Journal of Energy Challenges and Mechanics
http://www.nscj.co.uk/JECM/

ISSN 2056-9386
Volume 1 (2014) issue 1, article 8

The new oil to natural gas price ratio paradigm
石油对天然气价格比的新范式

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Accepted for publication on 6th August 2014

Abstract - **Before 2005, the ratio of the U.S. price of oil (dollars per barrel) to that of natural gas (dollars per thousand cubic feet (MCF)) stayed close to seven to one (i.e. close to 1 to 1.2 in dollars per giga joule (GJ) equivalent). The ratio was dependent on the fact that U.S. electric utilities were able to switch between oil derived fuel and natural gas for peak and intermediate electric power generation needs around that ratio. That means technology drove the oil to natural gas price ratio relationship. However, now that most generators use cheap natural gas in America and no longer switch to expensive oil, a new, volatile oil to natural gas price ratio paradigm has emerged in the U.S. where no one technology drives the relationship. However, that could change. For example in 2007, there was a massive switch from gasoline-fueled vehicles to natural gas-fueled vehicles in Utah, U.S.A. The costs and benefits of this switch showed a price ratio between oil and natural gas that could approach 22 to 1 (3.7 to 1 in dollars per GJ). This suggests that the major natural gas markets in Europe and America may be able to drive the world oil market to some degree.**

Keywords – **Natural gas, Energy prices, Oil Substitution**

I. INTRODUCTION

As the price of oil has risen, there is concern for how the world's economy will be able to operate with less oil. Ideas for oil substitution range from using coal-to-liquids to gas-to-liquids to electric cars. However, since natural gas is amenable to being used in internal combustion engines right now, then a much simpler idea is to use natural gas directly to replace oil derived fuels in automobiles. In the United States the price of natural gas has been low for several years and yet not many U.S. regions have used compressed natural gas (CNG) automobiles as a significant portion of their fuel use strategies. This analysis suggests that the costs of using natural gas may be too high yet to be able to make such a switch happen.

Looking at the U.S. natural gas market, it is clear that for many years, the price of natural gas in the United States and the price of oil were linked by power generation technology. Modern electric power plants are able to switch from residual fuel oil (or condensate fuel oil) to natural gas and back again as needed. Anytime the price of natural gas per thousand cubic feet (roughly the same price per giga joule), dipped below a ratio of 1/6th or 1/8th the price of oil per barrel (about 1 to 1.2 times the price of oil, in terms of dollars per GJ), power generation switched to natural gas. Whenever the price of natural gas increased above that rough ratio "rule of thumb," then power generation switched to oil. See [1], [2], [3], [4] and [5] and see Figure 1 for a history. Switching power generation feedstock back and forth meant that the price ratio stayed within the same bounds because any time the price of natural gas went above or below the ratio for any length of time, the demand for natural gas quickly altered to compensate. The oil market was the deeper, more stable energy market. If natural gas prices went too high, demand for natural gas quickly plummeted, if natural gas prices went too low, demand for natural gas quickly increased. The oil dog wagged the natural gas tail.

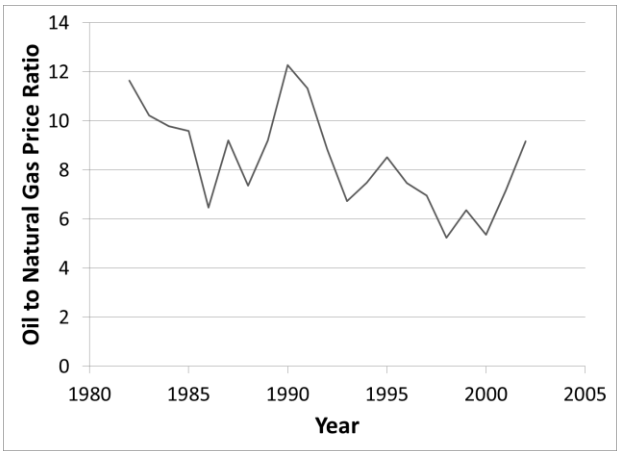

Fig.1, The roughly 6 to 1 or 8 to 1 price ratio of natural gas to oil. U.S. market, from EIA yearly data to 2002 before natural gas volatility occurred.

However, now that natural gas supplies in the United Sates have increased well above power and space heating demand, with very low natural gas prices, and new supplies look to be large, there is no more reason to switch to oil for electric power generation in the U.S. Although, as with the rest of the world, the U.S. still looks to use some coal fired generation in place of oil and natural gas as well. Therefore, oil does not look to be a factor in world electricity production. This is especially true since oil prices are forecast to remain high, and natural gas prices are forecast to remain low for several years if not decades, and there looks to be plenty of natural gas for all projected space heating and electric needs in the U.S. and possibly around the world due to shale gas. We could also look at Hotelling [6] rent as a cause for price rises for oil and natural gas, as Gordon [7] and Holland [8] suggest, nevertheless, Reynolds [9] shows that the Hotelling rule cannot be used.

