Measuring Willingness to Pay for Electricity

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Foreword

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Abstract

The measurement of willingness to pay for electricity relies critically on a reliable estimate of the demand for electricity function. However, standard microeconomic theory falls short in providing a plausible framework within which such estimation could be made, at least in the case of electricity. Empirical work to date generally tends to assume that the demand for electricity has no satiation point. Many electricity demand models assume a constant price elasticity, which implies infinite demand at low prices. Many demand models also do not allow for the possibility of goods at zero price because the price variable is in logarithmic form for which zero is undefined. The purpose of this technical note is to propose a plausible functional form for the demand for electricity. The proposed functional form is consistent with two properties of electricity demand functions for households and firms, namely, the negative relationship between price and quantity, and the finiteness of demand at zero price. The technical note also demonstrates that this functional form of the demand function leads to easily estimable economic benefits of electricity.
I. Introduction

Measuring willingness to pay for electricity relies critically on a reliable estimate of the demand for electricity function. However, standard microeconomic theory falls short in providing a plausible framework within which such estimation could be made, at least in the case of electricity. Empirical work to date generally tends to assume that the demand for goods has no satiation point. Many electricity demand models (for a survey of some of these models, see Taylor 1975 and Westley 1989) assume a constant price elasticity, which implies the double logarithmic functional form. It also implies infinite demand at low prices. It is intuitive that, even at zero price, the demand for some goods will be finite. Many single equation and demand system models also do not allow for the possibility of goods at zero price because the price variable is in logarithmic form for which zero is undefined. The main examples of these models are Stone’s (1954) double logarithmic demand model; Theil’s (1965) and Barten’s (1966) Rotterdam model; the translog model of Christensen, Jorgensen, and Lau (1975), and the almost ideal demand system of Deaton and Muellbauer (1980b). Nan and Murry (1992) developed a demand model that overcomes some of the theoretical shortcomings of the double logarithmic functional form identified by Deaton and Muellbauer (1980a), but it still employs the logarithmic price term. Although the use of a logarithmic price variable in econometric studies of electricity demand has little a priori justification, recent studies, for example Haas and Schipper (1998) and Beenstock, Goldin, and Nabot (1999), demonstrate the continuing popularity and use of this variable.

Empirical studies have typically treated electricity as just one good of many consumed by households. Strictly speaking, this is correct—households do consume electricity. But the demand for electricity is a derived demand and is essentially an input into the production of services from a stock of electricity-consuming equipment in the household. Electricity is never consumed on its own and, moreover, cannot be stored in an economical way. Therefore, there should be no reason to assume that electricity enters directly into a household’s utility function. Rather it should be expected that it enters indirectly through the user cost associated with the services produced by the electricity-consuming equipment. Consequently, the demand for electricity function cannot be derived using the normal constrained utility maximization procedure.

In practice, electricity demand models are seldom employed for measuring willingness to pay because sufficient amounts of data are not available, especially in developing countries. The usual approach is to calculate consumer surplus (CS) on the basis of a linear electricity demand function. Consumer surplus is estimated as:

\[ CS = \frac{1}{2} (p_A - p_B)(q_B - q_A) \]  

The linear demand function is often selected because only two data points are needed to estimate its parameters. One data point is the price and quantity of an alternative source of energy

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1 Deaton and Muellbauer (1980a) have shown that the double logarithmic demand function is not consistent with consumer theory because it violates the adding up condition.

2 Consumer surplus plus revenue equals gross economic benefit (or willingness to pay) by definition. See Figure 1 for a graphical representation.
consumed (converted to electrical units), for example kerosene, in an area where electricity is not available (point A in Figure 1). Data on the quantity of the alternative source of energy consumed is usually obtained from surveys while the price is obtained from market data. The other data point is the quantity of electricity consumed by the representative household and the corresponding average price paid for the consumption (point B in Figure 1). This information is readily available from the utility supplying the electricity.

