This report concludes that the published government and industry reports of potential supplies of natural gas resources have serious weaknesses if used for public policy purposes, as they are based on restricted assumptions and significantly under-estimate the potential supply of natural gas that is likely to be available in the coming years. Energy policy needs to be based on more accurate predictions of future supply than are contained in such static assessments. Although this report does not attempt such a forecast, the above broad scenarios are evident from a review of the literature.

II. Scenario 1 - Official Estimates of Natural Gas Reserves and Resources

This section of the report analyzes published official reports of the proven and estimated potential natural gas resources for both the U.S. and Canada. This report distinguishes between resources that are readily accessible to U.S. markets from the lower 48 states and the Canadian Western Sedimentary Basin, versus resources in Alaska or the Canadian frontier that are remote and not yet readily available to markets in the continental U.S. The potential role of gas from these frontier areas is discussed separately in section C below.

The estimates of potential natural gas supply typically distinguish between natural gas *reserves* and natural gas *resources*:

"*Proved reserves*" are discovered natural gas deposits that are thought to be economically recoverable using current technology. The term reserves is used for investment purposes as well, and requires a very high reliability and certainty. Proved reserves are not an estimate of future supply, but are likened to "on-the-shelf-inventory" that can be drawn upon as needed (EIA 1998, app. G). There appear to be few economic reasons to justify proving reserves beyond a ten-year time horizon, and the inventory of proved reserves is expected to remain at an approximate 10 year supply, the industry norm for the past two decades. (NPC 1992 at 6). Because proved reserves represent the inventory of existing ready-to-market resources, they should not be confused with potential supply, discussed below. When reserves are withdrawn for production, they are expected to be replaced by further additions from the resource base.

"*Natural gas resources*" is an inclusive term that can be applied broadly to denote all natural gas that presently exists, also referred to as "gas in place," or more narrowly to denote subsets of the total resource base, such as "recoverable" resources. It is important to note that virtually all published estimations of gas supply include only that part of the estimated in-place resource that is believed to be both technically and economically recoverable.

Resources that have been discovered and are considered "recoverable" either have already been produced, or else remain in place awaiting production, in which case they become "reserves." Potentially recoverable resources are however far greater than proved reserves, and consist both of undiscovered resources and discovered resources that are not yet economical to produce. Many of the so-called "unconventional" gas resources such as coalbed methane, tight gas, and gas in deep deposits and geopressurized aquifers fall in the latter category, as they are known to exist but are not considered economical to exploit. The essential tasks in making estimates of future gas supply are in estimating the size of the total gas resources, and what portion will become economically and technically recoverable in the future.

In the U.S., estimates of recoverable gas resources are made by the Energy Information Agency (EIA) of the U.S. Department of Energy, which includes data provided by the United States Geological Survey (USGS), and private groups including the Potential Gas Committee (PGC) of the Colorado School of Mines and the National Petroleum Council (NPC), a federal advisory committee. All estimates of the future supply of natural gas are based on several key factors, notably the estimated price of gas and progress in technologies for gas exploration and production. Although these are difficult to predict, estimates must be made for accurate assessments. The following chart from the National Petroleum Council shows how assumptions about technologies and prices will greatly affect estimates of recoverable resources.

Table 2.
Influence of Technology and Price in Estimating Recoverable Gas Resources

Price (1990$)	1990 technology	2010 technology
unspecified	1,065 Tcf	1,295 Tcf
$3.50 / mmBtu	600 Tcf	825 Tcf
$2.50 / mmBtu	400 Tcf	600 Tcf

Source: NPC 1992 at 5.

In general, current estimates of potential recoverable resources are based on "adequate economic incentives...and current or foreseeable technologies" (PGC 1997 at 10; see also EIA 1998a at 126). These estimates also limit their consideration to gas deposits found above certain depths, generally 30,000 feet on land and 1000 meters in marine areas other than the Gulf of Mexico (PGC 1997 at 9). These represent depths at which gas can be economically recovered with current technologies. Typically estimates also distinguish between conventional resources and unconventional ones, such as coalbed methane and gas in tight sands. Projections of additions to conventional resources consist of revised productivity estimates for existing gas fields, labeled "reserve growth" or "probable resources," and projected discoveries of new fields. Projected additions from unconventional resources depend on assumptions of foreseeable economic and technological trends that would allow their exploitation.

The estimates of future supply made by these groups are generally similar. EIA estimates the total recoverable natural gas resource in the U.S. to be 1,331 Tcf, intermediate between estimates by the Potential Gas Committee of 1,039 Tcf and the National Petroleum Council of 1,484 Tcf. Natural Resources Canada (NRC) estimates Canadian recoverable gas resources to vary between 888 Tcf and 3,238 Tcf, with the difference depending on potential resources of coalbed methane. Other Canadian forecasts tend to be below this estimate. Excluding Alaska and Canadian frontier areas yields official estimates of 1,174 Tcf for the U.S. and 593 Tcf for Canada, giving a total estimated resource of 1,767 Tcf.[1] These recoverable resources are enough to provide almost 60 years of supply for a projected combined U.S. and Canadian demand of 30 Tcf in 2010.