Although, the price of natural gas could go back up if demand picks up and the price of oil could go down if market forces change, nevertheless, as of 2014 the economics of using natural gas are so much better than the economics of using oil for power generation that there does not look to be any more switching in the U.S. and very little in the rest of the world. However, if supplies of natural gas continue to increase substantially, due to shale natural gas—as the Potential Gas Committee [10] and the EIA [11] show—and if oil prices go up—as UKERC [12], Fantazzini [13], Kumhof et. al [14], Lutz et. al [15], Mirchi et. al [16], Hallock et. al [17] and Reynolds [18] show due to "peak oil"—then a new substitution paradigm may well emerge. The technology around the natural gas switching may be with automobiles rather than electric power production.

According to Ramberg and Parsons [19], the historic cointegration relationship between oil and gas prices "may not be a very reliable predictor of future natural gas prices." Ramberg and Parsons do give one option for the future of natural gas prices which is that gas-to-liquids technology may determine the upward bound of the oil price to natural gas price relationship. However, there is a more feasible option. Natural gas and oil may in the future substitute directly for one another as a transportation fuel for automobiles seeing as natural gas looks to be a cheap energy source for a long time and has characteristics similar to a liquid fuel, although Flynn [20](2002) shows many of the drawbacks of using natural gas for an automotive fuel.

Nevertheless, Krause [21] shows that in Utah, starting in 2007, a new fuel switching paradigm took place where consumers switched from gasoline-driven cars to compressed natural gas (CNG) cars. Boyle [22] also shows that many developing countries could start using CNG vehicle technology. Typically, such conversions require that a large CNG tank be installed in the car and slight alterations done to the engine. Large cars such as SUVs and pickup trucks are amenable to conversion and there are plenty of those vehicles in the U.S.

In this paper, we will analyze a case study in Utah in order to understand what kind of rate of return consumers need in order to make the switch from oil to natural gas. In section III a simple cost estimate model for the relationship between the price of oil and the price of natural gas for automotive consumers is derived. In section IV, a competitive market analysis is done. In section V the implications for such an oil-to-natural gas price ratio paradigm are explored. If we assume natural gas supplies will be much larger than future oil supplies and will be at a reliable low cost, then the natural gas market could dictate the price of oil in the oil market. In the last section, I give concluding remarks.

II. The Utah Case

In Utah, in 2007 and 2008, a substantial number of motorists switched their transportation vehicles from using gasoline to using CNG because of the low price for natural gas and because there were relatively many utility and government sponsored natural gas fueling-stations. See Krause [23]. Flynn [24] shows that using CNG is difficult due to many factors including consumer cost markups, natural gas fuel-station availability and the perception that CNG vehicles won't work as well.

Turrentine and Sperling [25] suggest that perceived risk by the consumer will create resistance to a changeover, presumably the risk of a lack of natural gas fuel availability when needed, but also the risk of an explosion of the CNG tank itself. However, those concerns were overcome in Utah in 2008 when a surge in interest in purchasing CNG vehicles or converting to CNG vehicles occurred. Although there were many problems with fueling which were not emphasized, particularly the problem of having too few natural gas fueling-stations available, which we will look at below, nevertheless, it did work to a degree. Importantly, Aslam et. al. [26] show that CNG vehicles are comparable to gasoline vehicles in many performance characteristics. So, while some motorists in Utah simply bought automobiles built to use CNG, such as the Honda civic GX, many actually paid to have their existing gasoline automobiles converted to CNG vehicles. A close inspection of the costs and benefits for the switching option of turning an existing gasoline vehicle into a CNG vehicle shows the following economics.

The typical cost of conversion to switch from a conventional car to a compressed natural gas car was $12,000 in 2008. Assuming a typical car in Utah got 20 miles per gallon and drove 10,000 miles a year and that there was no appreciable change in mileage after CNG conversion, then a typical car used roughly 500 gallons of gasoline equivalent per year (63 GJ). The price of gasoline at the time consumer switching took place in Utah was $3.95 per gallon ($32/GJ) in 2008 with oil at about a $120 per barrel price. The city gate price of natural gas in Utah was about $8 per GJ which is equivalent to $0.87 per gallon of gasoline equivalent. Since natural gas retail stations were government run, the city gate prices were roughly the same price as the natural gas fueling-stations. Therefore the price difference of the oil based gasoline fuel compared to the natural gas fuel was $3.08 per gallon of gasoline equivalent. If you multiply that by 500 gallons, the cost savings come out to be $1,540 per year or roughly 13% of the cost of conversion. In other words consumers were saying that to pay for a $12,000 conversion, they needed a 13% return on their capital investment.

However, one of the problems that Utah had was that people were waiting in line to be able to fill up their CNG vehicles, or they were only allowed to fill up half way, or they had to come to fill their CNG car at night. That signifies an economic constraint on their options, which is a further cost of CNG vehicles. We will go into that constraint in section IV.

III. A Switching Cost Example

What we would like to do is to first understand what the costs and benefits are of switching from oil to natural gas as a fuel source using simple engineering economic concepts. Once we have the engineering costs and benefits, we can expand later into market implications. First, consider a simple case of converting from gasoline to CNG. If the price of natural gas is low, relative to the price of liquid fuels, than people who already own gasoline or diesel cars and trucks will switch to natural gas by converting their existing automobiles into CNG vehicles. People who are considering buying new vehicles, will simply buy pre-equipped CNG vehicles, although probably both would be bought on new car markets as not all U.S. regions are amenable to using natural gas.