From a mathematical perspective, a straight line closely approximates a curve for small changes in the variables and therefore the use of a linear demand function is justified. More often than not, however, the change in the price variable in the case of estimating willingness to pay for electricity is not small and the straight-line assumption does not hold. Therefore, to reflect curvature in the demand function, the practice has been to modify equation (1) to:

\[
CS = \frac{1}{\epsilon + 1} \left( P_A - P_B \right) \left( q_B - q_A \right)
\]  

where \( \epsilon \) is a proportionality factor greater or equal to unity. The parameter \( \epsilon \) may be calculated with a third data point. Unfortunately, a third data point is rarely available and consequently an assumption is usually made regarding the value of this parameter. Values in the range of 1.5 to 3 are often used. In the case of equation (1), \( \epsilon = 1 \).

There are two principal weaknesses of this approach to measuring willingness to pay. First, there is no theoretical basis for the linear demand function and the use of it is essentially a matter of convenience. Second, the assignment of a value to the parameter \( \epsilon \) is often arbitrary and leads to an arbitrary valuation of consumer surplus.

The arbitrary nature of the linear demand function, the shortcomings in applying constrained utility maximization to derive a demand for electricity function, and the need for a demand function that allows satiation indicate that an alternate approach to deriving the demand for electricity function is needed. The purpose of this technical note is to discuss such an approach.
II. Derivation of the Electricity Demand Function

A. The Household Demand for Electricity

In deriving the demand for electricity function, one begins with an individual’s or household’s utility function $U$ such as

$$U = U(q^x, q^y, q^z, ..., q^k)$$

where $q^x$ and $q^y$ are quantities of goods and services consumed, respectively. When the utility function is maximized subject to a budget constraint, ordinary demand functions for each good and service may be derived. These demand functions relate the quantity of the good or service demanded to income and all prices (in the case of goods) and user costs (in the case of services). Let us assume a single composite piece of electricity-consuming equipment to represent all such equipment to simplify exposition. The demand function for the services from this stock of equipment $q^y$ will be

$$q^y = f(y, p^y, p^o) \quad (3)$$

where $y$ is income, $p^y$ is the user cost of $q^y$, and $p^o$ is a vector of all other prices and user costs. For a normal good, the user cost is negatively related to the quantity demanded, that is, $df/dp^y < 0$.

Since the user cost $p^y$, of which the electricity price is a component, is negatively related to the quantity of services demanded from electricity-consuming equipment, it may be shown that the electricity price is also negatively related to the quantity of electricity demanded. The user cost and the price of electricity are positively related because the electricity price is a component of user cost. Thus,

$$p^y = g(p^r) \quad (4)$$

where $dp^y/dp^r > 0$ and $p^r$ is the price of electricity. The quantity of electricity demanded $q^r$ is also positively related to the quantity of services from electricity-consuming equipment because of technology. Thus,

$$q^r = b(q^y) \quad (5)$$

where $dq^r/dq^y > 0$. Substituting equation (4) into (3) and then substituting the result into equation (5), one gets

$$q^r = b(f(g(p^r))) \quad (6)$$

Differentiating equation (6) with respect to $p^r$, one gets
\[ \frac{dq^e}{dp^e} = \left( \frac{db}{dq^e} \right) \left( \frac{df^e}{dp^e} \right) \left( \frac{dg}{dp^e} \right) \]

and thus \( \frac{dq^e}{dp^e} < 0 \), that is, the electricity demand function is negatively sloped with respect to its price.

The demand for electricity should also have an upper bound. For a given stock of electricity-consuming equipment, the amount of electricity that is consumed is determined by the user cost of electricity-consuming equipment, composed of the electricity price and other costs such as capital depreciation, maintenance, etc. This is represented by point A in Figure 2. At point A, the user cost is \( p_{se}^A \) where the subsumed electricity price is \( p^e = p^* \) and corresponds to quantity \( q_{se}^A \). If the electricity price is allowed to fall to zero, the user cost will also fall, but only to \( p_{se}^B \) because the cost of other components has not changed. Electricity demand will increase by some proportion of

Figure 2. A Household Demand Function for the Services of Electricity-consuming Equipment

![Figure 2](image_url)

Figure 3. An Electricity Demand Function

![Figure 3](image_url)
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$q^e_B - q^e_A$, depending on the relationship between the electricity-consuming equipment and the amount of electricity needed to power it. As long as no other components of the user cost change, the demand for electricity cannot be increased and thus an upper bound on electricity demand vis-à-vis the electricity price has been reached.