Table 3.
Total Estimated U.S. and Canadian Natural Gas Reserves and Resources (Tcf)

Lower 48/ Canadian non-frontier	**US (1997)**	**Canada (1996)**	**Total**
Proved reserves	157	88	244
Unproved "conventional" resource	659	255	914
Unproved "unconventional" resource	358	250-2600	608-2958

[1] Mexico's gas resources are not considered because they are expected to be used to meet domestic demand within Mexico. EIA 1998d at 71.

Lower 48/ Canadian non-frontier	US (1997)	Canada (1996)	Total
Coalbed methane	50	250-2600	300-2650
Tight gas	308	not est.	308
Subtotal	1,174	593-2943	1767-4117
Alaska/ Canadian frontier			
Proved Reserves	11	25	36
Unproved "conventional" resource	227	270	497
Deduction for reserve changes 1991-97	-81	--	-81
Total potential resource	1331 Tcf	888-3238 Tcf	2219-4569 Tcf

Sources: EIA, 1998b, Table G1; NRC 1996, Chart 4.3; NPC 1992.

A. U.S. Natural Gas Reserves and Resources

Proved reserves in the United States totaled 167 Tcf in 1997, or about 9 times the annual U.S. production level in 1997. (EIA 1997). The EIA reserve figures are consistent with the estimates used in a 1992 study conducted by the National Petroleum Council and a 1996 study by the Potential Gas Committee of the Colorado School of Mines (See Appendix Table A-1). As noted above, proved reserves are equivalent to current discovered inventory, and are not to be confused with potential supply.

Potential gas resources in the United States are far greater than proved reserves. EIA estimates the total unproved but technically recoverable resources in the lower 48 states to be 1174 Tcf, or just over 60 times the 1997 U.S. production level (EIA 1998a, app. G). The EIA estimate is intermediate between the estimate of 1,295 Tcf by the NPC and 887 by the PGC.

B. Canadian Natural Gas Reserves and Resources

Canada's large natural gas resources represent a major source of supply for U.S. demand, as its current and potential supply exceeds its domestic demand. Canada currently produces 6.3 Tcf of natural gas annually. Of this, 2.5 Tcf, or less than half, is consumed in Canada, while 2.8 Tcf is exported to the United States and 1Tcf represents surplus capacity. Official projections from Natural Resources Canada anticipate that production will rise to 7.6 Tcf in 2010 and 7.7 Tcf in 2020, primarily to provide rising exports to the United States. Planned new pipelines to the U.S. include 255 Bcf/day into Chicago from Canada's major producing region, the Western Sedimentary Basin, and 325 Bcf/day from Sable Island fields to New England. Canada's surplus capacity of approximately 1 Tcf is predicted to last through 2020.

Table 4.
Canadian Natural Gas Production and Exports (Tcf)

Year	1995	2000	2010	2020
Domestic consumption	2.5	2.7	2.9	3.2
Exports	2.8	3.1	3.5	3.7
Surplus capacity	1.0	0.7	1.2	0.8
Total production	6.3	6.5	7.6	7.7

Source: Natural Resources Canada, *Canada's Energy Outlook, 1996-2020,* p. 47, Chart 4.11.

Canada's proved reserves and predicted recoverable gas resources are large, and approach those of the U.S. Reserves are estimated by Natural Resources Canada to be 88 Tcf in the Western basin, with another 25 Tcf located in the Canadian frontier that is not currently accessible to potential markets. NRC estimates potential gas resources to be 888 Tcf, comprising 323 Tcf of conventional resources in the Western Sedimentary Basin, another 295 Tcf in the frontier, and at least 270 Tcf of unconventional resources. These figures are slightly higher than the estimates by NPC and Canadian Gas Potential Committee (CGPC), due largely to higher estimates of gas recoverable from coalbed methane (See Appendix Table A-2).

C. Alaska and Canadian Frontier Areas

As can be seen from Table 3, Alaska and Canadian frontier areas hold significant gas resources - 36 Tcf in proved reserves and 497 Tcf in estimated recoverable resources.

However, the expense of transporting the gas from these areas makes it infeasible to market it in the mainland United States. In Alaska, the gas is instead consumed within the state, reinjected to support oil production, or liquefied and exported to Japan (EIA 1998d, p. 71).

These frontier resources could become marketable given an adequate rise in price, or technological advances that are not now foreseeable. In Alaska, for example, EIA estimates that "the Alaska Natural Gas Transportation System is assumed to come on line no earlier than 2005 and only after the U.S.-Canada border price reaches $3.89" (EIA 1998d at 228).

D. Overseas Supplies

Although the United States has rich natural gas resources, even more exist overseas, with almost 75% of the world's proved reserves in Russia and the Middle East (EIA 1998b). However, the low energy density of natural gas makes it prohibitively costly to transport gas from overseas unless it is liquified at a temperature of -260 degrees Fahrenheit, concentrating it 600 fold and allowing ship transport. This process is costly, so a price of at least $4 per Mcf, or major technological advances, is needed to cover the production and transportation costs to allow liquefied natural gas (LNG) to enter U.S. coastal markets. (NPC1992b at 215).

