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James L. Sweeney*

In the decades prior to 1973, demand for energy, particularly energy liquids and electricity, expanded exponentially. From 1950 to 1973, U.S. aggregate energy use grew by 3.5% per year, roughly matching real GNP growth (3.7%). Demand shifted toward petroleum (4.3% annual growth) and electricity (7.7%) and away from coal (1.0% annual growth). These trends, reflected throughout the world, were encouraged by flat or gradually declining energy prices.

Since 1973 energy price increases have been pervasive, although increases have differed radically among energy carriers and over time, being largest since 1979. From 1973 to 1982, real gasoline prices to consumers have increased 51%, natural gas delivered to households 139%, and residential electricity average price only 23%. Fuel prices delivered to electric utilities have varied more: oil increased 175%, natural gas, 350%, while coal price increased but 85%.

Energy demand adjustments have been profound. Between 1973 and 1982, U.S. consumption of oil and gas have both declined, oil averaging a 1.4% annual decline, and natural gas, 2.3%. Electricity growth has been reduced to 2.1% per year. Of the fossil fuels, only coal demand has been encouraged, rising at an average annual rate of 2.6%. U.S. primary energy use declined at an annual rate of 0.6%. And measured after subtracting electric utility conversion losses (secondary energy), use declined 1.3% annually since 1973. Non-communist world oil consumption declined from 48 million barrels per day (mmb/d) in 1973 to 46 mmb/d in 1982, and primary energy consumption has fallen annually since 1979. On the other hand, coal consumption increased an average of 2.3% per year. While demand reductions have been unsteady, occurring primarily since 1979, the old growth patterns have clearly been radically altered.

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Thus following large increases in energy prices, demands have shifted toward coal, the fuel experiencing the smallest price increase, and away from oil and gas, fuels experiencing the greatest increases. Overall energy demand growth has been severely curtailed.

A natural experiment was created allowing examination of sensitivity of energy consumption to prices. However, there have been government and utility sponsored conservation programs, information campaigns, tax incentives, and moral suasion. Since 1973, U.S. economic growth has diminished, with average real GNP growth only 1.8% per year. We are just recovering from a recession involving low capacity utilization. Thus although we have accumulated a vast body of evidence, that evidence is subject to a variety of interpretations.

My goal is to communicate key conclusions learned partially through the natural experiment and partially through information available prior to 1973. The exposition progresses from very general conclusions about the nature of energy demand toward more specific quantification of energy demand elasticities.

I. GENERAL CONCLUSIONS

Aggregate statistics suggest there have been significant reductions in energy use, referred to as **energy conservation** and significant shifts from one energy carrier to another, referred to as **interfuel substitution.**

Proposition 1. **Demand responses to higher energy prices -- energy conservation and interfuel substitution -- typically involve substitutions of other factors for energy, one energy carrier for another, or both mechanisms.**

Study of demand responses involves study of substitution mechanisms -- an idea subtly different from assumptions that energy conservation is reduction of "waste" in use of energy or "fat" in the system. Most involve substitution of one input for another: capital for energy, labor for energy, one form of energy for another, or, perhaps most commonly, combinations of capital, labor, and energy for other combinations having different factor proportions.

To understand substitution processes, one should understand several fundamental characteristics of energy use. The first can be summarized:

Proposition 2. **In virtually no uses are energy commodities desired for themselves. Energy demand is derived from demand for more basic end products: e.g. warm or cold space, process heat, transportation, light, or motive power.**

Many substitute processes to produce the same end product could use less energy or could use different energy carriers. Energy price increases motivate firms and consumers to select such substitute processes and thereby to conserve energy or to substitute fuels, even without changing the mix of end products. For example, insulation allows the same amount of warmth to be produced using less energy, more capital, and more labor to install the insulation. Natural gas, oil, or electricity can heat interior space.

Substitution among end products also occurs. When energy prices rise, end products characterized by high energy factor proportions (either used directly or indirectly) increase in price and users substitute from these products, reducing energy demand and demand for complementary products. For example, when electricity prices increase, cost of airconditioned space rises, firms and consumers use less, reducing demand for appliances and electricity.

Proposition 3. **Energy is used in virtually all economic activity, but factor proportions vary widely. Thus use of non-energy commodities involves indirect energy use, but quantities of such embodied energy vary greatly.**

Energy demand may be reduced even without change in energy used directly per unit of any activity. Increasing energy prices increase relative price for commodities embodying higher than average energy intensity and motivate substitutions from these commodities, thereby reducing energy demand in the economy. For example, transportation costs rise relative to telecommunication costs as energy prices rise, firms substitute telecommunication for transportation, and overall energy demand in the economy decreases.

