The Oil Drum
DISCUSSIONS ABOUT ENERGY AND OUR FUTURE

Energy Grades and Historic Economic Growth

Posted by Nate Hagens on August 24, 2007 - 10:30am
Topic: Economics/Finance
Tags: energy density, energy transition, environment, intermittancy, net energy, power density, spatial distribution [list all tags]

This is a guest post by oil and energy economist Douglas Reynolds. Dr. Reynolds is Graduate Director of Economics at the University of Alaska Fairbanks, and author of "Scarcity and Growth Considering Oil and Energy", and "Alaska and North Slope Natural Gas". Doug has a prior guest post on theoildrum on The Energy Utilization Chain. This post offers a different but related perspective on energy comparisons and transitions than last weeks post on Energy Transitions by Professor Cutler Cleveland.

> 1. Weight Grade
>
> The weight grade determines how much energy there is per pound of energy resource. For example, coal has about 12.7 thousand BTU/lb, natural gas about 10 thousand BTU/lb, oil about 19.3 thousand BTU/lb, and an electric battery typically has 100 BTU/lb. Electric batteries then are very heavy compared to their energy output which is why electric cars do not have very good driving ranges.

Professor Reynolds' paper is below the fold.

Introduction

In 1709, William Darby invented the coking process which led to the use of coal in 18th century England. From an economic stand point, one could say that this event more than any other ushered in the industrial revolution with its dependence on coal and steel produced from coal. However from an engineering perspective, there is another cause of the industrial revolution that is more subtle. This cause is the physical make up of the energy resources available to England.

According to Simon Kuznets, an economic epoch, which is a period of time defined by rapid population increase for a given region, "is determined and shaped by the application and ramification of an 'epochal innovation'." i.e. new significant technologies. (1)

Rondo Cameron further states,

> A possible explanation for the correlation of population growth/stagnation/decline with income movements can be fashioned by analyzing the interaction of the fundamental determinants of economic development (land, labor, capital and entrepreneurial capacity). With a given technology, the resources available to a society set the upper limits to its economic achievements ... technological change by increasing productivity and opening up new resources has the effect of raising the ceiling. (2)

This emphasizes technology as the major ingredient for periods of high economic and population growth. However, we believe another ingredient, equally as important as technology, is the grade or inherent value of energy resource inputs available to an economy. This has to do with productivity. Each type of energy resource has an inherent physical potential for being more or less productive and that potential is the energy grade. Higher grade energy resources have more potential for being productive than lower grade energy resources.

Energy is the driving force behind industrial production and is indeed the driving force behind any economic activity. However, if an economy's available energy resources have low grades, i.e. low potential productivity, then new technology will not be able to stimulate economic growth as much. On the other hand, high grade energy resources could magnify the effect of technology and create tremendous economic growth. High grade resources can act as magnifiers of technology, but low grade resources can dampen the forcefulness of new technology. This leads to the conclusion that it is important to emphasize the role of the inherent nature of resources in economic growth more fully.

To see better how this very subtle idea is a not so subtle cause of the industrial revolution, and possibly other economic epochs, we must look at some simple physics of energy resource characteristics. We believe that the most important resources for economic achievements are energy resources, therefore, we look at ways to compare energy resources.

The Energy Resource Characteristic Grade

In order to understand why some energy resources are better than others, we need a way to compare them. One way to compare energy resources is the energy grade concept defined here. This concept identifies the physical characteristics of competing energy resources that allow the economy to more cheaply extract services from each BTU (3) of energy. There are four grades.

1. Weight Grade (BTU / lb.)
2. Volume Grade (BTU / cubic foot)
3. Area Grade (BTU / acre)
4. State Grade (Liquid, Gas, Solid, Field)

Consider these grades in detail:

1. Weight Grade

The weight grade determines how much energy there is per pound of energy resource. For example, coal has about 12.7 thousand BTU/lb, natural gas about 10 thousand BTU/lb, oil about 19.3 thousand BTU/lb, and an electric battery typically has 100 BTU/lb. Electric batteries then are very heavy compared to their energy output which is why electric cars do not have very good driving ranges.

The weight grade determines energy performance. Usually, transportation devices must carry their fuel source along with them during use. The lighter is the weight of the fuel they use, the less energy they require to carry that fuel around which is why consumers and producers will be willing to pay a premium for higher weight grade energy resources.