Implementing this scenario would, however, require very significant new infrastructure investment, both in the exporting country and in the United States. Only four terminals exist to receive LNG in the U.S., two of which have been idle since 1980, with a combined capacity of only 0.794 Tcf per year. (EIA 1998d; NPC 1992b) However, in the long term, the availability of this international option places an upper bound on the price needed to assure a continuous supply of gas to U.S. sources for the next century.

III. Scenario 2 - Historical Increases in Resource Estimates Indicate a More Realistic Estimate of 100-200 Years of Supply

A. Historical Increases in Estimates of Proven and Potential Gas Resources

Estimates of the future supply of natural gas have not been static over past years. That is because government and industry estimates of potentially recoverable resources are based on current or foreseeable technologies and existing geologic information

(PGC 1997 at 10; see also EIA 1998a at 126). As a result, these estimates have been generally revised upwards each year to reflect advancing technologies and increased geologic information. This trend has been particularly evident in the past 15 years, as despite significant production, technological advances have led to a net increase in the estimates of reserves believed to be potentially recoverable.

Table 5.
Changing Estimates of Recoverable Gas in the United States, 1966-1996 (Tcf)

	Proved Reserves +	Potential Resources =	Future Supply	Cumulative Production
1966	286	690	976	300
1976	181	723	904	514
1986	159	620	779	693
1996	157	673	830	870

Source: PGC 1997, Table 9.

The table reveals that there has been a consistent growth in estimated supply over the past thirty years that has almost equaled annual production. As a consequence of technological advances and further exploration, the estimates of the future supply (proved plus potential resources) have only shrunk 146 Tcf during this period, or 4.8 Tcf per year, despite gas production of 570 Tcf, or 19 Tcf per year. Indeed, in the past decade since gas prices were fully deregulated, the estimated future supply of natural gas has actually increased, not decreased, from 779 Tcf in 1986 to 830 Tcf in 1996. Projecting forward such trends would imply that we have almost 170 years of actual natural gas supply at current demand levels.

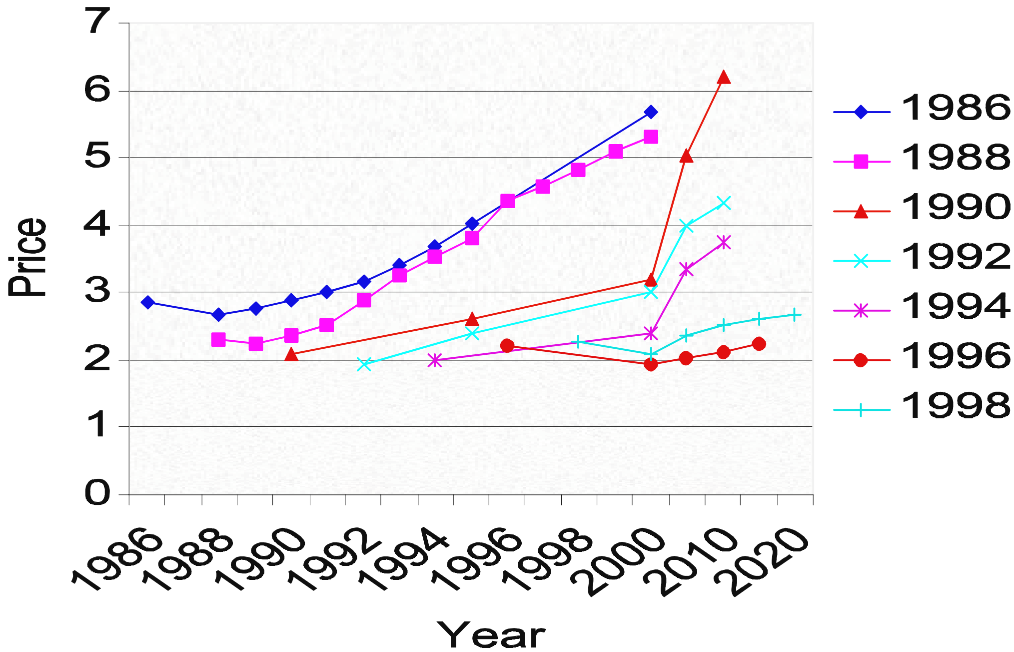
The same phenomenon is apparent in Canada: "Recent history shows a tendency for the potential to be revised upwards over time as new information becomes available and technologies improve....For example, the estimates of the Alberta Energy and Utilities Board ... have increased by 250% over the estimates made in the 1960s and 70s" (NRC 1996 at 42).

This history, and an analysis of the assumptions underlying the estimates, reveal that current estimates of future supply are more like snapshots for a given year based on current technologies and information, and in reality should be expected to grow over time. The actual evidence from past years confirms such growth, both in projections of recoverable resources, and in the steady reductions in forecasts of the prices at which a given supply would be available. Projecting forward such trends indicates that another 100-200 years of supply are foreseeable.