In the U.S., 150,000 natural gas cars have been sold, and if that number grows to one million, as expected, it still does not put a dent in the 250 million, U.S.-car fleet. Therefore, for the next ten or twenty years, millions of used cars in North America can be converted from using liquid-fuel to using natural gas. It is these used cars that will determine a switching market. There will be an increase in used car conversions if oil prices rise very high relative to natural gas and a decrease in used car conversions if oil prices are particularly low relative to natural gas, even as much of the rest of the world, and even some regions in the U.S., continue to purchase oil fueled cars due to having no other option. Such natural gas free regions could provide used cars that could be brought to the U.S. for switching. However, used, liquid-fueled cars will not be able to be sold easily in order to buy new natural gas cars, as no one will want a used oil fueled car when they can buy a new natural gas fueled car, and the used car market will become a buyers' market with discounted prices. So, the only option for millions of car owners would be technological conversion of used cars.

If the price of natural gas is high relative to the price of oil, people who already own gasoline and diesel vehicles will refrain from switching their car to use CNG. This means that there may emerge a switching relationship between oil and natural gas. To understand the potential relationship when natural gas starts from a high price and moves low, we need to do an engineering analysis of the costs of a switch from a gasoline vehicle to a CNG vehicle.

Assume consumers must pay a capital cost in order to convert their automobile from gasoline to CNG similar to what happened in Utah, and assume the natural gas fuel stations will emerge in only a few regions near dense cities or near well-developed natural gas infrastructure. Since the U.S. has a very deep natural gas market, all that is needed is for some U.S. cities or regions to develop CNG stations in order for the switching to occur, i.e. it is not necessary for a national CNG grid to have some conversions occur. Cars can also be bought to run only on natural gas and probably at a similar cost as gasoline driven cars; however at the margin, where switching will occur, it is the people that convert from gasoline to natural gas that could drive the price ratio of oil to natural gas.

Assume consumers who pay for CNG conversions consider the car itself is a sunk cost, then every year the consumer must be able to pay off the conversion investment with the following payment:

$$yearly\ cost = C \cdot r$$

where C is the cost of converting a gasoline vehicle to a CNG vehicle, and r is the interest rate paid by the consumer for the loan to pay for the conversion.

We also need to understand the advantage in fuel savings. Let:

$$G_r = \text{the retail price of gasoline (\$ per gallon)}$$
$$N_r = \text{the retail price of natural gas (in \$ per MCF)}$$

where $ per MCF is roughly equal to $ per GJ.

In order to make the above retail prices comparable, a conversion factor is needed. Assume N_r is dollars per MCF ($ per GJ) and G_r is dollars per gallon of gasoline equivalent, the conversion factor is:

1 gallon of gasoline = 0.125 MCF

or

The gasoline equivalent MCF = $8G_r$.

The consumer pays for the capital cost of conversion by saving money on driving, which means the difference in fuel cost multiplied by fuel use per year has to pay the conversion costs or:

$$(8G_r - N_r)F = C \cdot r \qquad (1)$$

where F = fuel use per year in MCF.

Right now the average U.S. light vehicle driver drives 10,500 miles per car per year, and that of a light truck drives 12,400 miles per year, but may drive more or less depending on their sensitivity to fuel prices (EPA [27]). The EPA assumed the average passenger vehicle drove 12,000 per year in 2005, so by now, it may be 11,000 due to higher gasoline prices. The natural gas fuel use for a typical CNG car, assuming similar characteristics for a CNG vehicle as for a gasoline fueled vehicle, is:

$$\text{Fuel use per year } (F) = \left(M_i / 8MPG \right)$$

M_i = miles driven per year

MPG = miles per gallon of gasoline equivalent.

Therefore the consumer needs the price difference to be the following:

(Price difference) x (fuel use) = investment cost

$$(8G_r - N_r)\left(M_i / 8MPG \right) = C \cdot r \qquad (2)$$

(note: 25 MPG = 9.4 liters per 100 km; or 10.63 km per litter).

The retail natural gas price in the United State is usually just above a city gate price, particularly for a fueling-station buying the natural gas in bulk. The actual cost for the fueling-station will be explained more in section IV. For now, assume the retail price of natural gas for a residence is roughly the same as for a fueling-station. Therefore the natural gas price to the retailer and to the customer is assumed to be roughly 50% higher than the Henry Hub price in North America, due to taxes, costs of distribution and returns:

$$N_r = 1.5 \cdot P_{HH}$$

where P_{HH} = the Henry Hub natural gas price ($/MCF).

By multiplying the gasoline price by 46 gallons (the GJ equivalent value of gasoline compared to the GJ equivalent value of crude oil per barrel rather than the normal 42 gallons per barrel), we get a per barrel of oil equivalent price of gasoline. Including taxes and the cost of refining, which all increase as the price of oil increases, due to the entropy subsidy problem (Georgescu-Roegen [28]), i.e. the problem where an initial cost estimate of energy technology inflates as the cost of energy used to make or run that technology increases. Therefore, the retail gasoline price is roughly twice that of the crude oil price or:

$$46 \cdot G_r = 2 \cdot P_{WTI}$$

where P_{WTI} = the West Texas Intermediate price of oil per barrel.

