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ABSTRACT

Any discussion about the future pattern of energy use invariably includes scernarios involving a switch-over to that source of energy which is available in abundant supply. It is taken for granted, for example, that coal will play a major role in the future and that the relative share of oil will decline with the passage of time. It is too simplistic to assume that a time series analysis will give the likely clues as to the pattern of switch-over from one source of energy to another. There has been a radical change in the structure of exchange relations between the energy consumers and producers which makes it impossible to use the past consumption data alone for the purpose of forecasting.

## 1

Since the input-output relations describing the structure of production constantly undergo changes in response to inventions, technological innovations and other market conditions, the demand for specific inputs also behaves likewise. Energy, being an integral part of the production process, is no exception. But in the case of energy there is a complication. Not only that the demand for energy undergoes changes in response in changing input-output relations, but that the demand for specific forms and sources of energy also behaves as if they were different commodities. Different periods in history have been marked by dominance of one source of energy over others. In the United States, for instance, till less than a century ago, wood and farm waste were the dominant sources of energy. Then came the coal epoch, only to be replaced by petroleum and natural gas in recent times. Now that the petroleum and natural gas have become relatively 'dear', one can speculate as to what other source of energy would replace petroleum and natural gas as the dominant source. It is this problem of substitution of one source of energy by another that is addressed to in this paper.

## 2

Marchetti (1977) used a simple economic model to estimate the probable period of dominance of a source of energy. Assuming different fuels as competing commodities, eager to expand their market shares, he hypothesized, on the lines suggested by Fisher (1974), that 'the rate at which a new commodity penetrates a market is proportional to the fraction of the market not yet covered.'

Thus,

$$(1/F)(dF/dt) = \alpha(1-F) \text{ or} \quad (1)$$

$$\ln(F/1-F) = \alpha t + C \quad (2)$$

where F = fraction of market penetrated and $\alpha$ and C are constants specific to particular source of energy.

Using energy consumption data for over a hundred years and denoting the difference between total energy demand and the demand for particular source as the share of market yet to be captured, Marchetti derived some interesting results. He believes that substitution, in general, proceeds at a very slow pace, and in the case of energy, it takes at least a century or so for one source to expand its market share from one percent to fifty percent. The prospects of any alternative source replacing petroleum and natural gas, in the near future according to him, are very dim, since the technological development of a new source has a very long lead time.

Marchetti's general results are too general and may not help the policy maker in designing or prognosticating about the future pattern of energy consumption. For one, any time series analysis only replicates the past. And the last one hundred and odd years of energy data are not a very useful guide for the future. There are several reasons for this. There has been a radical transformation of the environment in which past data were generated. Even though the principal producers and consumers of various fuels were two different sets of people, the consumers, in the past, were controlling the production of these fuels without much difficulty. There was no talk of producer or commodity power. The focus of the present energy problem is the dichotomy between producing and consuming agents, with different objective functions, and operating under various non-market forces. Secondly, the distribution of income among nations (in the context of North-South confrontation and the New International Economic Order), and the technological breakthroughs have generated a climate in which the signals for substitution are completely different from what they were in the last hundred years. Lastly, the awareness of the presence of relatively short and finite quantities of different sources of energy has created a new factor which modifies the consumption behaviour considerably. Because of these reasons a simple time series analysis may not be capable of guiding the policy-maker very much. In the next section a simple, but relatively more detailed, model is presented which takes into account the changed circumstances. It is presented in static terms for easy exposition, but it can be very easily converted into a dynamic model.

3

Let there be two sources of energy and let their demand functions be represented by

$$p_1 = p_1(q_1, q_2 t) \quad (3)$$

$$p_2 = p_2(q_1, q_2 t) \quad (4)$$

where $p_i$ are prices of primary energy sources and $q_i$ their quantities demanded. Let $C_i(q_i)$ represent their cost functions. Then the profit function is denoted by

$$\pi = p_1(q_1, q_2, t)q_1 - C_1(q_1) - p_2(q_1, q_2, t) + C_2(q_2). \quad (5)$$

The profit function could be of a firm or it could represent the gain to the nation by the use of two energy souces.