B. Prices and Supply

A similar trend is apparent if one views estimates of price over the past two decades, shown in the figure below. Although dramatically rising prices were typically forecast so as to elicit an adequate supply, in fact the actual wellhead price of gas has remained relatively constant or declined over that time: since 1980, the price of natural gas has fluctuated around $2 per thousand cubic feet, with a high of $2.68 in 1984 and a low of $1.55 in 1995. The graph shows that the gas industry has been able to provide steadily increasing supplies of gas at relatively constant prices. This is due in significant part to technological advances that have allowed the economical recovery of an increasing share of gas resources.

Figure 1. Natural Gas Wellhead Price forecasts, 1986-1998 ($ per thousand cubic feet)



Source: EIA Annual Energy Outlook (1987-1999).

In addition to technology advance, economic factors are also expected to moderate future price fluctuations. In general, gas prices would need to cover the resource cost of new nonassociated gas supply, which has ranged between $1.75 and

$2.05 in this decade (INGAAF, 1999). However, the multi-sector nature of natural gas demand is expected to moderate prices even if more gas is used for electricity generation.. Since gas demand is divided between residential (23%), commercial (15%), industrial (44%) and electric generation (15%), rising demand in one area is countered by the need to keep prices low to retain demand in others. The multi-sectoral nature of gas demand is expected to continue to moderate rises in natural gas prices, raising the possibility that increased supply may be accompanied by relatively stable prices.

C. Reasons for the Increasing Estimates

There are several recognized reasons for the steadily increasing estimates of total natural gas resources in the lower 48 states. One is rapid rate of technological advance, which has allowed exploitation of gas in areas once considered unrecoverable, such as coalbed methane and deepwater gas fields, and reduced the costs of exploitation to allow more gas to be considered economically recoverable. A second has been the conservative assumptions made in estimation protocols, which place limits not only on the nature of technological advance, but also the nature of the gas deposits considered in the estimates by factors such as their depth and permeability. A third significant factor has been growing geological information. A significant issue here is Ultimate Recovery Appreciation, or the tendency for predictions of the ultimate recovery of gas in conventional fields to increase substantially over time as more geological information is obtained. Although projections of ultimate recovery appreciation are included in estimates, these have historically been too conservative, and hence have been steadily revised upwards.

Some authors "attribute much of the debate between resource economists (the ‘optimists’) and physical scientists (the ‘pessimists’) over the quantity of ultimately recoverable resources to assumptions about the relative effects of technical progress versus depletion" (Fagan 1997, citing Cleveland and Kaufman 1991). Technical progress extends estimates of ultimately recoverable resources, countering the tendency of ongoing exploration and development to deplete the resource base. In general, in the past few decades, technological progress has substantially mitigated the effects of depletion to allow steadily increasing estimates of recoverable resources.

However, pessimists point out that the effects of depletion are inevitable, and argue that because the larger and more accessible reserves are discovered first, a gradually escalating level of effort is required to discover and exploit smaller and smaller fields. Others note that even estimates of reserves can be overstated by companies attempting to inflate their resource asset base. (Campbell, 1998). One study comparing natural gas resource depletion and technological change "explicitly test[s] and reject[s] the hypothesis that technological change has arrested or reversed the long-run decline in yield-per-effort". (Cleveland and Kaufman, 1997). This study "indicates that the net effect of depletion and innovation on yield-per-effort is stable for the last 50 years." They find an exponential decline in yield-per-effort for discoveries, which has been offset only by consistent appreciation in the ultimate recovery from existing fields, an issue treated below.

1) Technological Progress

Technological advances have expanded the recoverability of gas resources by opening new areas to exploitation and by reducing exploration and production costs.

Examples of new areas include deepwater resources and coalbed methane. Formerly, estimates of potential resources only included offshore fields at depths less than one thousand meters. This barrier was overcome in the 1980s, and economic wells are now operating at 5,000 feet in the Gulf of Mexico, allowing estimates to be raised. Similarly, advances in extracting gas from coalbeds have allowed gas from this source to be added to potential U.S. resources in 1988. According to a study by ICF Kaiser:

> New technologies in exploration and development aided in making more gas technically and economically recoverable in territories that were previously thought to be infeasible, such as the Deepwater Gulf of Mexico. These technologies, such as 3-D seismic and horizontal well drilling, are currently making gas recovery more efficient, and have made a major contribution to the growth of the gas resource in the U.S.... Another key participant in the recent growth of resources is the unconventional resource. In the past decade, the PGC potential resource for coalbed methane has increased over 60%, helping the ultimate resource grow 300 Tcf over the same period. ICF 1998 at 15.

