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EXTENDING GAS AND ELECTRIC LINES AT THE URBAN FRINGE: A STATISTICAL ANALYSIS

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ABSTRACT

The expansion process of gas and electricity distribution networks at the urban-rural fringe is modeled through statistical regression analysis, using gas mains and electric conductor mileages, market, and density data over a cross-section of California communities. The estimated models are used to analyze the impact of market size, to calculate the marginal mileage requirements of each market component, and to assess alternative staging policies for utility network development.

The analysis of the technological and economic structure of urban utilities has, in the past, primarily focused on water supply and sewerage systems. This emphasis is due to the importance of these systems in guiding and constraining urban growth, to the significant scale phenomena that characterize them, and to a relatively easy access to the necessary data, as most water utility projects are planned and implemented by local governments. In contrast, much less is known about the other urban utilities such as the gas, electricity, and telecommunications networks. However, the recent steep increases in these utilities' bills make it all all the more urgent to better understand these systems in terms of their cost structure, their interaction with and sensitivity to alternative patterns of urban development, their scale phenomena, and their degree of indivisibility. Such clarifications should lead to improved cost allocation, pricing, and development staging policies.

The purpose of this article is to shed some light on the expansion process of gas and electricity distribution networks at the urban-rural fringe, based on a statistical analysis of gas and electric lines mileage increases in samples of

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California communities served by Pacific Gas and Electric Company, a major privately-owned utility serving more than eight million people. After a review of related previous studies, the statistical modeling approach is discussed; the data base and the results are presented next, followed by the policy implications of the results.

PREVIOUS STUDIES

The economics of wastewater collection systems have been studied by several authors who have analyzed the variations of their costs through either engineering approaches [1, 2] or statistical regressions [3, 4]. Their results indicate that sewer capital costs for new urban subdivisions vary with both the density of the development and its distance from the sewage treatment plant, with economies of scale in transmission sewers arising if developments are located near one another. Studies of urban-level gas and electricity distribution systems are much scarcer. Guldmann, applying neoclassical cost function theory, developed urban-wide gas distribution cost functions using the historical value of the total gas distribution investment in communities served by utilities in the states of New York and Ohio [5]. Wells analyzed electricity distribution historical capital costs, using data from fifty-seven power districts of British Columbia Hydro and Power Authority, and related unit distribution costs to customer density [6]. More recently, Guldmann, using community-level data provided by Pacific Gas and Electric Company, developed an urban-wide econometric model of electricity distribution made of several input demand equations based on standard production function theory [7]. The three previous studies, which involve static analyses at the level of the whole urban area, clearly indicate the existence of inverse relationships between costs and urban-wide population density. However, they fail to provide information about the dynamics of utility system expansion. The only study reporting such information is *The Costs of Sprawl*, carried out by the Real Estate Research Corporation for the Council on Environmental Quality and other government agencies, with the broader goal of assessing the environmental and economic costs of alternate housing types and development patterns at the urban fringe [2]. Five different neighborhood prototypes with 1000 dwelling units each were considered, ranging from single family houses to high rise apartments. The gas pipeline and electric conductor mileages required to serve each neighborhood were estimated on the basis of street length minus 10 percent to 15 percent to reflect sophisticated engineering and design practices. Electric cables were assumed buried underground, and both mileages turned out to be the same in any given neighborhood. The mileage, population, and acreage data presented in Table 1 indicate, rather dramatically, a strong inverse relationship between utility mileage and population or dwelling density. While all five neighborhood prototypes were considered as typical of new suburban construction, pre-existing land uses and the relationships between

Table 1. Gas/Electricity Distribution Systems in Neighborhood Prototypes

Neighborhood Prototypes	*Population*	*Area (Acres)*	*Utility Mileage (Miles)*
Single Family Conventional	3520	500	10.23
Single Family Clustered	3520	400	6.78
Townhouse Clustered	3330	300	4.32
Walk-up Apartments	3330	200	2.58
High Rise Apartments	2825	100	1.52

