Optimum Economic Power Supply Reliability

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The standards of reliability of electricity supply have previously been determined on a rule-of-thumb basis. This paper presents a generalized simulation model for optimizing the reliability level by comparing the social benefits and costs of changes in power system reliability. The supply side costs of increasing system reliability can be determined from straightforward engineering considerations. On the demand side, the benefits to electricity users consist of cost savings from averted power failures or outages which may be measured by the disruption of the output streams due to idle input factors and spoilage. The theory is applied to the case study of Cascavel, Brazil, in order to determine a range of optimum reliability levels for long range electric power distribution system planning. The principal outage costs are incurred by industrial and residential consumers.

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Optimum Economic Power Supply Reliability

I. Introduction

Reliability standards for electricity supply in most countries are based on past engineering practice and rules of thumb. Such reliability standards typically originate in the developed countries and thus may be especially inappropriate for developing countries. Furthermore, in the next decade approximately 20% of public sector investments in developing countries are expected to be for electric power. The ad-hoc nature of standards of power supply, as well as the magnitude of investments in electric power by developing countries and the scarcities of capital and foreign exchange, indicate the need to develop a more rigorous economic framework which can be used to optimize electric power system reliability.

The issue of optimal levels of capacity and electric power reliability has received attention recently as part of the more general economic literature concerning public utility pricing under conditions of uncertainty (stochastic demand and supply). 1/ In this case, the utility is typically modeled as a net welfare maximizer, where net social welfare equals the difference between expected willingness-to-pay for electricity and either expected supply costs (Brown and Johnson) or the sum of expected supply costs plus the costs of rationing electricity according to consumers' willingness-to-pay (Crew and Kleindorfer, 1976, 1978). Such studies indicate that,

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1/ See, for example, Gardner Brown Jr., and M. Bruce Johnson, "Public Utility Pricing and Output Under Risk", American Economic Review, March 1969, pp. 119-128; Michael A. Crew, and Paul R. Kleindorfer, "Peak Load Pricing with a Diverse Technology", Bell Journal of Economics, Spring 1976, pp. 207-231; Roger Sherman, and Michael Visscher, "Second Best Pricing with Stochastic Demand", American Economic Review, March 1978, pp. 41-53; M.A. Crew and P.R. Kleindorfer, "Reliability and Public Utility Pricing", American Economic Review, March 1978, pp. 31-40.

ideally, both price and reliability should be jointly optimized to achieve maximum net social welfare. We may summarize this complex analysis in a very simplified form as follows: economic efficiency would be maximized if price was set equal to marginal cost, and the capacity level was fixed (thus also determining the reliability level) at the point where the marginal cost of adding to capacity (net of the energy saved) was equal to the marginal consumer benefits realized by the corresponding electric power shortages which were averted.

The short-run marginal cost (SRMC) may be defined as the cost of meeting additional electricity consumption, with capacity fixed. Therefore, in a given period, SRMC would be equal to the marginal energy costs plus shortage costs due to unmet demand; during the off-peak hours, since shortages are highly unlikely by definition, shortage costs could be neglected. The long run marginal cost (LRMC) is the cost of meeting an increase in consumption (sustained indefinitely into the future), in a situation where capacity adjustments are possible. Thus LRMC would include both marginal energy and capacity costs. When the capacity (and therefore the reliability level) is optimal, SRMC and LRMC coincide because marginal shortage costs are in fact equal to net marginal capacity costs.

The method of determining optimal reliability described in this paper differs from the basic approaches used in the papers mentioned above. Firstly, in the previous studies, electricity is treated as a good which directly provides consumers with satisfaction. Shortage costs are, therefore, measured primarily in terms of the resulting net reduction in consumer well-being, i.e. the reduction in consumer surplus (plus rationing costs in the case of Crew and Kleindorfer, 1976, 1978). However, in our paper, electricity is viewed as being an intermediate product, which provides no direct satisfaction to consumers, but which is used to produce final goods that are demanded by consumers. Thus we measure outage 1/ costs in terms of their effects on the production of final goods and services in various sectors of the economy. By taking this approach, the problem of having to use consumers' willingness-to-pay for planned electricity consumption as a measure of the costs resulting from unexpected outages is avoided. The consumer's surplus approach is questionable, especially when attempting to estimate short run outage cost, since outages may disrupt other activities complementary to electricity consumption. Thus actual outage costs may greatly exceed those estimated on the basis of willingness to pay for planned consumption. 2/ Moreover, the method of estimating outage costs described below does not necessarily assume that when outages occur load shedding takes place according to willingness to pay, i.e. the estimates of outage costs are not based on the assumption that those consumers with the lowest willingness-to-pay for electricity are the ones who suffer outages when demand exceeds supply. 3/

Secondly, given a rationing or load shedding scheme, previous studies maximized net welfare by satisfying first order conditions with respect to prices and capacity, indicating that partial approaches which attempt to

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1/ The term outage is used to represent all aspects of electric power shortages including supply interruptions, voltage and frequency changes. However, in the case study only the effects of interruptions are considered.