Thus, a household electricity demand function would resemble the curve in Figure 3. The maximum amount of electricity that can be possibly consumed, $q^e_{max}$, depends on the stock of electricity-consuming equipment. This stock, in turn, depends on the consumer’s income, the prices of other energy forms, and consumer tastes and preferences.

B. The Firm’s Demand for Electricity

The demand for electricity by firms follows a similar pattern. Microeconomic theory shows that the demand for an input by a firm, such as electricity, is negatively related to its price. It can also be shown that there exists an upper bound for the demand for electricity. The demand for a good $q^g_A$ produced by firms is determined by its market and is a function of the marginal cost of production, that is, its price, $p^g_A$ (point A in Figure 4). As in the case of the household, marginal cost subsumes the price of electricity, $p^e = p^*$.

If the electricity price were to fall to zero, the market price of the good would fall by an equivalent amount, *ceteris paribus*. Thus, the amount of the good demanded would rise (point B in Figure 4). In response, the demand for electricity would rise by a proportional amount. Thus, as in the household case, as long as no other components of the production cost change, the demand for electricity cannot be increased and an upper bound on electricity demand vis-à-vis the electricity price is reached. The form of the electricity demand function would therefore be similar to the curve in Figure 3.

Figure 4. A Demand Function for a Firm's Output
C. A Functional Form for the Demand for Electricity

The above exposition leads to a functional form for the household demand for electricity. If it may be assumed that the demand for electricity function is smooth and continuous, then the class of functions that resembles the curve in Figure 3, that is, one that includes an intercept on the abscissa, passes through any other feasible point in $(q^e, p^e)$-space, and is not a straight line, is

$$\ln q^e = \alpha + \beta p^e$$

(7)

where $\ln$ is the natural logarithm and $\alpha > 0$, $\beta < 0$. The price variable is in real terms. The upper bound of electricity demand (when the price is zero) is given by $e^{\alpha}$ (Figure 5) and $\beta$ is the price semi-elasticity of demand. The price elasticity is given by

$$\eta_p = \left(\frac{dq^e}{dp^e}\right)\left(\frac{p^e}{q^e}\right) = \beta p^e$$

(8)

which varies with the price level, as may be expected. This functional form also has the desirable property that willingness to pay rises exponentially as demand falls, as suggested by economic theory. The parameter $\alpha$ depends on income, prices of other energy forms, and other variables.

In the case of the firm, the electricity demand function may be derived algebraically under the assumption that the production function is weakly separable and the marginal product of electricity falls to zero over a range of feasible output levels. The production function that satisfies these conditions is

$$y = q^e \left(\ln q^e - \alpha - 1\right)/\beta + g(x^e)$$

(9)

where $y$ is output, $x^e$ is a vector of other inputs into the production process, and $\alpha > 0$, $\beta < 0$. Solving the profit maximization problem results in the same demand for electricity function given in equation (7).
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This functional form (7) readily lends itself to calculating the economic benefit (EB) of electricity. The economic benefit is simply the area beneath the demand curve (Figure 5), that is,

\[ EB = \int_{q_0}^{q_1} p^* dq^* \]

where \( q_0 \) to \( q_1 \) is the range of integration. Integrating with respect to \( q^* \) results in an economic benefit of

\[ EB = q_1 (p_1 - 1/\beta) - q_0 (p_0 - 1/\beta) \]

where \( p_0 \) and \( p_1 \) are prices corresponding to \( q_0 \) and \( q_1 \), respectively.

III. An Illustrative Example

The demand for electricity function may be estimated econometrically if sufficient data is available or by means of a survey. The econometric approach normally requires at least 20 years of time-series data on electricity sales, the marginal price of the electricity sold, and economic data such as income, the price of alternate fuels (kerosene, gas, wood, etc.), and weather and demographic data. Sufficient data are often not available, electricity supply may be constrained, and other statistical issues arise, such as the identification problem. It also may not be possible to relate the resultant parameters of the econometric analysis from a relatively large group of existing consumers, say on a country level, to the consumer group under investigation. Therefore, the econometric approach is usually used sparingly.