Source: Real Estate Research Corporation [2].

the neighborhoods and the rest of the metropolitan area were not taken into account. For instance, utility extensions may require the reinforcement or modification of the existing networks to meet the increased gas and electricity loads. Also, new urban developments may be located at varying distances from the existing utility lines, implying extensions of varying lengths. Next, it is important to remember that residential customers constitute only a part, important as it may be, of the gas and electricity markets. The neighborhood prototypes do not include non-residential land uses. However, actual new suburban developments are most likely to include at least commercial activities, and possibly industrial ones, each with their specific utility requirements. Hence, while illustrative, the data developed by the Real Estate Research Corporation are clearly insufficient to shed much light on the process of gas and electricity distribution systems expansion at the urban fringe.

RESEARCH METHOD

The local gas distribution network, designed to deliver gas from the town-border supply station to the customers' premises, is primarily made of pipeline mains that run throughout the city under the curbs and are linked to the customers by smaller-size short pipes called services. While the system includes other pieces of equipment such as valves, pressure regulators and meters, mains represent 50 percent to 70 percent of total investment costs, and the other costs are related either to main costs or to the number of customers (e.g., service and meter costs). Hence, measuring expansion in terms of main mileage increase will most likely capture the dynamics of the gas distribution network.

The local electricity distribution network, which carries power from the primary substations to the customers, consists of primary and secondary voltage conductors carried both overhead (sustained by poles) and underground (pulled through conduits). Voltage transformers constitute the link between primary and secondary conductors, and their capacity is directly related to the secondary-voltage market made up of residential, small commercial and industrial, and lighting customers. On the average, conductors, including services, represent 34 percent of the total distribution investment, while poles and conduits represent 20 percent and transformers 12 percent of this investment. Substations, which represent about 14 percent of the investment, constitute the major link between the transmission and distribution systems. Poles, conduits, and transformers are directly related to conductors, while substations have more system-wide functions. In view of the importance of these different components, it is clear that most of the dynamics of the distribution system can be captured by measuring conductor mileage increases.

The approach adopted in this study is to analyze the net increases in the mileages of gas mains and electric conductors during a given year and over a cross-section of communities, and to relate these increases to the characteristics of the newly served markets as well as of the whole existing market. Let M_0 and M_1 be the mileages at the beginning and end of a given year. The net increase

$$DM = M_1 - M_0 \tag{1}$$

is the product of the interaction of several processes. First, some of the utility lines of the initial system S_0 are retired because of obsolescence or deterioration beyond economic repair. Let DM_{ret} be the retired mileage, which may be in part or fully replaced by similar lines. It is, however, unlikely that all retired lines are replaced by identical new lines, as some lines may have lost their initial usefulness due to network changes. Let DM_{rep} be the replacement mileage. Next,

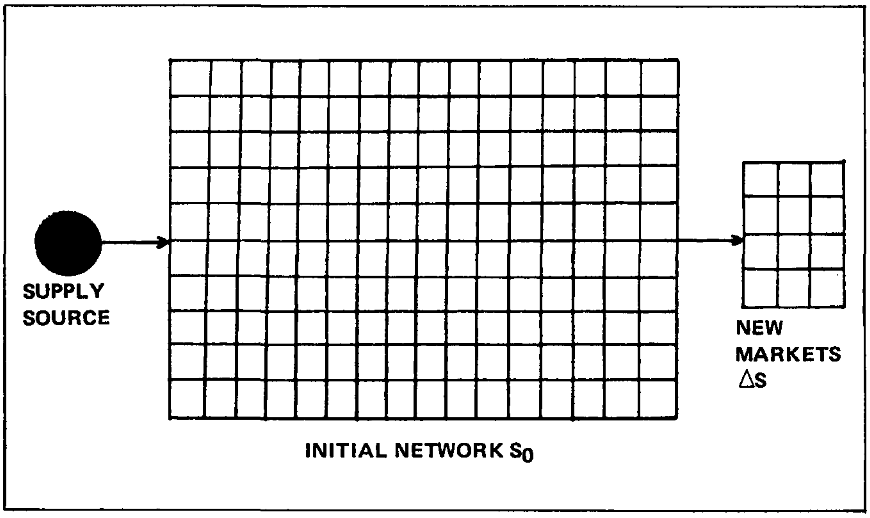

Figure 1. Utility system expansion.