2/ See R. Turvey and D. Anderson, Electricity Economics, Johns Hopkins Press, Baltimore, 1977, Chap. 14.

3/ For example, Michael Webb implicitly makes this assumption in "The Determination of Reserve Generating Capacity Criteria in Electricity Supply Systems", Applied Economics, March 1977, pp. 19-31; and, he uses it to suggest that a minimum estimate of (say) per KWH outage costs is the retail tariff level.

"optimize" reliability in the presence of given prices 1/ cannot ensure that resulting net benefits are maximized. In other words, satisfying the first order condition with respect to capacity alone does not ensure that the objective function is maximized. This is because a different combination of prices, capacity, and hence reliability, may, in fact, lead to greater net social benefits. However, we recognize that electricity tariffs are often not readily subject to change. Thus from a practical point of view, it may be appropriate (or necessary) to attempt to "optimize" reliability in the presence of fixed or given tariffs, at least on the first round. To the extent that this is accomplished, then the net benefits derived from the provision of electricity should at least be increased. This study develops a method of optimizing reliability by weighing the costs and benefits associated with alternative levels of reliability. As reliability increases, the costs which interruptions in the supply of electricity (outages) impose on society decrease, while the costs of providing electric power increase. This suggests that, given a demand forecast based on the assumed tariffs, reliability should be optimized at the point where the marginal cost of further increasing reliability is equal to the marginal social cost of outages that is foregone as a result of improvements in reliability.

Moreover, this method of optimizing reliability (given the tariff level) can be used in an iterative fashion to jointly optimize reliability and tariffs. Once optimal reliability (subject to given prices as defined above) is determined, tariffs can be revised to reflect any changes in the cost of supplying electricity implied by the new reliability level. Using this new

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1/ Michael L. Telson, "The Economics of Alternative Levels of Reliability for Electric Generation Systems", Bell Journal of Economics, Autumn, 1975, pp. 679-694.

level of tariffs and resulting demand, reliability can be reoptimized; and, the process can be continued until the self-consistent combination of tariffs and reliability that maximizes the net social benefits of supplying electricity is determined.

The remainder of this introduction is devoted to a brief review of outage costs (i.e. economic costs of power failures) and previous studies of them. Next, appropriate methods of estimating outage costs for various categories of consumer are presented. Then, a model is developed which, taking tariffs as fixed, optimizes the reliability of electricity supply by comparing the supply costs of meeting consumer demand for electricity at different levels of reliability with the corresponding outage costs. Finally, the theory is applied to the case study of Cascavel, Brazil, in order to determine a range of optimum reliability levels for electric power distribution system planning.

Electricity is used for productive purposes by different consumers, and one method of estimating the costs of outages would be in terms of their effects on such production. 1/ Specifically, random electric power outages 2/ tend to alter the stream of inputs and outputs characterizing a production process. Under conditions approximating those of perfect competition, the net social benefit of marginal units of output equals the market value of the

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1/ Outage related costs can also be incurred in the form of expenditures on standby sources of electric power. This type of cost is not considered in any of the previous attempts to estimate outage costs and was found to be insignificant in the present case study of Cascavel.

2/ The effects of known or planned power failures are neglected because costs may be minimized by rescheduling activities, etc. Similarly, the effects of brownouts due to voltage drops, and frequency fluctuations are ignored. The severity of outages considered in this study is unlikely to lead to drastic structural changes in the behavior patterns of consumers (e.g., changes in the production processes of industrial users). Such short and long term behavior changes would be extremely difficult to predict.

output minus the market value of inputs. In most cases, outages result in a reduction of these net social benefits since the stream of outputs is reduced or delayed while the cost of inputs may also be increased. 1/

In contrast, most previous attempts to estimate outage costs fail to view production as a process which occurs over a number of time periods and which is disrupted when outages occur. Studies typically estimate outage costs by the product of value-added per KWH times the KWH's of outages during working periods, thus ignoring the possibility of making up "lost" product later in the time stream by using existing capacity more intensively or by overtime production; 2/ or, they attempt to estimate outage costs in terms of the price consumers are observed to be willing to pay for marginal units of planned electricity consumption, despite the fact that unexpected outages lead to disruption of production and the forced idleness of complementary productive factors. 3/ In addition, most studies consider only the costs of outages that affect industrial consumers of electricity. 4/ While a few studies explicitly consider the costs of outages which affect residential

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1/ If the market prices of inputs and outputs are distorted, appropriate shadow prices have to be used. For further details, see L. Squire and H. van der Tak, Economic Analysis of Projects, Johns Hopkins University Press, 1974; M. Munasinghe and J. Warford, "Shadow Pricing and Evaluation of Public Utility Projects", GAS 14, Energy, Water and Telecommunications Department, World Bank, April 1977.