$\pi$ can be maximised under the following conditions

$$\frac{\partial\pi}{\partial q_1} = p_1 - q_1\frac{\partial p_1}{\partial q_1} - q_2\frac{\partial p_2}{\partial q_1} - \frac{\partial C_1}{\partial q_1} = 0 \qquad (6)$$

$$\frac{\partial\pi}{\partial q_2} = -p_2 + q_2\frac{\partial p_2}{\partial q_2} + q_1\frac{\partial p_1}{\partial q_2} + \frac{\partial C_2}{\partial q_2} = 0$$

$$\frac{\partial\pi}{\partial t} = q_1\frac{\partial p_1}{\partial t} - q_2\frac{\partial p_2}{\partial t} = 0$$

and the second order conditions are fulfilled. If $\varepsilon_{dij} = \frac{\partial q_i}{\partial p_j} \cdot \frac{p_j}{q_i}$ then (6) can be written as

$$p_1(1-\frac{1}{\varepsilon_{d11}}) - \frac{p_2 q_2}{q_1}\cdot\frac{1}{\varepsilon_{d12}} - \frac{\partial C_1}{\partial q_1} = 0 \qquad (7)$$

$$p_2(1-\frac{1}{\varepsilon_{d22}}) - \frac{p_1 q_1}{q_2}\cdot\frac{1}{\varepsilon_{d21}} - \frac{\partial C_2}{\partial q_2} = 0$$

$$\frac{q_2}{q_1} = \frac{\dot{p}_1}{\dot{p}_2}.$$

we would be very much interested in the ratio $q_2/q_1$ whose value greater than 1 indicates that $q_2$ is the dominant source of energy, with a market share greater than 50%.

The first two expressions of (7) would give

$$\frac{q_2}{q_1} = \frac{\varepsilon_{d12}}{p_2}[p_1(1-\frac{1}{\varepsilon_{d11}}) - \frac{\partial C_1}{\partial q_1}] \text{ and } \qquad (8)$$

$$\frac{q_2}{q_1} = \frac{p_1}{\varepsilon_{d21}}[\frac{1}{p_2(1-\frac{1}{\varepsilon_{d22}}) - \frac{\partial C_2}{\partial q_2}}]. \qquad (9)$$

Examining (8) and (9) we can lay down mathematical conditions under which $\frac{q_2}{q_1}$ will be greater than one or will tend towards as large a value as possible.

Since own price elasticities ($\varepsilon_{dii}$) and cross elasticities ($\varepsilon_{dij}$) can be estimated and marginal cost ($\partial C_i/\partial q_i$) and price ($p_i$) data are available over a period of time, a series of $\frac{q_2}{q_1}$ values for any set of two energy resources can be estimated to give trends, indicating how the substitution is taking place. These trends will give a better insight into the likely pattern that will emerge as will be based upon recent historical evidence. They can also be used for forecasting purposes if we can reasonably well estimate the elasticities, prices and cost variables.

This approach has several points to commend itself. It is based upon market conditions which reflect, in terms of prices, the changing market behaviour of different energy resources. The marginal cost estimates capture the technological changes that have taken place in production techniques. The own price elasticities of demand reflect the changing behaviour of consumers in response to a host of changes taking place in the market environment. It is therefore a great improvement over the method suggested by Marchetti.

The empirical work along these lines is underway which will be reported in a subsequent effort.

References:

Fisher, J.C. (1974) Energy Crisis in Perspective, Wiley.

Marchetti, C. (1977) "Primary Energy Substitution Models: On the Interaction Between Energy and Society", in Nordhaus, W.D. (ed.). International Studies of the Demand for Energy, North Holland.