consider the utility lines laid out specifically to serve newly hooked-up customers. Let DM_{exp} be this expansion mileage. Finally, both the expansion and retirement processes may require additional adjustments in the existing network, as illustrated in Figure 1. Indeed, the expansion market is to get utility services initially supplied by either town-border gas stations or subtransmission or primary voltage stations, and carried through the existing network S_0 until they reach the new markets. These additional gas or electricity loads may strain the capacity of the existing network, which may then have to be expanded by installing new lines parallel to the existing ones. Let DM_{adj} be this additional adjustment mileage. The net mileage increment is then:

$$DM = DM_{exp} + DM_{adj} + DM_{rep} - DM_{ret} \qquad (2)$$

What are the factors determining the magnitude of DM? Obviously, DM_{exp} is to be strongly related to the characteristics of the newly served markets, whereas DM_{adj} is likely to be a function of the characteristics of both the existing and new markets. The magnitudes of DM_{ret} and DM_{rep} are related to the age of the system, local network characteristics, and company-wide financial considerations that do not vary from one community to another. Let $X_0 = (X_{10}, X_{20}, \dots, X_{n0})$ be a vector of variables that characterize the initial system S_0, and $\Delta Y = (\Delta Y_1, \Delta Y_2, \dots, \Delta Y_m)$ a vector of variables characterizing the new markets ΔS. Thus:

$$DM = f(X_0, \Delta Y) \qquad (3)$$

The purpose of the next section is to specify and empirically estimate equation (3) for both gas and electricity distribution networks.

EMPIRICAL ANALYSES

The Data

An overview of the utility—The data characterize the net changes in gas and electricity lines mileages in communities served by Pacific Gas and Electric Company (PG&E) between the ends of the years 1978 and 1979. The characteristics of PG&E total gas and electricity markets are presented in Table 2. Gas customers are grouped in two categories—residential and non-residential—and electricity customers in three categories—residential, non-residential, and lighting. The non-residential category includes both commercial and industrial customers. The data in Table 2 indicate a vigorous growth in both markets, with the exception of the electric lighting sector, where the sales decline may be due to a few large customers (e.g., municipalities, commercial centers) shifting to another power source. The growth rates of both gas and electricity sales are higher than the corresponding customer growth rates, probably due to both higher consumptions by existing customers and addition of larger-than-average new

Table 2. PG&E Gas and Electricity Markets in 1978 and 1979

	Year		*Increment*	
Sector	*1978*	*1979*	*Absolute*	*Relative (%)*
	Electricity Market			
Annual Sales (MWH)				
Residential	18,314,721	19,605,541	1,290,820	7.05
Non-Residential	34,824,521	36,861,958	2,037,437	5.85
Lighting	485,724	455,445	− 30,279	−6.23
Customers (#) (End of Year)				
Residential	2,836,147	2,918,668	82,521	2.91
Non-Residential	420,824	433,873	13,049	3.10
Lighting	13,316	13,394	78	0.59
	Gas Market			
Annual Sales (MCF)				
Residential	220,076,421	234,294,712	14,218,291	6.46
Non-Residential	283,002,276	329,785,616	46,783,350	16.53
Customers (#) (End of Year)				
Residential	2,531,755	2,591,507	59,752	2.36
Non-Residential	165,970	171,890	5,920	3.57

Source: Annual Reports of PG&E to the California Public Utilities Commission.

customers. Weather pattern differences may also, in part, explain the difference in the case of electricity sales. In the case of gas sales, weather-related differences have been corrected for, as discussed in Guldmann et al. [8]. Finally, note that the steep increase in non-residential gas sales is due to the increase in gas consumption by interruptible industrial customers who were previously curtailed because of shortages, and started to enjoy, in 1979, a situation of gas supplies plentiful anew.