In the future, most of the natural gas in the United States will be produced from shale natural gas, although that shale natural gas is highly capital intensive relative to conventional natural gas. Currently, U.S. natural gas prices are $4.50 per thousand cubic feet (MCF) (€3.5/GJ) partly because many shale oil plays are producing both oil and natural gas simultaneously and producers are being forced to dump their natural gas on the market for whatever price they can get seeing as shale oil production provides all the profits and pays for all the costs of drilling. The rough cost of obtaining shale natural gas, where it is developed from scratch and where there is no associated oil, is about $7 to $9 per MCF (€6.5/GJ) in 2014 dollars depending on the shale natural gas play, technology and the price of metals used in the natural gas drilling capital machinery. See Rogers [29], Berman and Pittinger [30] and Mazur [31]. For now assume the future cost of shale natural gas developed in the U.S. from scratch will be $7 per MCF ($7 per GJ), and assume that eventually that greenfield cost will dictate the U.S. Henry Hub price of natural gas. In the long run, the price of shale natural gas will increase due to those real capital costs but is not expected to increase due to supply constraints. Therefore the long run price of shale natural gas should decrease due to technology and increase due to steel and metal costs and thus can be used as a real inflation index for capital and technology costs in general. That index would be:

$$I = {P_{HH}}/{A}$$

where P_{HH} is a long run average Henry Hub price, and where A is the average base year expected cost in dollars per GJ of extracting shale natural gas from a greenfield and I is a unitless inflation index that should equal unity in the long run.

Note, the inflation index is not expected to change over the long run, but it is a convenient way to integrate costs of capital in both CNG conversion and costs of extraction. The inflation index can be multiplied with the capital cost of converting a car to CNG to get an indexed real capital cost of automotive conversions, which can be added to Equation 2:

$$(8 \cdot G_r - N_r)\left[{M_i}/{8MPG}\right] = C \cdot r \cdot I$$

Since G_r, N_r and I have the P_{WTI} and P_{HH} variables subsumed, we can solve for the P_{WTI}/P_{HH} ratio, which gives us an oil to natural gas price ratio based on automotive fuel use of the two options (see appendix 1):

$$P_{WTI}/P_{HH} = 4.31 + \left[23(C \cdot r \cdot MPG)/(A \cdot M_i)\right] \quad (3)$$

Equation 3 is the future oil to natural gas price ratio paradigm. In Section II, it was seen that consumers look to require a rate of return of about 13% in order to invest in conversion capital. Also, retail borrowers often pay 13% for the cost of borrowing for automotive purchases, although we might expect a range of interest rates depending on market conditions. Assume the base cost of shale natural gas, (A), is $7 per MCF ($7 per GJ), the capital cost, (C), required to change a car from gasoline to CNG is $12,000. The typical car in America drives, 11,000 miles, (M_i), a year, and in the U.S., car mileage, (MPG), is inching up to 25 mpg. In that case, using equation 3, the price ratio of oil, in dollars per barrel, to natural gas, in dollars per MCF, will be 16 to 1 (see appendix 1). That means if natural gas at the U.S. Henry Hub is $7/MCF, then the P_{WTI} will have to be at $172 per barrel before switching occurs. However, right now oil is priced at $100 per barrel and natural gas is at $5 in the U.S. which is a ratio of 20 to 1. Such a high ratio with such a low natural gas price suggests the U.S. should already be switching to natural gas vehicles right now, but very little switching is occurring in the U.S. Part of this may be Dixit and Pindyck's [32] concept of sunk cost externalities, although there may be other barriers.

We need to look at the cost and complexity of having natural gas fueling-stations as that looks to be the reason no one is switching. In the Utah case, the government owned and ran natural gas fueling-stations, but the Utah government could not satiate demand and there were queues. So if we want market-driven, fueling-station retailers, then we need to include the cost of the retail fueling-stations themselves in our analysis. Indeed, as the Utah case shows, there tends to be limited availability of natural gas compressor fueling-stations, undoubtedly due to the expense of building them.

IV. Non-competitive market factors

One of the problems with using natural gas as a fuel for automotive transportation is the high expense of a compressor-fueling-station in order to fill up CNG tanks. Also Flynn [33] shows that market barriers to entry and monopolistic competition create a number of high costs for CNG cars including getting replacement parts. Therefore not all of the costs are taken account of in equation (3). Here, let us concentrate on the fueling-station costs, later we can look at geographical, monopolistic-competition aspects. Assume the high compressor-fueling-station costs preclude anyone from having a home compressor, but that a simple fueling-station is very expensive.

