[Regular Paper]

Evaluation on the Life of World's Natural Gas Supplies

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Utilization of natural gas as a primary source of energy has been increasing steadily. It constituted about 22.7% of the primary energy consumed by the world in 1991. In this paper the life of world natural gas reserves is evaluated in relationship to the rate of their consumption. An algorithm is used to calculate the rate of consumption and the life of these reserves as a function of annual growth rate of gas consumption. If the future rate of consumption is kept constant at the level of 1991, *i.e.*, zero annual growth rate, the gas reserves will last for about 62 years. The same reserves will last for only 34 and 28 years for annual growth rates of 3.33% and 5.0%, respectively. Increase in the amount of reserves will only increase its life slightly at high annual growth rates. On the other hand, natural gas reserves can last indefinitely if world annual growth rate is -1.63% or lower.

1. Introduction

World consumption of natural gas has been increasing steadily in the past. Its share of world energy market has been continuously growing. **Figure 1** shows the makeup of the primary energy consumed by the world in 1991¹⁾. Natural gas constituted about 22.7% of this energy. Although the overall growth rate of energy demand slowed down in the past decade, the demand for natural gas grew steadily. **Figure 2** shows the world annual gas production in the 80's. The production rose exponentially at the rate of 3.33% per year.

The rate of extraction of a mineral as a function of time is given by Eq. (1)^{2),3)}:

$$r(t) = r_0 e^{kt} \quad (1)$$

where:

r_0 = rate of extraction at $t = 0$.

k = fractional growth rate of extraction per unit

time.
 t = time.

The amount of the reserve is calculated by integrating Eq. (1) from time zero to abandonment time λ_a ³⁾:

$$R = \int_0^{\lambda_a} r(t) dt \quad (2)$$

This leads to:

$$R = \left(\frac{r_0}{k} \right) \left(e^{k\lambda_a} - 1.0 \right) \quad (3)$$

The life of the reserve is calculated by solving for λ_a from Eq. (3):

$$\lambda_a = \left(\frac{1.0}{k} \right) \log_e \left(\frac{Rk}{r_0} + 1.0 \right) \quad (4)$$

Fig. 1 World Primary Energy Consumption in 1991

Fig. 2 World Annual Gas Production in the 80's

where:

R = amount of reserves.

λ_a = life of reserves (abandonment time).

The life of a reserve is usually calculated by assuming a constant rate of extraction, *i.e.*, $k=0.0$. **Table 1** gives the life of the reserves of the regions of the world, assuming $k=0.0$, based on the data at the end of 1991^{d)}. In **Table 1** the rate of extraction of each region is assumed to be independent of the rate of extraction of other regions. In reality, if the world gas consumption is to remain at a given level, then the rate of extraction from a region is eventually affected by the depletion of the reserves of other regions. **Figure 3** shows the total world annual gas production, curve 1, using the annual rates of production of the regions given in **Table 1**. Note that the curve drops every time a reserve is depleted. The year in which a reserve is depleted is shown by an arrow. Curve 2 in **Fig. 3** illustrates the total world annual gas production if the production is maintained at the level of 1991. Area A in the figure represents the amount of

natural gas production lost due to the depletion of the reserves of UK, USA, Central Europe, Germany, Canada, Netherlands, Western Europe, and Asia. It is equal to Area B in the same figure which represents the remaining reserves of Ex-USSR, Latin America, Africa, and the Middle East after the year 2052. In **Table 1** the life of world reserves of natural gas is 61.4 years. Thus, for the rate of extraction to remain constant in the future, the life of the reserves of any region in **Table 1** will not exceed 61.4 years. As the growth rate (k) increases, the life of the reserves decrease. On the other hand, the life of the reserves can be extended indefinitely if the rate of growth (k_∞) is set equal to or less than $-r_0/R$. At the end of 1991, the world reserves of natural gas was estimated at 124.0 trillion cubic meters*1. World gas consumption for the same year was 2.02 trillion cubic meters. Using these numbers leads to a value of k_∞ of -0.0163 . In the following pages we will look at the effect of k on the life of the reserves of each region in **Table 1** using an algorithm developed by the author. The algorithm calculates annual gas production, end-of-year remaining reserves, and the life of the reserves of each region as a function of the amount of reserves, rate of extraction, rate of consumption, annual growth rate of extraction, and time.