The dynamics of the distribution systems for the whole company is described in Tables 3 through 5. Overall, the net mileage increase rates are 1.88 percent and 2.55 percent for electric and gas lines, respectively. However, the different types of lines contribute very differently to these increments. For instance, the expansion rate of underground electric lines corresponds, in part, to conversion of overhead lines. Plastic gas pipes are the only ones to experience a significant

Table 3. PG&E Electricity Distribution Lines Mileages
Ends of 1978 and 1979

	Year		*Increment*	
Type of Line	*1978*	*1979*	*Absolute*	*Relative (%)*
Overhead	78,263	79,160	897	1.15
Underground	6,720	7,417	697	10.38
Total	84,983	86,577	1,594	1.88

Source: PG&E Uniform Statistical Reports to the Edison Electric Institute.

Table 4. PG&E Gas Distribution Lines Mileages
Ends of 1978 and 1979

	Year		*Increment*	
Material	*1978*	*1979*	*Absolute*	*Relative (%)*
Steel	22,966	22,924	– 42	– 0.18
Plastic	4,179	4,950	771	18.45
Other	887	874	– 13	– 1.46
Total	28,032	28,748	716	2.55

Source: PG&E Uniform Statistical Reports to the American Gas Association.

Table 5. PG&E New Gas Line Mileage Installed During 1979

	Material			
Type of Line	*Steel*	*Plastic*	*Other*	*Total*
New	35	719	0	754
Replacement	12	57	0	78
Total	56	776	0	832

Source: PG&E Uniform Statistical Reports to the American Gas Association.

increase, reflecting the fact that plastic mains are about 15 percent to 20 percent cheaper than steel mains. The net decrease in steel and other (mostly cast iron) gas mains reflects the fact that most of these pipes, when retired, are replaced (if at all) by plastic mains. Tables 4 and 5 provide interesting additional details about the overall dynamics of the gas networks. In total, 116 miles of mains have been retired out of 28,032 miles (or 0.4%), and only 78 miles of these retired mains have been replaced, while the 754 miles of new mains represent the expansion and adjustment components (DM_{exp} and DM_{adj}) of equation (2). Retired steel mains consist of 98 miles, or 84 percent of the total retirement. Obviously, network expansion involves a process of technological change which could not, unfortunately, be accounted for in the community-level analysis because data such as those in Tables 3-5 were not available.

The sample data–Gas mains mileage and market data were provided by PG&E management for 94 communities in 1978 and 1979. Similar electric data were provided for eighty-three of these communities, all with a population of 10,000 or more. Main mileage is exclusive of service mileage. However, the electric conductor mileage includes primary and secondary, overhead and underground wires, services, as well as lines laid out for lighting only. The increments in mileages, sales and numbers of customers have then been computed for each community. In the electricity case, the lighting sector has been represented by the number of street lamps instead of lighting sales and numbers of lighting customers, because of the heterogeneity of this customer group. The numbers of street lamps were also provided by PG&E management. Only those communities displaying positive increments in both mileage and market characteristics were selected, leading to final samples of seventy-one and forty-five communities for the gas and electricity systems, respectively. Such a selection focuses the analysis on networks experiencing vigorous growth. The discarded communities experience little or negative mileage growth together with a decline in some or all market components. Explaining these changes would most likely require a knowledge of specific local conditions, which was unavailable. The means, standard deviations, minima and maxima of these increments are presented in Tables 6 and 7, together with the utility mileages at

Table 6. PG&E Communities Statistics—Electricity Distribution ($N = 45$)