This proposition implies that the energy demand elasticity for the entire industrial sector or economy can be greater than the energy demand elasticities averaged over all individual industries.

Proposition 4. **Most energy is used in conjunction with long-lived capital equipment which, once in place, has fairly fixed energy requirements per unit of equipment use.**

Mechanisms underlying short-run responses may be qualitatively different from those underlying long-run responses. Short-run responses are primarily related to changing intensity of utilization of energy using equipment and only secondarily related to changing factor proportions. In the long run, not only can usage intensity be changed, but also factor proportions of the new energy using capital equipment may be quite different from those of the old equipment it replaces. And equipment quantities can vary radically.

For example, existing automobiles can be driven less, and fuel efficient cars can be driven more, relative to less efficient ones. Maintenance can influence fuel performance, but fuel efficiency of existing autos does not change greatly in response to energy price increases. In the longer run fuel efficiency of new cars may be fundamentally altered when energy prices rise.

Although this proposition and conclusions have been empirically supported for gasoline in automobiles, electricity use by household appliances, residential space heating, and electricity generation, it has not been fully tested. But I expect further generalization.

Proposition 5. **Long-run energy price adjustments tend to be substantially greater than adjustments occurring over several years or even a decade. Thus conservation and interfuel substitution motivated by price rises can continue to increase for many years after prices stop rising.**

This result, suggested by differences in long-run and short-run adjustment processes, follows when the capital stock turns over slowly and when capital stock changes can quantitatively dominate utilization changes.

Gasoline use by automobile is a good example. Fuel efficiency of the average automobile in 1973 was 13 miles per gallon (mpg). Although new car on-the-road performance increased to 23 mpg by 1982, the average automobile in 1982 obtained only 16 mpg, since the automobile stock is dominated by older cars. In long-run equilibrium, if new car efficiency remains at the current level, average efficiency will increase toward 23 mpg. Thus long-run demand response through auto stock efficiency would more than double the response to date. Even if gasoline prices fall and new car efficiency drops somewhat, gasoline consumption per mile of driving would continue to decline.

The same phenomenon occurs for other uses. Survey data suggest that thermal properties of new U.S. homes heated by natural gas imply an average annual average consumption of 190 mmBtu/1000 square feet, compared to 280 in 1973. Since new homes constructed annually represent only 1%-2% of the stock, only a small proportion of the ultimate adjustment has been seen to date.

Limits on capital equipment supply can further reduce adjustment speed. For example, short-run limits on the rate of insulation manufacture and installation reduce capital stock adjustment speed and further lengthen adjustment time.

Development of new technology responds to higher energy prices. This process involves very long lags: research and development, testing, commercialization, capital stock turnover, and finally energy use. High energy prices have launched such processes and adjustments will continue for years. Examples include electronic monitoring, control, and software for HVAC systems, improvements in internal combustion engines, more efficient electric motors, solar panels for homes, and newly designed fuel efficient airplanes.

Proposition 6. **Although adjustment of demand to higher prices can be expected to be slow, the precise adjustment rates are unknown.**

Purely econometric studies using any common distributed lag functional forms are weak for estimating dynamics. Process models, theory, and end use data suggest slow adjustment, but all are based upon assumptions about short-run changes in utilization intensities and factor proportions.

Adjustment speed conclusions are important for understanding future effects of energy price changes and for interpreting recent history. The higher the adjustment speed, the greater the fraction of long-run adjustments experienced so far, the smaller the adjustments still to be expected, and the lower the implied long-run demand elasticity.

Other dynamic issues may be important. Economic downturns characterized by large drops in capacity utilization may lead to temporary energy demand reductions which will disappear when capacity utilization again increases.

Because post-1973 energy-using equipment generally uses less energy per unit of output than equipment from older vintages, input factor proportions vary widely in the existing capital stock. This capital heterogeneity implies that declines in capacity utilization allow firms to select which units to temporarily retire. Most likely to be withdrawn is older equipment with a high ratio of energy use to output. Thus declines in capacity utilization will reduce energy use standardized for output level; subsequent utilization increases should reverse the reduction. I speculate that the large drops in capacity utilization in manufacturing and electricity generating sectors during the recession have in this way temporarily reduced energy demand.

Because faster economic growth implies faster turnover of the capital stock, whenever new capital stock is more efficient than old, faster growth in economic activity implies more rapid adjustment and therefore declines in energy use per unit of economic activity. This phenomenon helps to explain Japan's impressively rapid adjustment to higher energy prices.