Consider again an engineering economic analysis for understanding the cost of a natural gas fueling-station market. First, we can add a fueling-station cost to equation 3. Right now a typical compressor-fueling-station would cost as much as $1 million and would operate 2 hoses. Typically, a customer can fill up a CNG tank in about 3 minutes, however, most customers may need additional time to organize themselves, put their credit card in and clean their windows. Therefore it could take 6 minutes per fill-up of an 8 gallon of gasoline equivalent CNG tank, that is 1 million British thermal units (mmBtu) or 1 GJ. If we assume that such a high cost facility requires about 35% of initial cost per year to pay for maintenance, operation, taxes and a return on capital investment, then that means typically there needs to be $350,000 per year of revenue to cover the yearly cost of a $1 million compressor-station, or roughly $1,000 per day.

If we assume most cars will be filling up during rush hour, 2 hours in the morning and 2 hours in the evening, and maybe one more hour in addition, then the fueling-station must achieve the requisite $1,000 per day in revenue, above the cost of natural gas, in 5 hours with 2 hoses, or in 600 combined minutes per day. The 600 minutes must be divided by the 6 minutes needed to fill up, which gives the number of fill ups per day at 100 that must pay for the fueling-station's capital, taxes and operational costs of $1000 per day. Thus each fill up must charge an extra $10 per fill up, i.e. $10 per GJ or roughly $1.25 per gallon of gasoline equivalent, just to pay for the compressor station. If competition is needed to make sure that one station does not have a geographical monopoly power, then you basically need two fueling-stations just to maintain competition. In that case, you would have half as many fill-ups with the same costs, which comes to $2.50 per gallon of gasoline equivalent or $20 per fill-up ($20 per GJ) just to pay for a competitive fueling-stations. Even then you could still have geographic monopoly power and barriers to entry that could well keep the price of natural gas above $3 or $4 per gallon of gasoline equivalent. This would make natural gas unusable under most assumptions until oil is well above the $200 per barrel range and even if natural gas is below $5 per MCF ($5 per GJ).

However, let us assume that compressor technology, or liquefied natural gas (LNG) technology, can be used to reduce costs of a fill-up, and let us assume that marketing strategies can be used to spread out the time when people fill-up their cars, then maybe the cost of a fueling-station can be reduced to a more reasonable $15 per fill-up ($1.85 per gallon of gasoline equivalent or $15 per GJ). Assume this creates enough spare fueling capacity to keep competition available. Using an inflation index similar to *I* above, let *b* be a technology of fill-up factor, where *b* = $15 per GJ, which is the cost of a fill up. Let us add the cost of a fill up to the equation 3.

First:

$$N_r = I \cdot b + 1.5 \cdot P_{HH}$$

So equation 2 becomes:

$$\left(8G_r - {}^{P_{HH} \cdot b}\!/_{A} - 1.5P_{HH}\right)\left({}^{M_i}\!/_{8MPG}\right) = C \cdot r \cdot I$$

And solving for P_{WTI} / P_{HH}, see appendix 2, we get:

$${}^{P_{WTI}}\!/_{P_{HH}} = 4.31 + \left({}^{23(C \cdot r \cdot MPG)}\!/_{(A \cdot M_i)}\right) + {}^{2.90 \cdot b}\!/_{A} \qquad (4)$$

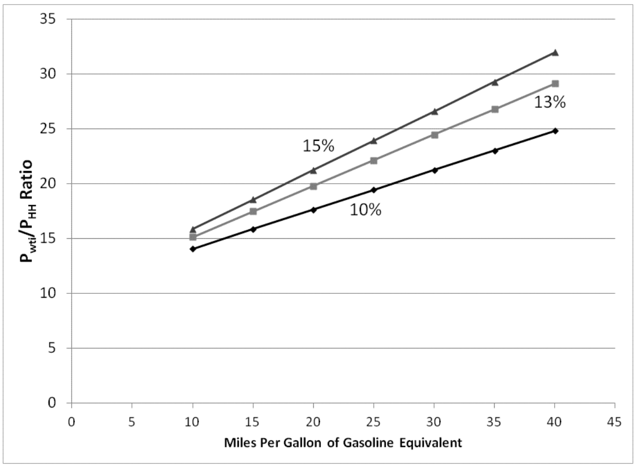

Fig 2, Oil price to natural gas price ratio, driving 11,000 miles per year and shale costs of $7 (various interest rates).

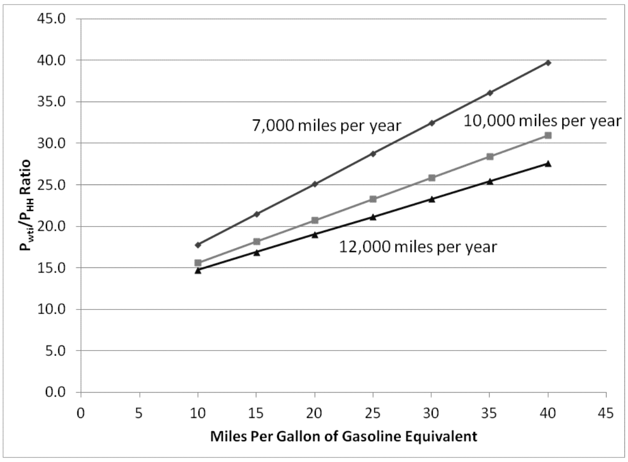

Fig 3, Oil price to natural gas price ratio with a 13% interest rate and shale costs of $7 (various miles driven per year).