The renewed interest in deep water areas is credited to better technology. Computers are now used to process geological and geophysical data and to create three-dimensional subsurface interpretations. This has improved exploratory success rates and made high-cost exploration, such as as that in deep water, economically feasible. Developments in extended-reach or horizontal drilling in the last 5 years have led to higher production rates and greater recoveries from both new and existing wells. Aside from the ability to increase recovery in borderline fields and protect environmentally sensitive areas, these wells can also provide geological information for sidelong distances of up to 5,000 feet in a single formation. (MMS 1998).

Many of the same technologies have also reduced the costs of exploration and development. Technology advances, for example, have reduced drilling costs 3% per year for the past two decades. (NPCa 1992 at 7). A study of technological change in oil costs found that "the reduction in finding costs in the United States is widely credited to application of state-of-the-art knowledge in computer technology, geophysics, and drilling" (Fagan 1997 at 92). This author found that despite the decline in oil exploration and development spending from approximately $28 billion to $5 billion between 1981 and 1994, technology drove an almost parallel reduction in the finding cost from an average of $28 to $6 per barrel. The author also documented an accelerating effect of technological change on finding cost, from 5% annual savings in the mid-80s, to 12% in the early 90s.

An interesting finding is that rapid technological change in areas such as information and communication technologies has had a considerable impact on hydrocarbon exploration and development costs. Computer graphics advances are mentioned above. In addition, advances in information technologies have allowed offshore platforms to be located more precisely, reducing costs of construction, and advances in communications technologies have reduced the amount of personnel needed to attend offshore platforms, reducing costs of operation. (Faber 1997 at 94).

2) Conservative Forecasting Assumptions

A fundamental reason why estimates of recoverable resources have consistently increased is that they are based on assumptions or boundaries that are necessarily conservative, and have been consistently surpassed by technological advances. Perhaps one reason for such conservatism is the influence of conservative accounting conventions governing how a firm can characterize its reserves and resources in order to protect investors, and which may influence assessments that are made for policy-oriented purposes.

Overall, perhaps the most important such boundary is that of basing forecasts on current or foreseeable technologies, which confines technology advances to a limited number of years. For example, 1997 estimations are generally based on foreseeable advances to 2010. This is necessarily conservative, as technology will no doubt advance after that point. Also, no estimates attempt to take account of unpredictable major technological advances, yet these also can be expected to occur, not only in gas technology, but also in information, communications and other rapidly developing fields, leading to lower costs and greater recoverability.

Conservative assumptions are also reflected in a number of boundary conditions that exclude certain gas deposits from estimates. Once technology overcomes the boundary, these deposits are then added to estimates. One such condition is drilling depth: most estimates do not include gas that exists at depths more than 30,000 feet, or where water depths exceed 1,000 meters (3,280 feet) except in the Gulf of Mexico (PGC 1997 at 9). Formerly, estimators excluded all water depths below 1,000 meters, until wells in the Gulf broke the 1,000 meter barrier, and are now at depths over 5,000 feet. Other boundary conditions include the minimum and maximum limits on permeability, gas content and seam thickness in estimating coalbed methane, the porosity of substrates in which "tight gas" may be extracted, and the like. Another such condition is that gas in tight sands or coalbed methane in Alaskan or Canadian frontier areas is simply not included in national estimates. As increasing geologic information becomes available, and technology advances, these conditions change, adding resources to the estimates.

3) Incomplete Geological Information

A third issue leading to conservative estimates is the role of incomplete geologic information. This is especially notable with respect to Ultimate Recovery Appreciation (URA), an important element in predicting future gas supply. URA refers to the phenomenon that predictions of the volumes of gas in conventional fields increase substantially over time.

Historically, extensions of existing fields have contributed significantly more to the growth in natural gas reserves than the contributions from newly discovered fields or pools, and is expected to do so into the future (USGS 1996). A retrospective analysis by Cleveland and Kaufman shows that the ultimate recovery from a field has been 3.5 times the original estimate made in the discovery year based on data through 1965, has been 4.4 times based on data through 1978, and 10 times estimates based on data through the 1990s (Cleveland and Kaufman, 1997). Growth through URA has therefore been a significant factor contributing to reserve additions that have almost equaled the annual withdrawal through production in the past decades, as shown above in Table 5.

It is, however, extremely difficult to predict the future of URA. According to a recent article in EIA’s Natural Gas Monthly:

> The historical record regarding ultimate recovery appreciation shows that the estimate of ultimate recovery appreciates over time for most reservoirs, the vast majority of fields, all regions, all countries and the world. First publically noted in 1960, it is a major source of both current and expected future oils and gas supplies....
>
> Despite its recognized importance to current domestic oil and gas supply, and its even greater apparent importance to future domestic oil and gas supply, the URA phenomenon is not well understood, and therefore cannot be reliably forecast... For that reason, the USGS considers analysis of URA "arguably the most significant research problem in the field of hydrocarbon resources assessment." Morehouse, 1997 at vii, x.

The first attempts to address URA were to draw inferences by analogy to the known past appreciation of similar reservoirs. Currently, EIA and USGS rely on more sophisticated models that are based on field-by-field data that became available in 1990. However, while this can reliably predict the URA behavior for the 86% of normally behaving fields, the URA paths of the remaining class of outlier fields "show no signs of approaching an upper bound ... [and] account for the bulk of URA activity." This behavior confounds the predictive capability of the model, and leads to conservative estimates of these fields, introducing a consistent conservative bias into estimation techniques (Morehouse, 1997 at xv).