The survey approach is likely easier to apply. The electrification of a village in the rural area is used here as an illustrative example. Households in villages usually share similar economic and demographic characteristics and thus there is likely little need to collect this kind of data. This approach usually begins with a survey of two villages: the village to be electrified, and another village already electrified but with a similar population size, and economic and demographic characteristics. The differences in the consumption of all energy in these villages may therefore be attributed to the electrification project. The necessary data from the nonelectrified village includes consumption of the various forms of energy and the prices paid for them. In the electrified village, similar data are collected along with the data on electricity consumption and its price.

The survey may find that households without access to electricity use kerosene for lighting while those with access use electric lighting as well as electricity for fans, radios, television, etc. Other energy consumption, for example gas for cooking, may remain the same for both villages. The kerosene that is displaced by electric lighting is a resource cost saving to the economy and the economic benefit of this should be valued accordingly. Normally, more electric lighting is used than the equivalent in kerosene form. This excess electricity consumption along with that used for other purposes is incremental consumption induced by electricity's lower price and other positive externalities and is valued in terms of willingness to pay. The price paid for kerosene lighting is an indication of the willingness to pay for the quantity of lighting consumed. In this illustrative example, willingness to pay for kerosene by the representative household is $0.20 per kWh equivalent for 30 kWh per month equivalent. In Figure 5, this would correspond to point \((q_0, p_0)\).
The quantity of kerosene consumed is an average for all households surveyed in the nonelectrified village.

Billing data for households in the electrified village shows that, at a marginal price of $0.08 per kWh, households on average consume 60 kWh of electricity per month. Therefore, with the electrification project, consumption is expected to rise to 60 kWh per month in the nonelectrified village, or an incremental 30 kWh per month. This corresponds to point \((q_1, p_1)\) in Figure 5. The parameter \(\beta\) in equation (7) is therefore estimated as

\[
\beta = \frac{(\ln q_1 - \ln q_0)}{(p_1 - p_0)} = \frac{(4.09 - 3.40)}{(0.08 - 0.20)} = -5.78
\]

and parameter \(\alpha\) is

\[
\alpha = \ln q_1 - \beta p_1 = 4.09 + 5.78 \times 0.08 = 4.56
\]

The economic benefit of the incremental 30 kWh per month consumption given by equation (11) and is calculated as

\[
EB = q_1(p_1 - 1/\beta) - q_0(p_0 - 1/\beta) = 60(0.08 + 0.17) - 30(0.20 + 0.17) = $3.90
\]

IV. Conclusions

The purpose of this technical note is to propose a plausible functional form for the demand for electricity. The functional form proposed in this note is consistent with two properties of electricity demand functions for households and firms, namely, the negative relationship between the price and quantity, and the finiteness of demand at zero price. This note also demonstrates that this functional form of the demand function leads to easily estimable economic benefits of electricity.

The above approach of measuring willingness to pay is applicable to other sectors where demand is finite, for example, in telecommunications and water supply. Appendix 1 provides an example in the telecommunications sector.\(^4\)

\(^3\) A demand for electricity function approximated by a straight line estimates the economic benefit using the same data at $4.20.

The measurement of an individual’s willingness to pay for goods or services for which there is a saturation point or finite demand even at zero price, such as telephone services, relies on a reliable estimate of a demand function. However, standard microeconomic theory falls short in providing a plausible framework within which such estimation could be made. Empirical work to date has generally tended toward assuming that the demand for goods or services has no saturation point. Many demand models assume a constant price elasticity, which implies infinite demand at prices approaching zero. Moreover, some single equation and demand system models do not allow for the possibility of goods at zero price because the price variable is in logarithmic form for which zero is undefined. It is intuitive that, even at zero price, the demand for some goods and services would be finite.

In general, the demand for telephone services is a finite demand, even at zero price. Consumers are physically bound by the number of hours in any time period that could be devoted to making telephone calls. In regions such as North America where there is no charge for local telephone calls, it is observed that consumers limit the number of telephone calls they make. A socioeconomic study in the mid-1990s found several additional characteristics on the demand for telephone services in the rural areas of Thailand. More than 80 percent of telephone calls are for personal reasons; the balance is for business-related matters such as banking and dealing with government agencies. The average length of a telephone call is 5 minutes. Thus, consumers in rural areas tend to use telephone services for functional purposes such as keeping in touch with relatives and business-related matters. Rural telephones are also perceived as a new service. It has not substituted, to any great extent, traditional forms of communication, such as letter writing and travel. Therefore, the demand for rural telephone calls is primarily an incremental demand.