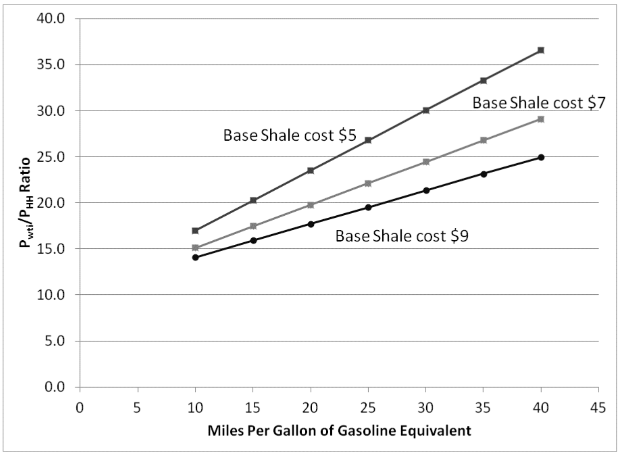

Figure 4. Oil price to natural gas price ratio with a 13% interest rate and 11,000 miles per year (various base shale costs).

Assume the base cost of shale natural gas, (*A*), is $7 per GJ, the capital cost, (*C*), required to change a car from gasoline to CNG is $12,000. The typical car in America drives, 11,000 miles, (M_i), a year, and in the U.S., car mileage, (MPG), is inching up to 25 mpg, and b = $15 per GJ. In that case, using equation 4, the price ratio of oil, in dollars per barrel, to natural gas, in dollars per MCF, will be 22 to 1. This suggests that the price of oil has to be $154 per barrel before such switching would happen. Figures 2, 3 and 4 show different scenarios for different assumptions on M_i, r and A.

V. The Natural Gas to Oil Markets

While there are many factors that could play into the automotive fuel market, such as electric cars, hybrid cars and mass transit, nevertheless, these options look to have low consumer utility. For example electric cars and hybrids look to be more expensive than liquid-fueled or natural gas cars due to the specialized materials required and mass transit typically requires two or three times the amount of passenger travel time compared to automotive travel time. So it will still be the case that in most places around the world, oil derived liquid-fueled cars will continue to be used extensively, and that as countries are able to expand natural gas options to more cities and regions, that natural gas will be able slowly to take the place of liquid-fueled cars. Therefore, we need to look closely at the economics of the switch.

Equation (4) depends on the inflation index in order to solve for P_{HH}. However, the P_{HH} variable used for the inflation index should be considered a long run average price rather than a short run volatile price. If real costs of capital increase in the long run for capital intensive shale natural gas production, then we would expect real capital costs to increase for the capital costs of converting an automobile to natural gas. Technology can cause the real costs relative to general inflation to decline, but steel and metal costs, which increased remarkably in 2007 and 2008, can cause real costs of conversions to increase relative to general inflation. The inflation index is also based on the assumption that the cost of extracting natural gas is not affected by supply constraints because natural gas supplies are considered so vast that the price of natural gas will undulate around the long run supply cost, which will be the average cost of extracting shale natural gas. Therefore this is a long run ratio.

In the future, if for any reason oil prices go above the roughly 22 to 1 ratio, everyone will begin to switch their cars to CNG vehicles, at least at the margin. If we assume that there is a deep market of existing gasoline and diesel vehicles that can be switched to CNG, then this market switch at the margin will continue to be available for many years. That means that there will be a reduction in oil demand as soon as oil prices go above the ratio and the demand for oil and the price of oil will then decline. If, though, oil prices go below the 22 to 1 ratio, then everyone who has converted their vehicles to CNG vehicles will not switch back to gasoline vehicles because the investment into CNG is a sunk cost and the price of natural gas will still be lower than oil fuels. Once the investment is made, then the consumer simply uses whichever fuel, gasoline or natural gas is cheaper per GJ and that will undoubtedly always be a natural gas option. This implies hysteresis on the part of the consumer switching, so that when oil prices go well below the roughly 22 to 1 ratio, the CNG cars will not switch back into oil.

However, another factor for the natural gas to oil price ratio is the supply of oil. Since UKERC [12] claims that the world is at peak oil and Reynolds [34] shows that shale oil may reach a peak, then if a decline in demand for oil causes the price of oil to go below the 22 to 1 ratio, the supply of oil will still be declining worldwide due to peak oil which will eventually push the price of oil back up. Considering that many underdeveloped countries will not have easy access to natural gas, but will continue to increase their automotive usage due to higher incomes, then there will always be a substantial demand increase for gasoline driven vehicles, as the world GDP increases, that will keep oil prices pushing upward. There will not be quick reaction to oil prices that go below the 22 to 1 ratio, so oil and natural gas prices can remain quite volatile, nevertheless, the overall market forces will tend to push back to the 22 to 1 ratio.