In sum, several factors can be shown to be at work in causing resource appreciation under current estimating methods. One is the lack of adequate geotechnical information, as it is difficult to predict resources without adequate information upon which to base inferences. Increased exploration increases geologic information, which allows further resources to be estimated. Another factor is the systematic effect of conservative procedures in estimating resource supply. Perhaps most important is the unpredictable nature of technological progress, which has tended to be underestimated. If the historical trends in all these factors continue, they would indicate that significantly greater supplies of gas than predicted in current estimates are likely.

IV. Scenario 3 - Technological advances may allow exploitation of the vast amounts of gas currently considered technically or economically unrecoverable

In addition to estimating unproven conventional gas resources, analysts also estimate the amount of gas available from "unconventional" resources, or those in which gas does not occur in discrete reservoirs of limited area. It is generally uneconomical today to extract gas from such sources, and emerging technologies that may do so are just beginning to become viable. However, gas from these sources is expected to play an increasing role in overall supply, as the demand for natural gas increases and extraction technology improves. Indeed, technology, rather than prospecting and exploration, is the main constraint on future development of many unconventional resources. The NPC notes that "[t]here is actually less uncertainty involved with the non-conventional resource compared to the undiscovered conventional resource in the sense that the locations of the non-conventional resource are relatively well known.... However, the level of recoverability is much more uncertain due to a higher dependence on the deployment of extraction technology" (NPC 1992). Technologies allowing recovery of unconventional resources could extend U.S. gas supplies for hundreds of years.

At present, the two most important types of unconventional resources are coalbed methane and so-called "tight" gas extracted from low-permeability geological formations. Other promising but more long-range technologies involve extraction of natural gas from deep zones, geopressurized aquifers, and from methane hydrates, resources that are currently unrecoverable. Gas from each of these sources would significantly add to U.S. supplies, in some cases multiplying it many-fold. Indeed, the most speculative of these resources, methane trapped in hydrates, could add 200,000 Tcf to U.S. resources – over a hundred times the currently recoverable resource base.

A. Coalbed Methane

Coalbed methane is natural gas contained within the coal bed itself, as opposed to gas that is associated with coal formation but contained in adjacent reservoirs and analyzed as conventional gas (PGC 1996). Historically diluted or vented as a hazard to coal-mining operations, over the past decade coalbed methane has gained importance as a resource in its own right, spurred in part by U.S. federal tax credits for development of unconventional gas resources. In-place resources for selected basins in the U.S. are estimated at 300 Tcf, excluding Alaska (NPC 1992); in Canada NRC estimates there are up to 2500 Tcf of coalbed methane resources in place (NRC 1996), of which CGPC considers 135-261 Tcf to be recoverable.

As described above, coalbed methane is already considered a viable productive resource, with over 11 Tcf of coalbed gas presently included in U.S. proved reserves and 20 Tcf in Canadian proved reserves. The EIA estimates an additional technically recoverable coalbed resource of 50 Tcf in the continental U.S. (Table 3), and the PGC estimate adds another 59 Tcf from Alaska. On one hand, the PGC notes much of its estimate is "speculative," or predicted to be recoverable from coal groups with no established production. On the other hand, advances in extraction technology could dramatically increase future estimates. "New technology may substantially change both the amount of coalbed methane that is recognized and the percentage that is deemed recoverable" (CGPC 1997 at 74).

In Canada, as in the U.S., coalbed gas has the potential to make up a significant portion of natural gas supply in the future. Available estimates of Canada’s unconventional resources vary widely, which is largely a reflection of the need for further geological exploration and analysis, especially in frontier areas. Natural Resources Canada estimates a potential coalbed resource of anywhere between 250 and 2600 Tcf (Table 7). In comparison, the Canadian Gas Potential Committee’s estimate is from 304-543 Tcf, and represents their attempt at a "realistic resource estimate" that considers coal deposits only within certain parameters of depth, permeability, gas content, and thickness to determine technical and economic recoverability (CGPC 1997). However, the same study also acknowledges that estimates of the total coalbed methane resource in place range as high as 3000 Tcf in Alberta alone (CPGC 1997 at 73). The National Energy Board estimate is the most conservative at 50 Tcf, as the Board emphasizes cost uncertainty and only measures the most readily accessible sources.

B. Tight Gas/Shale Gas

A second, and less-developed unconventional resource is natural gas extracted from sandstones, shales, and chalks that have low permeability, making it difficult for the gas to flow through the formation to the well, and referred to as "tight" gas.[2] Tight gas is derived from rock formations with organic content, such the Devonian shale belt

[2] FERC defines tight gas as that in reservoirs characterized by an average rock permeability to gas ratio of 0.1 millidarcy or less, and, absent artificial stimulation of production, by production rates that do not exceed certain specific daily volumes of gas. 18 CFR 271.703.

in the Appalachian region or several other hard, low-permeability sandstone formations throughout the U.S. The advent of hydraulic fracturing techniques in the 1940s and subsequent advances, as well as tax credits, have made it possible for tight gas to be produced economically (NPC 1992 at 34). Currently, production is around 2 Tcf annually.