2. Volume Grade

The volume grade determines how much energy there is per unit of volume of the energy resource. Natural gas is very bulky at about one thousand BTU/cubic foot at standard atmosphere and pressure, and 177 thousand BTU/cubic foot at 3000 psi. Oil, though, has about one million BTU/cubic foot. The volume grade is important again, because it determines performance for certain energy uses. For example, if we had to use natural gas in place of oil for cars, the volume of the fuel tank would have to be much bigger and thus much heavier, or if it was the same size, then refueling would need to be done more often.

A low volume grade energy resource is also difficult to transport. For example, a low volume grade resource like natural gas can be many times as expensive to obtain from an over seas source, such as the Middle East, than from the North American continent due to storage expense during transportation. So here again consumers and producers will be willing to pay a premium for higher volume grade energy resources.

3. Area Grade

The area grade determines how much energy there is per area of occurrence of the energy resource in its original state, i.e. how much energy per acre. For example, the area grade of wood is roughly 1 to 5 Billion BTU/acre because wood is spread out in forests over many acres. Its original energy state, then, is much more spread out. The area grade for oil is usually tens or hundreds of billions of BTU/acre, as it is found in thick under ground reservoirs in a high volume grade state.

The area grade determines how much service including cost savings the economy can extract from a given energy resource. If the energy content of the resource is spread out, then it costs more to obtain the energy, because a firm has to use highly mobile extraction capital, which must be smaller and so cannot enjoy increasing returns to scale. If the energy is concentrated, then it costs less to obtain because a firm can use larger scale immobile capital that can capture increasing returns to scale. Therefore, energy producers will be willing to pay an extra premium for higher area grade energy resources.

4. State Grade

The *state grade* defines what form or state the energy resource occurs in. The four major state grades are the following:

1. Liquid
2. Gas
3. Solid
4. Field

1. Liquid

The liquid state grade is simply where the energy resource occurs in a liquid form at standard atmosphere and pressure, such as oil does. This state is the highest state grade, because energy resources that are liquids are easier to transport and use than any other energy state. For example, a machine can use less moving parts to inject, burn and remove a liquid in a burning chamber, such as a piston cylinder, than it can a solid. Less moving parts usually means less costs. Also one can more easily transport and store a liquid, than a solid or a gas, since a producer can carry a liquid in un-pressurized containers or pump it through pipes. This makes liquids cheaper to use than energy resources that occur in other states.

2. Gas

Gas at standard atmosphere and pressure is the next highest state grade. A gas is more difficult to transport and use than a liquid, because it by nature must have a lower volume grade and must be kept under pressure. However it is still fairly easy to use. A machine can inject gas into a burning chamber just like a liquid.

3. Solid

A solid energy resource is the third highest state grade. It is simply an energy resource in solid form at standard atmosphere and pressure such as coal or wood. Solid fuels are more difficult and thus more costly to use, because in order to burn them, complicated mechanisms must continually place them in a burning chamber and remove the ashes once they are burned. A machine cannot pump the fuel into place but must mechanically move it. This makes solid fuels more costly to use per BTU than liquid or gas fuels in many energy uses.

4. Field

A field energy resource includes such phenomena as radiation fields, like solar and nuclear power, and pressure fields, like wind energy and hydro power and are the least useful state grade.

The main problem with fields is that they are difficult to store. For example, one of the biggest problems with solar energy is storing the day time heat energy for night time use. The only field that does not have this problem is nuclear fields, but they are difficult to contain from creating environmental hazards.

There are four different physical manifestations of the field state grade:

1. Pressure
2. Electric
3. Magnetic
4. Radiative

1. Pressure

The pressure field is where there is a difference in pressure. An example of such a field is like the wind pushing a wind mill. The wind creates a pressure differential that in turn pushes the arms of the mill. Another such field occurs with hydro power. Firms often use pressure fields to make electricity.

2. Electric and
3. Magnetic

Electric and magnetic fields are most often used in energy conversion processes only after another energy resource is used. Therefore, they are not sources of energy.