Proposition 7. **Energy consumption occurs at some location. Changes in economic activity may change the location of energy consumption but may or may not influence total energy consumption.**

Migration of industries between nations or regions may occur in response to energy price differences. Such migration reduces energy consumption in the initial location, but may increase, decrease, or leave unchanged energy consumption overall. Such migration will occur in response to energy price locational differentials but not to general increases in energy prices.

This proposition has methodological significance. Empirical cross-section studies measure long-run demand differences motivated by locationally differentiated prices. These studies thus implicitly include inter-regional migration motivated by price differentials. Because a general increase in energy prices will not create such differentials, such studies may overstate long-run price elasticities relevant to a general increase in energy prices.

I now turn to quantification of elasticities. Aggregate responses will be discussed prior to fuel specific responses. Except where noted, all quantitative estimates refer specifically to the United States.

II. AGGREGATE RESPONSES TO ENERGY PRICE INCREASES

The aggregate elasticity of energy demand measures the impact of energy prices on the consumption of all energy. The term "aggregate elasticity" implies a rule or index for aggregating prices and quantities of various energy commodities. The precise rule is important because energy prices and quantities do not all change in the same proportions.

A common quantity aggregator uses heat values per unit of specific energy carriers to convert physical quantities into total quantities of energy. Such a sum is typically expressed in millions of Btu's (mmBtu) or quadrillions of Btu's (quads). Alternatively, one could treat energy like any other commodity and aggregate using price and quantity weights, e.g., Paasche, Laspeyres, Ideal, or Tornquist indices. In what follows a Tornquist index is used. Although results would be virtually invariant among these four indices, choice of heat values as an aggregator could change the measured elasticity.

Total energy use can either include conversion losses in electricity generation (generally referred to as primary energy) or exclude these losses (secondary energy). Demand elasticity varies systematically depending upon where prices and quantities are measured. Elasticities measured at the point of first production (primary energy) will be lowest, those measured at the busbar and refinery gate (secondary energy) will be higher, while those measured at the point of delivery (delivered energy) will be the highest.

Proposition 8. **The long-run aggregate elasticity of demand for secondary energy is likely to be in the range of -0.4 to -0.7. Measured at the point of delivery, the probable range is 25% to 50% higher, while at the primary level the probable range is 10% to 30% lower.**

Since primary and secondary elasticities are probably smaller than unity, increases in energy prices can be expected to increase the share of output used to pay for energy costs even in the long-run.

Propositions 5, 6 and 8 all suggest that under current prices energy demand adjustments are far from over. The producer price index for fuel and power increased relative to the GNP implicit price deflator by a factor of 2.6 from 1972 to 1983. The -0.4 to -0.7 range suggests a 32% to 49% long-run reduction of secondary energy use per dollar of GNP. U.S. consumption per GNP dollar has decreased 25%, significantly less than the long-run estimate.

What is the basis of Proposition 8? Secondary demand elasticity estimates were derived through the Energy Modeling Forum study [2], but the general range is consistent with much evidence. See Hogan [4,5] for more detailed discussion. Econometric studies based upon U.S. data -- either time series or cross-section -- have been conducted using a variety of techniques and give results well within this range. Cross-sectional studies among OECD countries tend to provide the highest estimates. In addition, more detailed international comparisons, particularly between Sweden, the U.S., and Canada suggest much room for further North American adjustment. Structural models suggest that factor proportions can adjust greatly in the U.S. economy. Evidence from engineering studies of specific technologies such as refrigerators and detailed studies of energy consuming sectors show that much energy conservation and fuel switching has occurred and is continuing to occur, and that at current prices much more is cost effective. All this evidence is generally consistent with the cited range and strongly supports the proposition that more adjustments are to come.

Factors in Proposition 8 for translating to delivered or primary elasticity are still fairly judgmental. They are based upon estimated cost markups, including taxes, at different stages of the supply chain.

Aggregate elasticity must be used with caution. Aggregate elasticity is sensitive to precise composition of price changes and is only a rough guide.

One complicating factor which could potentially make analysis of the historical record more difficult is the role of government programs:

Proposition 9. **The extent to which government sponsored energy conservation programs or other non-market forces have reduced the demand for energy is unknown. However at least 80% and probably much more of the demand reductions can be attributed to price and economic activity changes.**

Educated opinions vary on the effects of the Federal energy conservation programs and other non-market forces such as utility conservation programs and fear of shortages. Econometric estimates attribute to non-market forces as much as 20% of conservation occurring to date [3] or as little as 0% [5]. Department of Energy [7] estimates based upon program reviews suggest less than 5% of the observed conservation is based upon Federal programs, but ignore the role of the fuel efficiency standards for new cars (CAFE standards).