Although the U.S. has vast amounts of tight gas, there are varied estimates of the economic recoverability of these resources. The EIA estimates a technically recoverable U.S. tight gas resource of 308 Tcf in the lower 48 states, while the NPC estimates 349 Tcf. Both studies emphasize that the presently recoverable resource is a fraction of the tight gas in place that may become recoverable. For example, the NPC estimate for tight gas only considered formations under development or expected to be developed between 1990 and 2010, while EIA notes that "only a small portion of the in-place continuous-type resource accumulations are estimated to be technically recoverable now" (EIA 1998a, app. G).

Since 1977, the USGS, with support from the Department of Energy, has engaged in assessing the in-place gas resources of tight-gas sands in Rocky Mountain basins, including the Bighorn, Greater Green River, Piceance, Uinta and Wind River basins. To date, these have documented over 6,000 Tcf of in-place gas in these tight sands:

Table 6. Estimates of In-place Gas in Tight Sands

	Estimate (Tcf)	Source
Bighorn Basin	forthcoming	Johnson et al. 1999
Green River Basin	5,063	Law et al. 1989.
Piceance Basin	423	Johnson et al. 1987.
Wind River Basin	995	Johnson et al. 1996b
Appalachian	163 (partial)	Law et al. 1993

The interplay of economic and technological considerations can be seen in estimates of the potentially recoverable tight gas resources in the Green River Basin. In 1990, the USGS estimated that using current technology and a price of $5 per Mcf, 27 to 148 Tcf was recoverable (USGS 1990 at 77). By 1995, technological advances had been such that the authors considered a significantly greater amount of gas, 56 to 213 Tcf, to be both technically and economically recoverable (USGS, 1995). Both economics and technology advances will significantly determine the amount of tight sands resources that will become recoverable, including the availability of tax and other incentives.[3]

Published estimates of the Canadian tight gas resource vary greatly. The NPC conducted the only study of recoverable tight gas in Canada, and estimated a recoverable resource of 89 Tcf. The CGPC's study does not estimate tight gas resources, but does cite earlier studies: a 1992 estimate by the Alberta Energy Resources Conservation Board, which found a potential tight gas resource of between 175 and 1500 Tcf of gas in place in that province; and a 1984 case study published by the American Association of Petroleum Geologists, which estimated 3500 Tcf of tight gas in place in the Deep Basin of Alberta and British Columbia (CGPC 1997 at 74, citing Masters, 1984). Again, this is an area where further geological data and analysis are needed, particularly for the Canadian frontier.

C. Deep Gas Deposits and Gas from Geopressurized Aquifers

Two additional very large speculative sources of supply are gas from deep deposits and geopressurized aquifers, totaling an estimated 3,200 Tcf and 5,700 Tcf respectively.

Deep gas deposits are trapped in sedimentary basins, which reach maximum depths of 30,000 to 45,000 feet in the United States. Despite high temperatures and pressure at these depths, methane is still in a stable phase. Although only a small fraction of deep sediments have been explored, very large gas resources have already been identified at depths in the 14,000 to 22,000 foot range. Estimates of these speculative deep gas resources in the United States show nearly 3,200 Tcf of methane. (NPC 1992b at 138). Because drilling costs have historically increased at roughly the square of well depth, new technology will be required to recover such resources.

A second abundant but speculative gas resource is that in aquifers. Under pressurized conditions, gas exists in brines at depths of 8,000-9,000 feet. The USGS has estimated 5,700 Tcf of methane in deep aquifers. (NPC 1998b at 139). However, the low energy density of the brines and the environmental problems of brine disposal delay any near-term use of this resource.

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[3] The Federal government has provided economic incentives for the exploration and development of tight gas. From 1980-88 and 1990-92, a tax credit of 51 cents per mmBtu was made available for the production of tight gas under section 29 of the Crude Oil Windfall Profits Tax Act of 1980, and an incentive price set in section 107 of the Natural Gas Policy Act of 1978.

D. Methane Hydrates

Within the last decade, research has shown that most continental margins are reservoirs for immense amounts of gas that are concentrated in frozen, icelike gas hydrates. These exist within the top several hundred meters of sediment in deep water on the continental margins, including those of the United States from the Gulf of Mexico to the Alaskan arctic. The worldwide amount of methane in gas hydrate deposits is conservatively estimated to be the equivalent of 10,000 gigatons of carbon, or about twice the amount of carbon held in all conventional fossil fuels on earth. Gas hydrates may prove to be the only hydrocarbon resource that could significantly affect the future world energy mix. The production history of the Russian Messoyakha gas hydrate field demonstrates that gas hydrates can be produced by conventional methods. Gas from hydrate deposits may become a major energy resource if economically profitable techniques are devised to extract the methane (MMS 1998).