4. Radiative

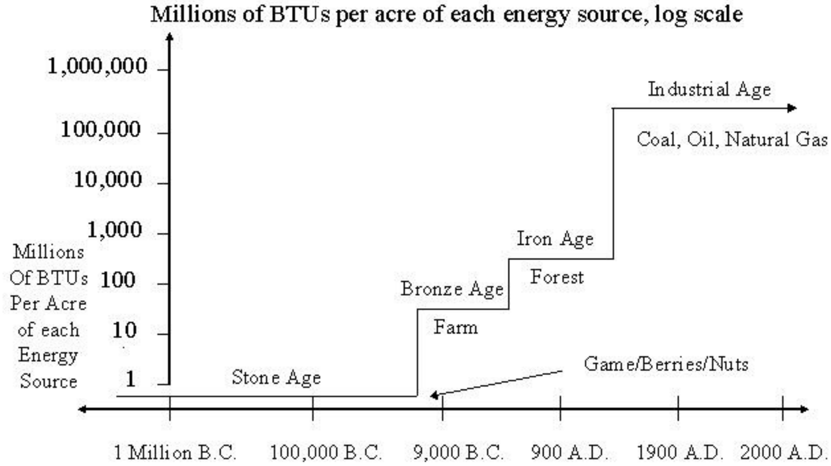
A radiative field is like solar energy. The sun's light radiates on the Earth. That radiative energy in turn creates heat or even electricity. All nuclear power too is a field type characteristic grade, since nuclear fuels, like Uranium, radiate alpha, beta or gama particles.

Energy Resources and The History of Economic Growth

Energy Resource	Weight Grade (MJ/Kg)	Volume Grade (MJ/M^3)	Area Grade (MJ/Hectare)	State Grade
Oil	44	35,000	25 - 2,500 Million	Liquid
Natural Gas	53	35 at std 6,000 at 20.7 MPa	25 - 2,500 Million	Gas
Coal	18 – 29	23,000 - 35,000	25 - 2,500 Million	Solid
Oil Shale	up to 4.4	7,000	25 - 2,500 Million	Solid
Uranium	N/A, field	N/A, field	Trillions	Field
Wood	18 dry	9,000	1 - 12 Million	Solid
Ethanol	25.5	20,000	Made from grain	Liquid
Methanol	19	15,000	Made from Natural gas	Liquid
Hydrogen	141	12 at std, 4,000 when super cooled	Made from natural gas, oil, coal or electricity	Gas, Liquid (at super cool temperatures)
Solar Energy	N/A, field	N/A, field	2,500 – 25,000 every hour	Field
Grain	15.5 dry	7,000	7,500 – 100,000 every year	Solid
Wild Game	15.5	12,500	up to 750 every year	Solid
Wild Berries/Nuts	up to 15.5	350 - 14,000	up to 7,500 every year	Solid

In Table 1 and figures 1, 2, 3 and 4 (*not reproduced here*), there is listed and shown many energy resources and their characteristic grade values. These show how the different energy resources compare with each other. Note that oil is one of the most valuable energy resource since it leads the other resources in most categories.

Figure 3.1 History of Human Economic Ages
1 million B.C. to 2000 A.D.
Millions of BTUs per acre of each energy source, log scale



This comparison gives us a new way to analyze economic history. Many of the greatest economic epochs in history seem to occur at the point in time when the economy starts to use a high grade energy resource. Examples are ancient man's switch from hunting to farming, which created the great ancient civilizations of Egypt and Mesopotamia; England's switch from wood to coal in the 18th century, which helped to create the industrial revolution; and the U.S.'s switch from coal to oil in the 20th century, which created the modern mobility revolution, also identified by some historians as the second industrial revolution (4). All of these were changes to higher grade resources.

From these grades, we can infer that as humans have advanced over time, they have used higher grade energy resources. We believe that one of the causes of human economic development is the fact that humans used higher grade energy resources which created lower costs for production. Furthermore, we believe that much of economic growth is not due to better technology alone, but rather due to a combination of technology and higher grade resources.

It can be said that technology was the reason for the use of higher grade resources, and thus it is technology that is the only reason for human economic growth. This is true. However advances in technology without the availability of higher grade resources would surely not have created as much economic growth success as was possible with the availability of these higher grade resources. This gives some evidence that the degree of success in human economic growth was determined to a large degree by the grade of energy resources available. Consider the example of

England's energy switch in the 18th century.