The implication of this ratio is that if natural gas is say $7 per GJ, then at a 22 to 1 ratio, oil should be $150 per barrel. If natural gas costs are higher, at say $10 per GJ in real terms, and the inflation index base price of natural gas is $10, i.e. where A = $10, then the oil to natural gas price ratio will be 17 to 1 and the price of oil will be $170. Such high oil prices would normally create speculation that oil sands, oil shale or other alternative oil technologies can create a vast and viable substitute for oil, assuming there are no supply constraints for those options such as capital, pipelines and labor, and that those substitutes force the price of oil down below such a ratio. However, many of these oil alternatives have yet to take off in substantial quantities that can take care of a significant share of the world's 80 to 90 million barrel a day thirst for liquid oil-type fuels. When oil prices rose after 2004 and the oil sands industry was primed to pick up its output, environmental problems, labor constraints and high royalties all conspired to hinder that expansion, and so oil sands bitumen supply hasn't been nearly as abundant as originally touted. See Reynolds [35].

Assuming shale natural gas supplies are vast and the CNG switching occurs, then that implies the price of natural gas could drive the price of oil worldwide rather than the reverse. In the past, oil drove natural gas prices since natural gas supplies were limited by pipeline access. Certainly natural gas has been cheaper than oil in regional natural gas markets, where supplies could not leave the region due to bottlenecks of natural gas exports. However, natural gas was never more expensive than oil since oil could relatively easily and cheaply be transported to wherever it was needed worldwide at close to the same oil price as oil was in Texas or the Middle East.

One issue with natural gas though is being able to get enough natural gas to the various markets at one time. The North American and European natural gas markets are relatively flush with natural gas pipelines from producers to consumers (see Tussing and Tippee [36]), but much of the shale natural gas occurs in new regions that may not have enough exit pipeline capacity, and much of the CNG switching will be in far flung consumer regions where natural gas entry supply capacity is still limited. Therefore, as the price of oil increases and the demand for natural gas increases in parallel, the speed with which natural gas infrastructure develops could slow down the availability of shale natural gas and cause local natural gas prices to be too high to give consumers the incentive to switch into natural gas. Pipeline bottlenecks could still hinder the price ratio relationship. However if natural gas prices manage to stay low in a give region for a year or two, then that may instill enough confidence in consumers to make the switch to CNG vehicles.

Another issue with CNG vehicle switching is the true size of the shale natural gas supply. As of now, shale natural gas potential reserves look vast, but we also saw how oil sands reserves in Canada looked vast in the past, but did not expand to that potential. Even if the shale natural gas reserves turn out to be as large as stated, it remains to be seen if the capacity of the shale natural gas production can increase in parallel to the high reserves especially since shale reserves often have high initial production rates but are followed by very low outputs for each natural gas well. Nevertheless, the world may be looking for shale natural gas to replace oil on a grand scale, and while shale natural gas may be able to replace conventional natural gas in America, it remains to be seen if shale natural gas reserves are vast enough to replace oil in the world. Clearly, oil-sands has proven to be limited in its role as an oil replacement, the same could be true for shale natural gas.

VI. Conclusion

In the past, the ratio of the price of natural gas to the price of oil was driven by electric power feedstock needs, where natural gas could easily substitute for oil fuels as an input into generating power and back again. In the future with plentiful natural gas supplies forecast, most intermittent electric power needs will be supplied from natural gas and not oil and therefore there may not be any new electric power feedstock switching. However, there still will be a relationship between the price of oil and the price of natural gas which could be driven by the switching of automotive fuels. World shale natural gas supplies may or may not be vast depending on technology, on how many shale sweet spots there are, and on political considerations. However, assuming shale natural gas is vast, then we can analyze how switching between natural gas and oil fuels will work.

Oil derived gasoline used to be considered the only low cost and dependable fuel source for automobiles, especially when compared to the problems of using and storing natural gas for CNG vehicles. Now, CNG automobile conversion is relatively easy and natural gas supplies can be relatively cheap. This suggests that switching to CNG for vehicle fuel needs will be common place in the future. If oil prices ($/Bbl) increase above a roughly 22 to 1 ratio compared to natural gas prices ($/GJ), then many vehicle owners will switch to CNG vehicles which will keep oil prices from rising farther. If the price of oil declines below the 22 to 1 ratio, then CNG vehicles will not switch back to gasoline, but new car buyers especially in countries that do not have access to natural gas will continue to buy gasoline automobiles rather than CNG cars and increase the demand and price for oil. Therefore some of the reaction to oil and natural gas price changes will be slow.

The switching of automotive fuels, at the margin, rather like the switching of electric power generation fuels at the margin in the past, will moderate the price of oil worldwide assuming that the supply of shale natural gas is as vast as speculated. That means if natural gas is say $7 per GJ, then at a 22 to 1 ratio, oil should be $150 per barrel. Currently shale oil and shale natural gas are produced simultaneously with the shale natural gas being dumped on the market which has kept U.S. natural gas prices low, but if compressed natural gas vehicles demand increases, the price would up to $7 per GJ. If natural gas costs are closer to $10 per GJ, then the oil to natural gas price ratio will be 17 to 1 and the price of oil will be $170. Volatility of oil and natural gas prices should remain high due to the lack of incentive to switch back to oil from CNG when oil prices go low; due to the possibility of bottlenecks for natural gas delivery when oil prices go high; and due to peak oil. However, in general the 22 to 1 ratio may become the new oil and gas price paradigm.