2/ See for example: Taiwan Power Company, "Evaluation of Generating Capacity Reserve", 1975; A. Kaufman, "Reliability Criterion - A Cost-Benefit Analysis", Office of Research, N.Y. State Public Service Commission, August, 1975; and M. Telson (op. cit).

3/ See Section II for a more detailed discussion.

4/ See for example: EMENA Public Utilities Projects Div., "Appraisal of The Istanbul Power Distribution Project", IBRD, 1973; Jamaica Public Service Company, "Reliability Dollar Value Analysis" and "The Selection of a Generation Reliability Criterion for JPSC", November 1975; Taiwan Power Company (op. cit.); A. Kaufman (op. cit.); and M. Telson (op. cit.).

consumers, the treatment is typically not very rigorous and empirically untested. 1/

II. Estimation of Outage Costs

Residential

When the household is treated as a productive unit which uses inputs such as the householder members' time and market goods (e.g., electric appliances, electricity itself, etc.) to produce outputs such as leisure and nutrition which provide utility, 2/ then the cost of an unexpected outage may be estimated in terms of inputs spoiled or made idle (i.e. opportunity costs), as in the case of the industrial and commercial user categories.

Household outputs utilizing electricity as one of their principal inputs are of particular relevance. The most important of these are housekeeping, nutrition and leisure. At any given moment during the day, there is likely to be significant substitutability between electricity-using and non-electricity-using housekeeping activities. Furthermore, over a given time period (e.g., 24 hours), housekeeping activities temporarily interrupted by an outage may be rescheduled without much difficulty. Therefore, outage costs associated with housekeeping may be considered small. In general, nutrition is an activity which could be severely hampered by outages occurring during periods of cooking. However, in the case of Cascavel no significant outage cost was observed because cooking is done almost entirely by gas.

1/ See for example: P. Jaramillo and E. Skoknic, "Costo Social de las Restricciones de Energia Electrica", Officina de Planification, Chile August 1973; and D. Julius, "The Economic Cost of Power Outages: Methodology and Application to Jamaica", EW&T Dept., World Bank, August 1976.

2/ See G. Becker, "A Theory of the Allocation of Time", Economic Journal September 1965, pp. 493-517; and K. Lancaster, "A New Theory of Consumer Behavior", Journal of Political Economy, 1966.

Leisure differs from the previously discussed household activities in ways which make the associated outage costs more significant. Firstly, the enjoyment of leisure is constrained, at least for wage earners, to occur over a relatively fixed period of time. Secondly, the use of electricity could be considered essential to the enjoyment of certain leisure activities (e.g., TV watching, reading, etc.) during these night time hours; thus there are very limited substitution possibilities for non-electricity-using activities during an outage which occurs in this period, at least in the short run. A model of household activity based on the consumers labor-leisure choice, and presented elsewhere, 1/ yields an expression for outage cost which embodies the opportunity costs of other complementary inputs used to produce electricity-dependent leisure, which are made idle by the lack of electricity. Therefore, since the main opportunity cost involved is due to the lost input of time, the household's net income earning rate provides an estimate of marginal outage cost during the leisure hours. 2/

The results of a survey of residential electricity consumers in Cascavel does confirm that: (a) the chief outage cost imposed on this category of user is the loss of leisure during a critical 1.5 hour period in the

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1/ See M. Munasinghe, "The Leisure Cost of Electric Power Failures", World Bank Staff Working Paper, Dec. 1977.