These characteristics provide a guide for a functional form for the demand for telephone calls by an individual in the rural areas of Thailand. First, a quasilinear utility function ($U$) for a representative individual may be assumed, the form of which is

$$U = V(q) + \lambda M$$

where $V$ is a utility function for telephone calls only, $q$ is the quantity of telephone calls demanded, $M$ is a composite commodity called “money”, and $\lambda$ is the marginal utility of money. The quasilinear utility function is separable and strongly additive and is appropriate because the demand for telephone calls is usually independent of the demand for other goods and services. This functional form also assumes that the marginal utility of money is constant or, equivalently, that the income effect is zero, an assumption that is reasonable for an individual whose demand of telephone calls is relatively small compared to other goods and services.

The constrained maximization of utility leads to the following demand function

$$V = (\ln q - \alpha - 1)q / \beta$$

where $\ln$ is the natural logarithm, $\alpha > 0$ and $\beta < 0$. This utility function has the desirable property of diminishing marginal utility. It also has a point where satiation occurs ($\ln q = \alpha$), that is, a point of demand where marginal utility is zero.

The constrained maximization of utility leads to the following demand function

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5 This appendix is reproduced from the project performance audit report for the Second Rural Telecommunications Project in Thailand (Asian Development Bank 2001).

\[ \ln q = \alpha + \beta \lambda p \] (3)

The upper bound of the demand for telephone calls function (when the price is zero) is given by \( e^\alpha \) and \( \beta \lambda \) is the price semi-elasticity of demand. The price elasticity is given by

\[ \eta_p = \left( \frac{dq}{dp} \right) \left( \frac{p}{q} \right) = \beta \lambda p \] (4)

which varies with the price level, as may be expected. The demand function also has the desirable property that willingness to pay rises exponentially as demand falls, as suggested by economic theory.\(^7\) Thus, the functional form incorporates the following three characteristics. First, it is negatively sloped with respect to price, as economic theory suggests for a normal good. Second, it is a smooth and continuous function. And third, it intercepts the abscissa to allow for the finiteness of the demand for telephone calls.

The economic benefit (EB) derived from a new telephone service is the area beneath the demand curve (Figure 1). The quantity of telephone calls demanded is \( q^* \) at the given price of \( p^* \).

The demand curve (3) readily lends itself to calculating the economic benefit of telephone calls, namely,

\[ EB = \int_{q}^{q^*} pdq \] (5)

Integrating with respect to \( q \) results in an economic benefit of

\[ EB = q^* \left( p^* - 1/\lambda \beta \right) \] (6)

**Estimation of the Demand for Telephone Calls Function**

The parameters of the demand for telephone calls function (3) were estimated from data collected in March 2001 by a survey of 23 individuals with similar socioeconomic characteristics resident in the rural areas within reasonable access to the rural telecommunications network. Individuals were asked questions about their current telephone usage and about two hypothetical scenarios: one on telephone usage if there was no

\(^7\) Equation (3) should normally be used to estimate demand functions of consumers with the same socioeconomic characteristics because of the absence of an income variable. If income varies significantly among consumers, an income variable should be included in equation (3).
telephone service available nearby and travel to the next nearest telephone in another village was necessary; and the other on telephone usage if telephone calls were free. From the survey responses, it was found that there was a distinct pattern in telephone usage. If no telephone were available nearby, on average, rural people would make four telephone calls per month at an average cost of B62 per 5-minute call. These calls were primarily to relatives and friends and sometimes for business purposes. If telephone calls were free, survey responders indicated that they would likely make one call a day, or about 30 telephone calls per month. This information indicates that the parameter $\alpha$ has a value of 3.4012 while $\beta$ has a value of –0.0325, or the following demand for telephone calls function,

\[ \ln q = 3.4012 - 0.0325p \]  

(7)

The accuracy of the demand for telephone calls model (7) was verified by comparing actual telephone usage and the price paid with that predicted by (7). The comparison concluded that the demand for telephone calls model is reasonably accurate.
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