Table 1 Natural Gas Reserves and Production Data of Regions of the World at the End of 1991

Region	Reserves ^{a)} [$\times 10^{12}$]	Production ^{b)} [$\times 10^9$]	λ_0 [Years]
1. UK	0.5	54.2	9.2
2. USA	4.8	506.2	9.5
3. C. Europe	0.5	31.3	16.0
4. Germany	0.3	18.1	16.6
5. Canada	2.7	105.7	25.5
6. Netherlands	2.0	69.1	28.9
7. W. Europe ^{c)}	2.3	55.5	41.4
8. Asia ^{d)}	8.4	175.9	47.8
9. Ex-USSR	49.5	724.7	47.8
10. L. America	6.8	97.5	69.7
11. Africa	8.8	71.3	123.4
12. Middle East	37.4	110.1	339.7
13. World	124.0	2,019.6	61.4

a) Proved reserves only.

b) Total production of 1991.

c) Excluding the Netherlands, UK, and Germany.

d) Excluding the Middle East.

Fig. 3 Total World Annual Gas Production and Year of Reserves Depletion of World Regions ($k=0.0$)

2. Life of Reserves

The life of a reserve is directly influenced by: (1) the amount of the reserve, (2) the recovery factor of the original gas in place, and (3) the rate of extraction. In addition to these three factors, there are other indirect factors which affect the life of a reserve. These factors include cost, availability of other primary energy sources, politics, weather conditions, environmental issues, energy market activity, world economic conditions, etc. In this paper we are only concerned with the direct factors which influence the life of a reserve.

Figure 4 is a flow chart of the algorithm used to calculate annual production, end-of-year reserves, and the life of the reserves of each region in **Table 1**. The input data for the algorithm are reserves, annual production, annual consumption of each region for some base year, and annual growth rate. The output data of the algorithm are annual production, end-of-year reserves for each subsequent year, and the life of the reserves as a function of annual growth rate and time. When the reserves of a region are depleted, the algorithm

*1 1 cubic meter=35.31467 cubic feet.

Fig. 6 Annual Gas Production of the U.S.A. as a Function of k

Fig. 9 Annual Gas Production of Canada as a Function of k

Fig. 7 Annual Gas Production of Central Europe as a Function of k

Fig. 10 Annual Gas Production of the Netherlands as a Function of k

Fig. 8 Annual Gas Production of Germany as a Function of k

Fig. 11 Annual Gas Production of Asia as a Function of k

compensate for the depleted reserves of UK and USA. Its annual production again rises slightly in 2007 because of the depletions of the reserves of Central Europe and Germany. The same can be said for the Netherlands, **Fig. 10**, except that its reserves will last until 2018. We can also notice a very small rise in its annual production in 2016 caused by the depletion of the Canadian reserves. The gas reserves in Asia will last until 2030, **Fig. 11**. Notice also the slight rises in the annual production of this region caused by the depletion of the four mentioned regions. The reserves of

Western Europe will last until the year 2033, **Fig. 12**. Its production curve remains flat throughout the life of its reserves because the region is a net importer of gas. The life of its reserves is greater than the previous regions because of its low annual production. The annual production curves of Ex-USSR and Latin America, **Figs. 13 and 14**, respectively, are almost identical, with the reserves of Ex-USSR being depleted first in 2041 and the reserves of Latin America two years later. The reserves of Africa will be depleted in 2050, **Fig. 15**. Note the large increases in the annual production

Fig. 12 Annual Gas Production of Western Europe as a Function of k

Fig. 15 Annual Gas Production of Africa as a Function of k

Fig. 13 Annual Gas Production of Ex-USSR as a Function of k

Fig. 16 Annual Gas Production of the Middle East as a Function of k

Fig. 14 Annual Gas Production of Latin America as a Function of k

in 2041 and 2043 due to the depletion of the previously large reserves of Ex-USSR and Latin America, respectively. By the year 2050 the last remaining reserves of natural gas in the world are in the Middle East, **Fig. 16**. These reserves will last until the year 2053.