18th Century England's Change From Wood to Coal

To show how the grade level of different energy resources affects the overall cost of using energy, consider England's energy resource switch in the 1700's from wood to coal. England needed wood throughout the Middle Ages for fuel and building. However, by the 18th century, England's forests were very depleted, and it threatened England's economy. 5 The price index of wood charcoal quadrupled in 100 years from 1560 to 1660 while the price index of everything else doubled in the same time span. This signaled problems with getting enough energy. 6 Eventually though, coal replaced wood for energy.

Consider this transition in detail. The area grade for wood is roughly 1 to 5 billion BTU's per acre but coal can have 10 billion to 1 trillion BTU's per acre. In fact, it often averages about 50 billion BTU's per acre or more. Therefore, coal's area grade is about 10 times greater than wood's. This allows miners to set up and use large scale production machinery, because they do not have to move the machinery from coal bed to coal bed since one coal seem has a lot of energy per acre. This is in contrast to wood charcoal where the gathering of wood required relatively more mobil capital. The result was that coal mining could have increasing returns to scale. Even such archaic mining machinery as they had in the 18th century benefited from that, which was why coal at that time was cheaper.

Since fuel is the largest input for making iron, iron furnaces were located closer to the fuel source than the iron ore. So it was the fuel source that determined the economies of scale of iron making. With coal as the new source of fuel for iron, producers could set up larger and more iron production furnaces close to a single coal seam. When iron production depended on wood, which was expensive to transport, wood being half the weight grade as coal, then that meant that the size of an iron furnace could only be as big as the supply of wood would allow. So charcoal furnaces had to be kept smaller and more spread out which caused lower returns to scale and so higher costs. Ashton gives some examples,

A single furnace associated with a single forge was clearly the predominant order (before 1750). ... In 1549, there were 23 men working a furnace at Sheffield (Sussex) in addition to the two wainmen who attended the fourteen oxen and at a forge in the forest of Worth 33 men were engaged. ... at Duffield in 1691 it appears that 105 tons of metal were cast in 18 weeks, and that 75 tons of this pig iron were required to make the 50 tons of bar iron which were produced at the forge in six months. 7

So there were comparatively few laborers and low outputs.

However these furnaces often needed a lot of extra labor just to get the wood fuel. Again Ashton says,

> "... at Backbarrow (using the method of wood charcoal casting) ... there were in 1714 no fewer than 130 people supplying fuel to the works - sometimes in almost minute quantities". (8)

However a few decades after Abraham Darby invented coke, furnaces began to be located near coal mines. The furnaces were bigger, there were more of them located in one place, and outputs were higher. Ashton states,

> "...by 1803 Richard Crausby owned ... six furnaces and employed over 2000 men at Cyfarthfa." (9)

Most furnaces in that day produced 40 tons of iron per week, which is about a seven fold increase per furnace. (10) So with coal it was possible to have larger operations closer together creating increasing returns to scale. Plus the coal mine operations themselves could be bigger and enjoy increasing returns to scale.

However, in addition to having the larger returns to scale, the operations of mining and iron production were all in one place which allowed for more specialization and also greater technical interaction which created new technological advancements. As Raistrick says,

> ... it was now (from 1760 onward) an economic proposition to apply a large cylindered (watts) engine to mine pumping. This in turn made much deeper and more extensive mining possible and a cycle of development by interaction - foundry - engine parts - deeper and better pumping - easier and cheaper ore and fuel - larger furnaces and foundries - larger engines - was soon established. (11)

So we see that larger scale operations with more specialization and greater technological progress was a direct result of the high area grade of coal, because more operations were located closer together. If England ran out of wood and had to use a lower area grade fuel for iron production such as grain turned into alcohol or renewable forests, then surely England could never have had the economies of scale and so the technological leap that it did with high area grade coal. If England did continue to use wood however, it may have required the use of farm lands so that it could not support as many of its citizens as it had. This leads us to conclude that there would not have been as large a bang in the industrial revolution, nor may never have been an industrial revolution, without a high area grade resource like coal. Furthermore, we cannot see technology as being the only ingredient for an economy being able to overcome a resource shortage. Rather, it is technology applied to a new abundant higher grade resource that more often than not saves an economy hit by a resource shortage.

Another way to view the importance of high grade resources is to ask, what if England of the 1700's had today's technology but still only had wood, grains, wind and solar energy as its primary energy resources, without even the coal it used for heating, would the economic growth for England of the last 200 years have been possible?