Analysis of non-market forces is necessary for interpreting the historical record. The greater the role of forces other than prices and economic activity, the smaller the market response that can be inferred from observed energy consumption reductions. However, even using the highest estimates of non-market forces, at least 80% of the observed demand adjustment has resulted from price and economic growth changes.

Proposition 10. **The extent to which the current recession has contributed to the reduced energy demand is subject to debate.**

As discussed above, with heterogeneous capital stock, low capacity utilization could reduce energy demand. How much of the current industrial sector demand reduction can be attributed to this phenomenon is not clear, although some electric utility fuel shifting undoubtably can be. Thus, to the extent the recession has contributed to the sharp drop in oil and energy use of the last two years, these recent data may overstate the demand reduction to be expected for the next few years, although not for the long-run.

Propositions 6, 9, and 10 help explain why one cannot simply infer long-run price elasticities from measuring demand reductions occurring to date. Some reductions are due to factors other than economic activity and price; we cannot be sure how much reduction is due to changes in economic growth or to the recession; we do not know adjustment speeds precisely and thus do not know the ratio of long-run elasticity to short or intermediate-run elasticities.

III. FUEL SPECIFIC PRICE RESPONSES

Since energy price changes can lead to conservation and interfuel substitution, demand for an energy carrier will be decreasing in its price and increasing in prices of competing fuels: own elasticities will be negative and cross elasticities will be positive. The aggregate elasticity must be smaller than the weighted average of fuel specific own elasticities. Thus the fuel specific secondary elasticities should on average be more negative than the -0.4 to -0.7 range and delivered energy elasticities should on average be more negative than the -0.5 to -1.0 range.

Proposition 11. **The long-run delivered price elasticity of demand for electricity probably exceeds unity but may be as low as -0.7.**

While most studies suggest elasticities exceeding unity, many careful studies estimate lower figures [1,6]. But these econometric studies would not be expected to capture effects of new technologies created in response to increases in electricity prices. While the lower estimates cannot be rejected, the higher elasticity is more probable.

If the elasticity does exceed unity, electricity price increases may not increase long-run revenue for utilities; however, such increases can improve the financial situation of regulated utilities by greatly reducing or eliminating the need for new capital equipment.

Consistent with economic theory, marginal electricity prices empirically seem more important than average prices in determining demand. In recent years many public utility commissions have ordered utilities to structure rates to eliminate declining block structures and to introduce "lifeline" and other increasing block rate structures. These changes may have contributed to the demand growth decline and may continue to do so.

The many studies of electricity demand have collectively established that estimated elasticities can vary widely when different data bases or methods are used [1]. Thus demand growth uncertainty remains. Since uncertainty will be greatest for equipment requiring long lead times, such as coal fired or nuclear generators, I expect utilities to continue to shun such projects.

Proposition 12. **We have only poor information on the long-run demand elasticities for natural gas.**

There has virtually never been an unconstrained market for natural gas; in early years pipelines were being constructed and access was limited, in later years shortages precluded new hookups. Thus econometric studies could capture the role of prices in influencing conservation but underestimate interfuel substitution. Therefore we have only poor information about demand for natural gas and about the effect of natural gas prices on demands for other energy carriers.

Proposition 13. **The demand of oil, natural gas, and coal in the industrial sector (including electricity generation) is a highly non-linear function of price of those fuels and of competitive fuels.**

Many electric utility or industrial boilers are fitted to use either oil or gas, or sometimes coal slurries. In the longer run, new construction also allows coal to be used for large boilers. Therefore direct interfuel substitution can be extensive when fuel prices are nearly equivalent on a cost per Btu basis. But for prices significantly different from Btu equivalence, almost no interfuel substitution can be expected. Thus own and cross elasticities will be very large at prices which could motivate the substitution and virtually zero elsewhere.

Proposition 14. **There is almost no possibility for interfuel substitution in non-rail transportation; thus the demand for petroleum in this sector will be virtually independent of other energy prices.**

Energy conservation can be expected to dominate with little interfuel substitution since liquid fuels are virtually required for these transportation activities.

Proposition 15. **Short-run delivered elasticity of demand for gasoline is near -0.2 and long-run elasticity is probably in the -0.6 to -1.0 range.**

Petroleum is the predominant fuel for transportation, with gasoline for automobiles the largest component. The demand elasticity through automobile utilization is low (in the range of -0.2) while the elasticity through changes in automobile efficiency is far higher (in the range of -0.7). Elasticity estimates are far more consistent across studies than for other fuels.

IV. IN SUMMARY

There remains much quantitative uncertainty about responses of energy demand to higher prices and thus much opportunity for further research. However, the natural experiment has made virtually unrefutable the proposition that price changes have motivated much conservation and interfuel substitution and that much more adjustment should be expected over the years.

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