Variable Definition and Notation	*Mean*	*Standard Deviation*	*Minimum*	*Maximum*
DW: Conductor Mileage Increment (Miles)	34.20	45.65	1	247
DRC: Residential Customers Increment (#)	730.60	794.90	59	3447
DCC: Non-Residential Customers Increment (#)	93.10	101.00	10	565
DRK: Residential Sales Increment (KWH)	7,689,878	9,299,192	865,295	48,854,760
DCK: Non-Residential Sales Increment (KWH)	9,312,121	12,808,056	255,748	76,889,346
DL: Street Lamps Increment (#)	99.70	168.10	2	1000
DN: Population Density (People per acre)	4.84	2.72	1.27	17.20
W8: Conductor Mileage—End of 1978 (Miles)	790.51	809.17	98	4559
TK8: Total 1978 Sales (KWH)	247,216,851	246,933,640	46,115,983	1,336,040,537

Table 7. PG&E Communities Statistics—Gas Distribution ($N = 71$)

Variable Definition and Notation	*Mean*	*Standard Deviation*	*Minimum*	*Maximum*
DM: Main Mileage Increment (Miles)	6.56	10.13	0.02	57.26
DRC: Residential Customers Increment (#)	537.60	681.80	9	3482
DCC: Non-Residential Customers Increment (#)	58.40	69.00	2	388
DRM: Residential Sales Increment (MCF)	126,778	142,066	3192	821,367
DCM: Non-Residential Sales Increment (MCF)	187,393	550,627	1951	3,889,661
DN: Population Density (People per acre)	5.37	2.42	1.00	11.38
M8: Main Mileage—End of 1978 (Miles)	175.96	236.60	35.89	1668.85
TM8: Total 1978 Sales (MCF)	3,124,180	5,220,495	385,339	35,244,239

the end of 1978 and the total sales during 1978, as well as with the population density computed with 1970 population and acreage data drawn from the 1970 Census of Population [9].

The total conductor mileage increment of the forty-five "electric" communities represents 1539 miles, or 96.5 percent of the total PG&E increment (see Table 3), the balance being related to smaller communities (less than 10,000 people) with positive increments and to small and large communities with negative increments. The total conductor mileage of these communities was equal to 35,573 miles at the end of 1978, or only 41.86 percent of the total PG&E mileage, indicating that a large share of PG&E distribution lines have not experienced any growth. The statistics in Table 6 also indicate that all the variables have skewed distributions, with high concentrations of observations at the lower end of the ranges.

The total main mileage increment of the seventy-one "gas" communities represents 466 miles, or 65 percent of the total PG&E increment (see Table 4). The total main mileage of these communities at the end of 1978 was equal to 12,493 miles, or 44.57 percent of the total PG&E mileage. As in the electricity case, the distributions of all the variables are strongly skewed to the right.

Statistical Model Specification and Estimation

In line with the general form of equation (3), the following general functional relationships have been considered:

$$DW = F(DRX, DCX, DL, DN, ES8) \qquad (4)$$

where:

DRX = DRC or DRK
DCX = DCC or DCK
ES8 = W8 or TK8

$$\mathrm{DM} = G(\mathrm{DRX}, \mathrm{DCX}, \mathrm{DN}, \mathrm{GS8}) \tag{5}$$

where:

DRX = DRC or DRM
DCX = DCC or DCM
GS8 = M8 or TM8

The variables DRX and DCX (as well as DL in the electricity case) are measures of the size of the newly served markets, whereas the variables ES8 and GS8 are measures of the size of the pre-existing markets (i.e., at the end of 1978). The 1970 population density was used because the 1980 data were not yet available when this study was undertaken. This density characterizes the whole community. However, the density of new suburban developments, while lower than the overall density, is likely to be closely related to the latter, that is, a densely built community is likely to have denser suburbs than a low-density community. As density data for the new markets were not available, the variable DN is to measure the density effects of both the pre-existing and new markets. As little is known about the true structure of equations (4) and (5), the customers and sales increments were alternatively considered as measures of the sizes of the newly served markets. Likewise, total pre-existing sales and line mileages were alternatively considered as measures of the capacity of the initial (end of 1978) system. Both linear and log-linear specifications of equations (4) and (5) were considered for any possible combination of the independent variables, and estimated through ordinary least squares regression. The selection of the appropriate form was based on the comparison of their respective residuals sums of squares [10, pp. 197-211]. The log-linear specification turned out to be superior to the linear one in all cases. The procedure for selecting the best log-linear equation involved searching for the highest R^2 regression while eliminating equations with low-significance variables (the threshold selected was a *t*-value equal to 1). The models finally selected are:

$$\begin{array}{lllllll}
\ln \mathrm{DW} = & -8.360 & +\,0.436\ln \mathrm{DRC} & +\,0.133\ln \mathrm{DCK} & +\,0.310\ln \mathrm{DL} & -\,0.468\ln \mathrm{DN} & +\,0.316\ln \mathrm{TK8} \\
(t) & (-2.77) & (2.75) & (0.96) & (3.09) & (-2.09) & (1.46) \\
(\mathrm{sig.}) & (0.009) & (0.009) & (0.344) & (0.004) & (0.043) & (0.153)
\end{array}$$

$$R^2 = 0.692 \qquad \text{Adj. } R^2 = 0.653 \tag{6}$$

$$\begin{array}{llllll}
\ln \mathrm{DM} = & -6.555 & +\,0.836\ln \mathrm{DRC} & +\,0.180\ln \mathrm{DCC} & -\,0.326\ln \mathrm{DN} & +\,0.187\ln \mathrm{TM8} \\
(t) & (-3.91) & (8.04) & (1.40) & (-1.44) & (1.38) \\
(\mathrm{sig.}) & (0.000) & (0.000) & (0.167) & (0.154) & (0.173)
\end{array}$$

$$R^2 = 0.734 \qquad \text{Adj. } R^2 = 0.718 \tag{7}$$

The customers increments turned out to be the relevant variables for the new markets, except for the non-residential electricity market which is better (though with a barely acceptable significance) represented by the sales increment. Gas sales increments, in particular, turned out to be highly insignificant. Likewise, total sales turned out to be much more significant than total mileages in representing the effects of the pre-existing systems. The achieved R^2 indicates that about 70 percent of mileage increments variations are explained by the selected independent variables. Also, the signs of all the coefficients are as expected: the larger the new markets and the larger the existing ones, the larger the mileage increments, while the opposite effect exists for density. For both equations, a visual scan of the regression residuals and the application of the Goldfeld-Quandt test at the 5 percent level of significance [11] produced no evidence to reject the null hypothesis of homoscedasticity.

POLICY IMPLICATIONS

Impact of Market Size

The log-linear equations (6) and (7) imply that the mileage increments in gas mains and electric conductors are the products of non-separable factors, and that the coefficients of the independent variables indicate the elasticities of the mileage increment with respect to these factors. In the case of equation (6), for instance, an increase of 1 percent in the residential customers increment leads to an increase of 0.436 percent in the conductor mileage increment. As the coefficients of all the market increment variables (lnDRC, lnDCC, lnDCK, lnDL) are lesser than one, both equations clearly show that mileage expansion is characterized by sectoral economies of scale. Moreover, the elasticity of the mileage increment to a simultaneous increase of 1 percent in all markets is equal to the sum of the corresponding coefficients, with: $\epsilon_E = 0.436 + 0.133 + 0.310 = 0.879$ in the electric case, and $\epsilon_G = 0.836 + 0.180 = 1.016$ in the gas case. As demonstrated by Baumol, the parameters ϵ_E and ϵ_G measure overall economies of scale when several products (or markets) are involved in the production process [12]. For given density and existing market, savings in conductor mileage can be achieved in larger new developments, whereas the size of the new developments has little effect on the marginal gas main increment. For given new markets, the impacts of density and size of existing markets are stronger in electric than in gas systems. The impact of the existing market size is particularly significant. For instance, the conductor mileage increment computed with equation (6) for the mean values of the independent variables (see Table 6) is equal to 31.34 miles. The same increments computed with the minimum and maximum values of TK8, while keeping the same other mean values, are equal to 18.43 and 53.41 miles, respectively. Hence, the multiplier effect of the existing market varies by a factor of 1 to 2.89 in the selected "electric" sample. The same multiplier effect varies by a factor of 1 to 2.33 in the selected "gas" sample.