The interaction between consumers switching from oil to natural gas, LNG markets taking supplies from the U.S. to Europe and Asia, OPEC making agreements, and the Gas Exporting Countries Forum (GECF) including Russia making natural gas market moves should make for an exciting future oil and gas market and could further create bottlenecks for natural gas. The entire world oil market, and LNG market, may well be waged from the North American shale natural gas supply market and the emerging East European shale natural gas market if one emerged there. However, due to the hysteresis of switching from oil to natural gas and the possibility of short run limits to shale natural gas supplies, there should be a lot of volatility in both the oil and gas market in the future even more so than in the past.

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APPENDIX 1

Variables:

G_r = the retail price of gasoline
N_r = the retail price of natural gas
C = the cost of converting a gasoline vehicle to a CNG vehicle
r = interest rate paid
M_i = miles driven per year
MPG = miles per gallon of gasoline equivalent
P_{WTI} = the West Texas Intermediate price of oil per barrel
P_{HH} = the Henry Hub natural gas price

Assume:

$$H_r = 1.5P_{HH}$$
$$G_r = 2\left({P_{WTI}}/{46}\right)$$

and an inflation index is:

$$I = {P_{HH}}/{A}$$

where, A = the average base year expected cost in dollars per GJ of extracting shale (the gasoline equivalent price per GJ = $8 \bullet G_r$.

The cost of natural gas with the inflation index set at 1 is:

$$\left(8G_r - N_r\right)\left[{M_i}/{8MPG}\right] = C \cdot r \cdot I \qquad (2)$$

Solving for ${P_{WTI}}/{P_{HH}}$

$$\left[\left({8 \cdot 2 \cdot P_{WTI}}/{46}\right) - 1.5P_{HH}\right]\left[{M_i}/{8MPG}\right] = C \cdot r \cdot \left({P_{HH}}/{A}\right)$$

$$\left({8 \cdot 2 \cdot P_{WTI}}/{46}\right) - 1.5P_{HH} = {8MPG \cdot C \cdot r \cdot P_{HH}}/{A \cdot M_i}$$

$$0.3478\ P_{WTI} = \left[{(8MPG \cdot C \cdot r)}/{(A \cdot M_i)} + 1.5\right] P_{HH}$$

$${P_{WTI}}/{P_{HH}} = \left[{1.5}/{0.3478}\right] + \left({8}/{0.3478}\right)\ \left[{(MPG \cdot C \cdot r)}/{A \cdot M_i}\right]$$

$${P_{WTI}}/{P_{HH}} = 4.31 + {23(MPG \cdot C \cdot r)}/{A \cdot M_i} \qquad (3)$$

When C =\$12,000; r = 13%; MPG = 25 mpg; A = \$7.00 per MCF, and M_i = 11,000 then:

$${P_{WTI}}/{P_{HH}} = 16$$

If P_{HH} = \$7, then P_{WTI} = \$112 per barrel.

APPENDIX 2

Competitive fueling-station cost of natural gas scenario:

$$N_r = I \cdot b + 1.5 \cdot P_{HH}$$

where b is the expected cost per MCF (equivalent to the cost per GJ) of the fueling-station.

Start with equation (2)

$$\left(8G_r - N_r\right)\left[{M_i}/{8MPG}\right] = C \cdot r \cdot I \qquad (2)$$

Substitute for Nr gives:

$$\left(8G_r - b \cdot I - 1.5P_{HH}\right)\left[{M_i}/{8MPG}\right] = C \cdot r \cdot I$$

Then, solving for $\left({P_{WTI}}/{P_{HH}}\right)$ we have:

$$\left[\left({8 \cdot 2 \cdot P_{WTI}}/{46}\right) - \left({b \cdot P_{HH}}/{A}\right) - 1.5P_{HH}\right]\left[{M_i}/{8MPG}\right] = \left({C \cdot r \cdot P_{HH}}/{A}\right)$$

$$\left({8 \cdot 2 \cdot P_{WTI}}/{46}\right) - \left({b \cdot P_{HH}}/{A}\right) - 1.5P_{HH} = \left({8MPG \cdot C \cdot r \cdot P_{HH}}/{A \cdot M_i}\right)$$

$$0.3478 \cdot P_{WTI} = \left[{(8MPG \cdot C \cdot r)}/{(A \cdot M_i)} + \left({b}/{A}\right) + 1.5\right] P_{HH}$$

$${P_{WTI}}/{P_{HH}} = \left[{1.5}/{0.3478}\right] + \left({8}/{0.3478}\right)\ \left[{(MPG \cdot C \cdot r)}/{A \cdot M_i}\right] + \left({1}/{0.3478}\right)\left({b}/{A}\right)$$

$${P_{WTI}}/{P_{HH}} = 4.31 + \left[{(23 \cdot MPG \cdot C \cdot r)}/{(A \cdot M_i)}\right] + 2.875\left({b}/{A}\right) \qquad (4)$$

When C =\$12,000; r = 13%; MPG = 25 mpg; A = \$7.00 per MCF; b = \$15 per MCF, and M_i = 11,000 then

$$P_{WTI} / P_{HH} = 22$$

When P_{HH} = \$7 per MCF (i.e. per GJ), then P_{WTI} = \$154 per barrel.