The answer is that even today it is more expensive to use these alternative energy resources then current high grade energy resources of coal, oil and natural gas. The fact that England's economy, and all industrial economies, choose not to use those alternative energy resources during the oil price shocks shows that it is more efficient to use the high grade ones. This implies a loss of GDP if our economies were forced to use the lower grade resources, which further implies England's growth of the last 200 years was greater with the high grade resources than without them. The magnitude of the impact of having a high grade resource available is not possible to find.

An Energy Theory of Value

At this point one might ask if it is possible to compare competing energy resources on a price per BTU basis. Such a price per BTU criteria would allow us to have a better basis for comparing past energy transitions and future energy transitions. Unfortunately, such a criteria does not work as a comparison because competing energy resources have different characteristics that BTU content cannot capture. For example, consider the following problems.

An electric car using electricity at $1.50/MMBTU is less costly to run per mile even with maintenance costs than a regular gasoline car using gasoline at $8.00/MMBTU, 12 yet most people drive gasoline vehicles rather than electric vehicles. The reason for this is the overall service of gasoline vehicles. Gasoline vehicles have a range of 200 to 400 miles or more before needing to be refuelled where as electrics can only go 30 to 60 miles. Plus it takes five minutes to refuel a gasoline car but an electric requires 30 minutes to 8 hours of recharging depending on the system before it is ready to go again. So electrics are inconvenient. Thus the price per BTU does not account for the difference in service provided and so cannot take into account consumer preferences nor total producer costs of using such alternative fuels which in turn will decide which energy resource is best.

Another problem with the cost per BTU concept is that when energy resources are converted from one form to another, there is typically a 10% to 90% reduction in energy even while there is a cost associated with such conversions. Thus natural gas at a well head can cost as little as $0.10/MMBTU, but when it is converted into methanol it will cost about $8.00/MMBTU and there will be a loss of 40% of the original energy content causing greater scarcity of the natural gas. 13 However, this change in cost may be worth while, because the change in energy characteristics from natural gas to methanol may be worth the extra cost. Nevertheless, the cost or price per BTU concept does not capture that added value gained by turning natural gas into methanol nor does it explain the higher loss of the natural gas source.

Another problem is that location of energy can change the price per BTU. Natural gas for example that is produced in say Saudi Arabia would cost at least $4.00/MMBTU delivered in New York city where as natural gas from Pennsylvania can cost as little as $0.35/MMBTU in New York 14. The reason for such a huge difference is that natural gas from Saudi Arabia must be shipped in cryogenic tankers that cool the gas to a super cooled liquid state in order to minimize the cost of transportation. The energy required to get the gas that cold and keep the gas super cooled during the duration of transit costs so much that it causes the price of the gas to be more costly for such long distances even though that is the cheapest method of transport. Thus the location of an energy resource affects the price per BTU. Then the question is which price does one use, the price of origin of the gas or the price of destination, and if we use the price of destination then do we use the price of gas coming from Pennsylvania or the price coming from Saudi Arabia.

Given these inadequacies, the price per BTU of energy does not adequately capture the real value of competing energy resources and so cannot determine which energy resources are most competitive. This means we cannot simply compare energy resources on a price per BTU basis nor even a simple BTU basis, but must compare them on a grade basis. Further, when energy statistics are presented in BTU terms and not grade terms, then those statistics tacitly assume one to one substitution per BTU between energy resources of different grades. This is clearly is not the case. We recommend that energy statistics for supply and demand of different types of energy not be lumped together using the BTU measure.

Future Energy Transitions

If we compare our emerging energy transition of oil to oil alternatives with other energy transitions in history, it is important to distinguish the change in the grade level of the competing energy resources from changes in technology. Low grade energy resources create higher cost production than high grade resources, which in turn produces a drag on the economy. This leads to the conclusion that humans have made several energy transitions before in history and enjoyed growing economies during or after these transitions, but that most of the more successful energy transitions in history were transitions to higher grade energy resources not to lower ones. Therefore, we are concerned with how successful the next energy transition will be. We propose three alternative scenarios for the future transition from oil to oil alternatives.

1. The economy goes to a higher grade resource, creating a successful energy transition.

2. The economy goes to a lower grade energy resource with better technology, creating a less successful but palatable energy transition.

3. The economy goes to lower grade energy resources with virtually unchanged technology, creating an unsuccessful energy transition.