Utility Line Cost Allocation

As utility line increments are joint products of the different market variables, it is impossible to straightforwardly allocate these increments as would be the case if linear specifications of equations (4) and (5) were used. However, this allocation is possible on the basis of the marginal contribution of each market variable to the total increment. These marginal mileages may be converted into marginal costs while using unit line costs, and these marginal costs may be used in pricing the utility service. The marginal mileages, computed by using the partial derivatives of the mileage increment function, have been estimated at the sample mean values in the electricity case, with:

$$\frac{\partial DW}{\partial DRC} = \frac{0.436\ DW}{DRC} = 0.0204 \text{ miles/new residential customer,}$$

$$\frac{\partial DW}{\partial DCK} = \frac{0.133\ DW}{DCK} = 0.48846*10^{-6} \text{ miles/new non-residential Kwh,}$$

$$\frac{\partial DW}{\partial DL} = \frac{0.310\ DW}{DL} = 0.10634 \text{ miles/new lamp,}$$

$$\frac{\partial DW}{\partial TK8} = \frac{0.316\ DW}{TK8} = 0.043715*10^{-6} \text{ miles/existing Kwh.}$$

Using the 1978 average consumptions of 2432 Kwh per lamp and of 6498 Kwh and 95,374 Kwh per residential and non-residential customer, respectively, the marginal mileages have been estimated on a customer basis for both the new and existing markets, as indicated in Table 8.

As could be expected, the marginal impacts of the existing customers are much smaller than those of the new customers. The ranking of the marginal effects of the new customers is also as expected, though the lighting sector impact appears surprisingly large. On the basis of data provided by PG&E management, the unit cost of new lines was estimated at $1.233/foot, leading to charges of $133 and $303 per new residential and non-residential customers, respectively.

Table 8. Marginal Electric Conductor Mileages Estimated at Sample Mean

	Sector		
Market	*Residential (feet/customer)*	*Non-Residential (feet/customer)*	*Lighting (feet/lamp)*
New	107.76	245.97	561.47
Existing	1.50	22.01	0.56

Utility Expansion Staging Policies

A perennial issue in utility planning is the extent to which excess capacity should be incorporated into the system in order to take advantage of economies of scale and indivisibilities. In the case of regulated privately-owned utilities, the allowed rate of return applies to the plant actually in service, with special provisions for the recovery of costs related to long-duration constructions, such as power plants. However, in the case of distribution lines, there is generally no advance layout, and network extensions closely follow new subdivisions constructions, and hence market extensions. The acquisition of rights-of-way constitutes the major advance cost in the case of distribution. However, a question may be raised as to the possible economic benefits of advance construction of new utility lines. The purpose of this section is to illustrate the possible use of the statistical models of mileage increments to clarify this issue.

Consider again equation (6) for electric systems. It may be rewritten as:

$$\mathrm{DW} = \mathrm{k\,DRC}^{\alpha}\,\mathrm{DCK}^{\beta}\,\mathrm{DL}^{\gamma}\,\mathrm{DN}^{-\delta}\,\mathrm{TK}^{\theta} \tag{8}$$