The world annual production of natural gas has been increasing steadily for the past decade at an annual growth rate of 0.0333 (3.33% per year), see **Fig. 3**. Increasing the annual production rate by 0.0333 per year for each region results in the curve labeled $k=0.0333$ in **Figs. 5** through **16**. The life

of world reserves in this case will be cut by almost half, *i.e.*, 33.4 years. The annual production of the regions increases exponentially with time until year of abandonment. The trend of the annual production curves of each region will be the same as for the annual growth rate of zero except the peaks and the depletion times will appear earlier.

World energy consumption has been steadily rising at an average annual growth rate of about 7% for the past 150 years^{6),7)}. Even though this rate has decreased significantly during the past decade, natural gas consumption increased steadily. The reasons are (1) on a BTU base, natural gas is much cheaper than oil; (2) environmentally, natural gas is much cleaner fuel to burn than oil; and (3) natural gas is the most suitable alternative fossil fuel to oil for several applications, such as power generation, transportation, heating, air conditioning, etc. Therefore, it is quite feasible that the annual growth rate of extraction of natural gas will increase in the future. Further increase in annual growth rate will result in a shorter life of reserves. **Table 2** shows the life of each region as a function of annual growth rate. A 0.05 annual growth rate (5% per year) will reduce the world reserves life to 28.1 years. The annual production of the regions

is shown by the curve labeled $k=0.05$ in **Figs. 5** through **16**. Note that for growth rates of 0.0333 and 0.05, a high annual production is required to fulfill the market needs specially for Ex-USSR, Latin America, Africa, and the Middle East. These production rates may be technically impossible to achieve. Furthermore, such high rates will reduce recovery efficiency which will ultimately reduce the life of the reserves.

To find the maximum annual growth rate (k_{∞}) that will result in indefinitely-lasting reserves, the argument of the natural log in Eq. (4) is set equal to zero which leads to $k_{\infty}=-r_0/R^0$. For our base year, this gives a value of k_{∞} being equal to -0.0163 . In the last run of the program we used a value of k being equal to -0.015 . The results of this negative annual growth rate are shown in **Figs. 5** through **16** by the curve labeled $k=-0.015$. In this case world reserves will not last indefinitely, because k is greater than k_{∞} , rather it increases significantly to 169.2 years. The increase in the life of the reserves of the individual regions varies from very little for UK and USA to 150–175% for Africa and the Middle East. The maximum value of k for which the individual regions can sustain their reserves indefinitely is given in **Table 3**. Note that for all regions k is negative. The annual growth rate of the first eight regions in **Table 3** is less than the annual growth rate of the world as a whole. This means that these regions must decrease the annual extraction of their reserves at a rate faster than that of the rest of the world in order for them to have their reserves last

indefinitely. The reason is that their r_0 value is too high compared to their reserves. The annual growth rate of the rest of the regions is greater than that of the world. However, these regions must also decrease the annual extraction of their reserves at a rate of at least 1.63% per year for their reserves to last indefinitely. This is because these four regions will have to increase their annual production every time a reserve of the first eight regions is depleted.

So far we have discussed the effect of growth rate on the life of the reserves. Technological advances in deep drilling is likely to lead to new discoveries of gas deposits in the future⁹. We will now discuss the impact of such discoveries. Increasing the recovery factor of a reserve due to improved recovery techniques, will result in higher reserves. Therefore, increasing the recovery factor or increasing reserves due to the discovery of new fields or both will amount to the same thing, namely, increase in reserves. The second direct factor which influences the life of a reserve is the amount of the reserve itself. Let us assume that world natural gas reserves will increase in the future by as much as 50 and 100% because of either new discoveries or improved recovery methods or both. In **Table 4** the life of world reserves is shown as a function of k and the amount of reserves. The life of the reserves increases with the amount of the reserve and decreases with k . The percentage increase in the life of the reserve ($\Delta\lambda$) for a particular amount of a reserve decreases with k . $\Delta\lambda$ increases at a slower rate with the amount of reserve for high values of k than low values of k . For example, for $k=0$ doubling the amount of the reserve will double its life. While for $k=0.05$ doubling the amount will only increase the life of the reserve by 39.9%.