In 1995, the USGS completed an assessment of U.S. gas hydrate resources, refined in 1997 using information from the Ocean Drilling Program. The USGS estimates the in-place gas resource within the gas hydrates of the United States to be in the range of 200,000 Tcf -- larger by several orders of magnitude than previously thought and dwarfing the current estimates of 1,330 Tcf of recoverable gas resources in the United States. The scale of these estimates was recently confirmed by a more detailed study of the hydrate resources of northern Alaska (Collet, 1997). If only 1 percent of the methane hydrate resource could be made technically and economically recoverable, the United States could more than double its domestic natural gas resource base.

The U.S. Department of Energy has launched an initiative to evaluate the production potential of methane hydrates in U.S. coastal waters and world-wide, under its "Strategy for Methane Hydrate Research and Development" issued in August 1998. Bills have also been introduced in Congress to support methane hydrate research and development. These programs will help to document and field test techniques such as depressurization, thermal processes, and solvent injection, and also addresses stability and safety concerns.

V. Conclusion

This paper presents scenarios of future supply of natural gas based on government and industry data and estimates, but using a more varied set of assumptions regarding technological progress. Which scenario is most likely to emerge?

Scenario 1, equivalent to current government and industry estimates, is based on existing geological information and limits technological progress to what is currently foreseeable; it indicates a 60 year supply of gas at the expected demand level of 30 Tcf per year in 2010. However, if exploration and technological advance are assumed to continue, this is an underestimate that would be expected to grow over time. Scenario 2 is based on historical trends over the past few decades, in which the steady march of technological progress coupled with growing geological information has fueled a steadily upward trend in estimates of the recoverable gas resources in the lower 48 states and Canada. These trends indicate that it is reasonable to assume that there may be 100-200 years of supply.

Scenario 3 projects forward the rapid technological improvements in exploration and extraction, as well as in unrelated fields such as communications and information technologies, that have steadily reduced the cost of recovering gas from conventional and unconventional resources in recent years. This makes it distinctly possible that in the decades to come, as conventional resources are depleted, there will be significantly increased recoverability from the vast in-place unconventional gas resources, adding hundreds more years to supply.

Prices and policies are also shown to affect the future supply of gas. Scenario 4 indicates that significantly lower demand could reduce prices and restrain the geological exploration and technological advance needed to develop future supplies. This could come about if environmental policies fail to reward the use of gas and other low-emitting fuels. However, Scenario 5 indicates that higher prices would foster greater supplies of gas, and a price of $4 per Mcf would trigger major new international supplies that place an upper limit on the price needed to assure a continuous supply of gas to U.S. sources for the next century.

This review indicates that current government and industry estimates are based on limiting assumptions of technology advance, and significantly under-estimate the potential supply of natural gas that is likely to be available in the coming years. These estimates should be expected to grow in the future with increased geologic information and technical progress. In addition, policies that reward efficiency and the use of cleaner fuels would contribute significantly to prompting the technological advances that would assure a stable supply of natural gas.

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Appendices

APPENDIX A

Table A-1.
Comparative Estimates of U.S. Natural Gas Reserves and Resources (Tcf)

Lower 48 States	**EIA 1997**	**NPC 1992**	**PGC 1996**
Proved Reserves	157*	160	157
Potential "conventional" resource	659	616	598
Reserve growth	328	203	158
New fields	332	413	440
Potential "unconventional" resource	358	519	132
Coalbed methane	50	98	132
Tight gas	308	349	
Other		72	
Subtotal	1,173	1,295	887
Alaska			
Proved Reserves	9	9	9
Potential "conventional" resource	227	180	143
Deduction for production 1991-96	-80	--	-80
Total recoverable resource	1,331 Tcf	1,484 Tcf	1,039 Tcf

*Includes 10.6 Tcf proved reserves of coalbed methane.

Sources: EIA, 1998a; National Petroleum Council, 1992; Potential Gas Committee, 1996.

Table A-2.
Estimates of Canadian Natural Gas Reserves and Resources (Tcf)

	NRC 1996	NEB 1999	CGPC 1997
Proved reserves	113	95	106
Western Sedimentary Basin	68	57	62
Frontier	25	38	44
Coalbed methane	20		
Unproved "conventional" resource	525	472	187 (partial)
Western Sedimentary Basin	255	176	124
Frontier	270	296	63 (partial)
Unproved "unconventional" resource	250-2600	50	135-261
Coalbed methane	250-2600	50	135-261
Tight gas / shale gas	ne	ne	ne
Total potential resource	888-3238 Tcf	687 Tcf	428-554 Tcf (partial)

Sources: Natural Resources Canada, *Canada's Energy Outlook, 1996-2020*, p. 42, Chart 4.3; National Energy Board, *Canadian Energy - Supply and Demand to 2025* (Draft of January 1999); Canadian Gas Potential Committee, *Natural Gas Potential in Canada* pp. 1-5 (1997).

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