Consider an initial system TK_0 and market increments $(2{*}\mathrm{DRC}_0, 2{*}\mathrm{DCK}_0, 2{*}\mathrm{DL}_0)$ expected to take place over two consecutive years in a uniform fashion. Two alternative development staging policies are considered. Alternative A involves laying out the complete system expansion during the first year, and thus having parts of it unused until second-year market increments take place. Alternative B involves spreading system expansion over the two years, following market expansion. Let C_1 and C_2 be the unit cost of utility lines in the first and second year, r the interest rate, and Z_R and Z_L the average electricity requirements of a new residential customer and a new lamp, respectively. Let:

$$\mathrm{DW}_0 = \mathrm{k\,DRC}_0{}^{\alpha}\mathrm{DCK}_0{}^{\beta}\mathrm{DL}_0{}^{\gamma}\mathrm{DN}^{-\delta}\mathrm{TK}_0{}^{\theta} \tag{9}$$

Under alternative A, the total mileage increment is $\mathrm{DW}_A = 2^{\alpha+\beta+\gamma}\,\mathrm{DW}_0$, and the present cost C_A is:

$$C_A = \frac{C_1}{(1+r)}\mathrm{DW}_A = \frac{C_1}{(1+r)} * 2^{\alpha+\beta+\gamma} * \mathrm{DW}_0 \tag{10}$$

Under alternative B, the mileage increments in the first and second years are DW_0 and $\mathrm{DW}_0 {*} (1 + \Delta\mathrm{TK}/\mathrm{TK}_0)^{\theta}$, where ΔTK is the first-year increase in sales ($\Delta\mathrm{TK} = Z_R\mathrm{DRC}_0 + \mathrm{DCK}_0 + Z_L\mathrm{DL}_0$). The present cost C_B is then:

$$\begin{aligned} C_B &= \frac{C_1}{(1+r)} W_0 + \frac{C_2}{(1+r)^2} W_0 \left(1 + \frac{\Delta\mathrm{TK}}{\mathrm{TK}_0}\right)^{\theta} \\ &= \frac{C_1 W_0}{(1+r)} \left[1 + \frac{C_2}{C_1} * \frac{1}{(1+r)} \left(1 + \frac{\Delta\mathrm{TK}}{\mathrm{TK}_0}\right)^{\theta}\right] \end{aligned} \tag{11}$$

Let x and y be the rates of growth of unit line costs and total sales, with $x = C_2/C_1$ and $y = \Delta TK/TK_0$. Alternative A (immediate total development) is preferable to alternative B (staged development) if $C_A < C_B$ or if:

$$2^{\alpha+\beta+\gamma} - 1 < \frac{(1 + x)}{(1 + r)} (1 + y)^{\theta} \tag{12}$$

Using equation (6) coefficients, inequality (12) becomes

$$0.839 < \frac{(1 + x)(1 + y)^{0.316}}{(1 + r)} \tag{13}$$

Inequality (13) shows the complex interaction between market growth, cost growth, and interest rate in the determination of the best alternative. Estimating y at the sample mean (= 0.058) and assuming an interest rate of 25 percent, inequality (13) indicates that A is preferable to B as long as the growth in unit cost is more than 3 percent. If there were no economies of scale (i.e., if $\alpha+\beta+\gamma = 1$) and if there were no multiplier effect due to the existing market (i.e., if $\theta = 0$), then A would be preferable to B as long as $x > r$. The observed wider gap is naturally due to the observed economies of scale and multiplier effects.

CONCLUSIONS

The expansion of gas and electricity distribution lines at the urban fringe has been analyzed with data pertaining to a sample of California communities. It has been shown that the net annual mileage increment is a function of both the newly connected residential subdivisions and non-residential developments, and of the size of the total existing market, and that the log-linear specification of the mileage increment function is superior to the linear one, implying a non-separability of the different variables determining the mileage increment. Network extensions are characterized by increasing and constant returns to scale in the cases of the electricity and gas systems, respectively. The multiplier effect due to the existing market is significant and varies by a factor of 1 to 3.

Finally, the applicability of the estimated models has been illustrated with respect to policy issues such as the impact of market size and population density, the allocation of utility costs, and the optimal staging of utility lines layout.

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