4. Conclusions

Natural gas has been an important source of energy for many years, and its importance will undoubtedly increase in the future. The world-proved natural gas reserves, as they stand at the end of 1991, will be depleted by 2160, 2052, 2024, and 2019 for annual growth rates of -1.5% , 0.0% , 3.33% , and 5.0% , respectively. Doubling the natural gas

Table 3 Maximum Annual Growth Rate of Regions of the World for Indefinitely-lasting Reserves^{a)}

Region	Annual growth rate
1. UK	-0.1084
2. USA	-0.1055
3. C. Europe	-0.0626
4. Germany	-0.0603
5. Canada	-0.0391
6. Netherlands	-0.0346
7. Western Europe	-0.0241
8. Asia	-0.0209
9. Ex-USSR	-0.0146
10. L. America	-0.0143
11. Africa	-0.0081
12. Middle East	-0.0029
13. World	-0.0163

a) Based on reserves and annual production data at end of 1991.

Table 4 Life of Natural Gas Reserves of the World as a Function of Reserves Size and Annual Growth Rate (k)

Reserve [$\times 10^{12}$ m ³]	$k=0.050$		$k=0.0333$		$k=0.00$		$k=-0.015$	
	λ [Yrs]	$\Delta\lambda$ [%]	λ [Yrs]	$\Delta\lambda$ [%]	λ [Yrs]	$\Delta\lambda$ [%]	λ [Yrs]	$\Delta\lambda$ [%]
124	28.1	0	33.4	0	61.4	0	169.2	0
186	34.5	22.8	42.1	26	92.1	50	∞	∞
248	39.3	39.9	48.9	46.4	122.8	100	∞	∞

proved reserves will increase their life by 100%, 46.4%, and 39.9% for annual growth rates of 0.0%, 3.33%, and 5.0%, respectively. High growth rates will necessitate very high annual productions which will be technically impossible to achieve and will reduce the ultimate gas recovery factor.

Oil and natural gas reserves are being depleted at a fast pace today. These reserves will not last long. No adequate alternative energy sources that are economically attractive and environmentally acceptable can replace these two fossil fuels. Long-term planning for the conservation of these two fuels is the only way to insure energy supply for future generations.

Nomenclatures

e	: base of natural logarithms=2.718282....	
k	: growth rate of extraction	[fraction/year]
k_{∞}	: maximum growth rate of extraction for infinitely lasting reserves	[fraction/year]
r	: annual rate of extraction	[m ³ /year]
r_0	: initial annual rate of extraction ($t=0$)	[m ³ /year]
R	: amount of reserves	[m ³]

t	: time	[years]
$\langle \text{Greeks} \rangle$		
λ	: life of a reserve	[years]
λ_a	: abandonment time	[years]
$\Delta\lambda$	: percentage change of the life of a reserve	[%]

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要 旨

世界の天然ガス資源の寿命予測

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一次エネルギーとしての天然ガスの利用は着実に増加している。1991年には天然ガスは世界の一次エネルギー消費量の22.7%を占めている。本論文では世界の埋蔵天然ガスの寿命をその消費速度から予測した。アルゴリズムを組み、消費の伸び率の関数として天然ガスの消費速度と埋蔵天然ガスの寿命を計算した。今後、天然ガスの消費が1991年の水準に維持される、

すなわち伸び率ゼロならば、ガス資源は約62年間持続する。消費の伸び率が3.33%あるいは5.0%ならば、ガス資源は34年あるいは28年しかもたない。消費の伸び率が高ければ、埋蔵量が増加しても寿命の値はわずかである。逆に、消費が年率1.63%で減少するならば天然ガス資源は永遠に残る。

Keywords

Gas reserve, Gas supply, Life of gas reserve, Natural gas, Regional gas reserve