2/ It is assumed that housewives are not constrained to enjoy leisure only during the evening hours, and hence their outage costs are small. Therefore, it is possible to avoid complications arising from having to estimate the value of housewives' time, e.g., see: R. Gronau, "The Intra-family Allocation of Time: The Value of Housewives' Time", American Economic Review, September 1973, pp. 634-651.

evening, and (b) the mean income earning rate for a household is an acceptable monetary measure of the marginal leisure loss due to an outage. 1/

Generally, the above measure of outage cost is considerably higher than the value of KWH lost, if the latter were priced at the consumer tariff level. In terms of the (short run) household demand curve for electricity, this underlines the fact that the KWH's lost due to a random outage are not always marginal. Therefore, the outage cost reflects not just the small wedge shaped area of consumers' surplus lying between the downward sloping demand curve amd the horizontal price line, owing to KWH's lost at the margin, but rather a much larger amount of consumers' surplus foregone corresponding to inframarginal KWH lost. 2/ Moreover, even if the marginal KWH is lost, the resulting outage cost may be significantly greater than the above-described area of consumer surplus because such an outage is unplanned and thus leads to the forced idleness of complementary productive factors. The willingness of residential consumers to pay the equivalent of their net income earning rate to avoid evening-time outages is not surprising in terms of the absolute

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1/ A downward sloping demand curve for leisure would imply higher outage costs per unit time for outages for long duration (e.g. 2 hours), involving inframarginal units of leisure.

2/ This point is often overlooked: see, for example, M. Webb, "The Determination of Reserve Generating Capacity Criteria in Electricity Supply", Applied Economics, March 1977, pp. 19-31; or D. Priestmann, "The Cost of Long-term Electrical Energy Shortage due to Underplanning", Eleventh Annual Pacific Northwest Regional Economic Conference, Eugene, Oregon, May 1977.

amounts of money involved, 1/, e.g. on this basis, in 1976 a typical electricity using home in Cascavel with an annual income of Cr$60,000 (i.e. about Cr$28.5 per working hour) 2/, would have to pay only Cr$57 per annum more (i.e. about 6% of their annual electricity bill of Cr$920), if the incidence of evening outages was halved from 4 to 2 hours per annum.

The principal advantage of this method for estimating the leisure costs of outages to residential consumers is its reliance on relatively easy-to-obtain income data. For example, as in the case of Cascavel, it is often possible to obtain a good relationship between family income and KWH electricity consumption for a typical sample. Therefore, on the basis of the electric utility company's billing records, the income levels of the electricity using households may be estimated. However, the empirical test of the value of leisure lost due to an outage depends on the short-run willingness-to-pay criterion. 3/

1/ Note that this is a purely monetary measure. If there is diminishing marginal utility of income/consumption, then it is possible to weight the outage costs, depending on the average income level of the household. Such social weights, which should reflect societies income distributional goals, would tend to reduce the disparity between the disutility of outages to low and high income households. See: I.M.D. Little and J.A. Mirrlees, Project Appraisal and Planning for Developing Countries, Heinemann, London, 1976.

2/ US$1 = Cr$12.5 (end 1976).

3/ However, there are several theoretical problems. Firstly, traditional work practices such as the 40 hour week, insufficient employment opportunities, union rules concerning hours of work, and so on, may make it difficult to justify equating the wage to the marginal value of leisure. But in the case of Cascavel, unemployment was very low due to rapid economic growth in the area, and union pressures were minimal; thus these problems may not be severe Secondly, the cost to non-wage earning members of the family is effectively ignored by allowing only the wage earners to represent the household as an income earning unit. Thirdly, there may be some outage expectation, especially in areas where outages are frequent, which tend to reduce outage cost. In certain perverse case, outages may even provide utility, e.g., enjoyment of a novel situation. Finally, leisure may be enjoyed outside the home, in which case it should be treated separately.

Industrial

In general, industrial consumers suffer outage costs because materials and products are spoiled, and normal production cannot take place. 1/ The cost of spoiled products and materials (SPC) which result because outages affect a given firm or industry over a time period (say one year) can be measured as:

$$SPC = \sum_{i=1}^{f} [v(d_i) + m(d_i)] \frac{Q}{h}$$

Where Q = total annual value-added, h = hours of operation in a benchmark year, f = frequency of outages per annum, d = duration of the i^{th} outage, and $v(d_i)$ and $m(d_i)$ = value-added and the value of non-factor inputs respectively embodied in the spoiled products and materials (with both $v(d_i)$ and $m(d_i)$ expressed as a fraction of average value-added per working hour).

Disrupted production results in an opportunity cost in the form of idle capital and labor (IFC) which can be measured as:

$$IFC = \sum_{i=1}^{f} \left[E \cdot d_i + \bar{E} \cdot \gamma(d_i)\right] \cdot \frac{Q}{h}$$

Where E and $\bar{E}$ = the fractions of normal output not produced during the outage and restart 2/ periods respectively, and $\gamma(d_i)$ = restart time for an outage of duration of d_i.

1/ See D. Julius (op. cit.), and Swedish Committee on Supply Interruption Costs, "Costs of Interruptions in Electricity Supply", O.A. Trans. 450, The Electricity Council, UK, September 1969.