The first scenario suggests we go to a higher grade energy resource. However, the question is, what other high grade resources exist. Most alternative energy resources such as natural gas have mostly lower grade characteristics. The only alternative energy resource that might be of higher grade is solar energy or nuclear energy resources, all of which are fields. Solar energy is hard to store. This makes solar energy impractical to substitute for oil for transportation and other purposes. Nuclear energy has other problems.

Nuclear fusion energy, which is the energy of the sun, uses water and would have an extremely high area, weight and volume grade. However, fusion is only possible in large scale facilities with multi million dollar lazars. It can therefore only be used for producing electricity on a large scale. Because of the highly technical and specialized capital, materials and labor it needs, it does not look to be any cheaper an energy resource for producing electricity than coal is currently. Nuclear fission energy, or conventional nuclear power, also has a high area, volume and weight grade for its energy source of Uranium. However, Uranium is extremely toxic and difficult to keep contained from the environment, and unless breeder reactors are used, a highly dangerous proposition, then uranium supplies will shortly run low. Furthermore, conventional nuclear power is too unsafe for using in numerous small scale operations such as running trucks.

The second scenario suggests we go to lower grade resources but with improved technology. This is like how western civilization has achieved greater productivity in farm production over time due to new technology even though soils are the same. If technology does advance fast enough, than maybe the negative effects on the economy of going to a lower grade energy resource will be minimized.

The third scenario suggests the worst possible out come, that the world's economies will endure an unsuccessful energy transition and have very low growth rates or even economic decline. As the economies go from the high grade resource of oil to lower grade resources, there could be drag on economic productivity. Whether technology will or will not come through for us is very open to debate.

Concluding Remarks

We believe that many economic epochs in history should not be defined as being caused mostly by epochal innovations, but rather by innovations as well as the change in energy grade to higher grade energy resources. Furthermore, both technology and high grade energy inputs deserve equal status as causing economic epochs. The greatest economic epochs seem to occur when there are energy transitions from low grade to high grade energy resources. The economic intuition behind this is that higher grade energy resources allow for increasing returns to scale since they are either less spread out, more concentrated when in bulk, or more flexible in use.

In our own day, we must eventually move to lower grade energy resources as we slowly run out of oil. Therefore, we might expect the transition from oil to oil alternatives to be a decisively less successful energy transition than previous energy transitions in history, since all the previous transitions were from low grade to high grade energy resources, and the coming oil transition is from a high energy resource of oil to lower grade energy resources. Greater technical progress should help our impending energy transition, but certainly we need to expect a lower growth rate during and probably after the next energy transition. Since industrialized country growth rates seem to be lower after 1973, the year oil production limits became apparent with high prices, then this could mark the beginning of lower growth rates due to the world's economies having to transition to lower grade energy resources with their corresponding higher costs of production and lower productivity for the economy.

Footnotes:

1. Cameron, Rondo. A Concise Economic History of the World. Cambridge University Press, 1989, p. 187.

2. Ibid. p. 9.

3. The term BTU stands for British Thermal Unit, which is the energy required to heat one gallon of water by one degree fahrenheit.

4. Barnes, Harry Elmer. An Economic History of the Western World. New York: Harcourt, Brace & Co., 1942, p. 445.

5. DeVries, John. The Economy of Europe in an Age of Crisis: 1600 - 1750. Cambridge University Press, 1976, pp. 166,167.

6. Cipolla, Carlo M.. Before The Industrial Revolution: European Society and Economy, 1000 - 1700. W.W. Norton and Company Inc., N.Y., 1976, pp. 266, 268.

7. Ashton, Thomas Southeliffe. Iron and Steel in The industrial Revolution Manchester University Press, 1924, p. 96.

8. Ibid. p. 187.

9. Ibid. p. 96.

10. Ibid. p. 6-7.

11. Raistrick, A.. Dynasty of Ironfounders London 1933 p.148, in Alan Birch The Economic History of The British Iron and Steel Industry. Franck Cass and Company Limited, London, 1967, p. 59.

12. Starr, Gary. The Shocking Truth About Electric Cars. Earth Options, Santa Barbara, California, January 1991.

13. Othmer, Donald F.. "Methanol is the Best Way to Bring Alaska Gas to Market". Oil and Gas Journal. November 1, 1982 p. 84.

14. International Energy Agency. Natural Gas: Prospects to 2000. Paris 1982.

(this post adapted from paper posted here)