2/ Often production cannot begin immediately after the supply of electricity is restored because there is a restart time during which machines must be cleaned, furnaces reheated, and so on; in most cases, E = $\bar{E}$, and therefore we adopt this simplifying assumption.

If slack productive capacity exists, then a fraction λ of lost value-added 1/ can be made up by using the productive capacity more intensively after the outage than during normal working hours. Therefore, a part of the outage costs (RC) can be recovered:

$$RC = \lambda \cdot IFC$$

Firms which do not produce 24 hours per day also have the option of making up some fraction ρ of lost output by working overtime. In most cases, it is unlikely that a profit-maximizing firm would have an economic incentive to do so. However, contractual obligations or other short-run constraints on a firm's behavior might lead to a decision to work overtime to make lost output. The hours of overtime production necessary to accomplish this is given by:

$$h_0 = \rho \sum_{i=1}^{f} [v(d_i) + \{d_i + \gamma(d_i)\}.(1-\lambda).\epsilon]$$

and the opportunity cost of overtime production (OTC) can be measured as: 2/

$$OTC = h_0 \left(\frac{\bar{w}}{w}\right) \frac{L}{h}$$

where L = annual labor value-added, $\bar{w}$ and w = overtime and normal wage rates respectively, 2/ and it is assumed that there is no opportunity cost of using capital during overtime production periods.

1/ λ varies with the time an outage occurs and its duration. However, an average value of λ can be calculated. In fact, in Cascaval $\lambda = 0$ for most firms.

2/ In cases of wage distortion, shadow wage rates could be used to represent the opportunity cost of labor both during normal working hours, and overtime.

Thus allowing for the possibility of both slack productive capacity and overtime production, a general measure of the costs of outages which affect a firm or industry over a given time period (OC) can be determined.

$$OC^{I} = \frac{Q}{h} \sum_{i=1}^{f} \left\{ m(d_i) + \left[1 - \rho\left(1 - \frac{\bar{\omega}}{\omega} \cdot \frac{L}{Q}\right)\right] \left[v(d_i) + \{d_i + \gamma(d_i)\}(1-\lambda)\epsilon \right] \right\}$$

In most cases, $\lambda = 0$ and $\rho = 0$ so that:

$$\underline{OC^{I} = \frac{Q}{h} \sum_{i=1}^{f}} \left[m(d_i) + v(d_i) + \{d_i + \gamma(d_i)\}\epsilon \right]$$

As ρ increases from 0 toward 1, OC will increase if $\frac{\bar{W}}{W} > \frac{Q}{L}$, and OC will decrease if $\frac{\bar{W}}{W} < \frac{Q}{L}$. That is, the greater is the overtime pay rate, the more likely it is that increasing the outage-related opportunity cost of using labor for overtime production will more than offset the reduction in the outage-related opportunity cost which results as the idle period of capital is reduced.

A survey of the 20 principal industrial users of electricity in Cascavel, based on the above methodology, provided the results given in Table 1. The firms were broadly representative of the industrial sub-sectors in the table. Each of the sub-sector outage cost functions was derived from the outage cost functions of the firms making up that sub-sector, weighted according to each firms share of value added within the sub-sector.

Table 1: Industrial Outage Cost Functions

No.	Industry	OC Function Type /2	Estimated Coefficients /1 a ($x\ 10^{-4}$)	b ($x\ 10^{-4}$)	Remarks /3
A.1, & B.3	Mechanical and Metallurgy	linear	0.0013	3.9	D
A.2	Non-metallic Minerals	linear	0.077	3.5	D
A.3	Wood	linear	0.094	3.9	D
A.4	Vegetable Oils	Piecewise-linear	0.037 3.6	2.1 1.9	$d < 0.5$ hours, A $d \geq 0.5$ hours, A
A.5	Food and Beverages	Piecewise-linear	1.22 7.07	2.30 2.02	$d < 0.5$ hours, D $d \geq 0.5$ hours, D
		linear	0.66	0.72	N
A.6	Other	log	7.2	2.9	$d \geq .01$ hours, D
B.2	Telephone	linear	0.002	1.1	A
B.3	Water Treatment	linear	-0.27	1.1	$d \geq 2$ hours, D

/1 $\bar{R}^2 > 0.95$ for all estimations.

/2 Linear and log refer to functions of the type $C/Q = (a + b.d)$ and $C/Q = (a + b.\log_{10} d)$ respectively, where C = outage cost, Q = annual value added and d = outage duration (hours).

/3 D = daytime operation; N = Night-time operation; A = 24 hour operation.

Other

As in the case of leisure, the provision of public illumination is constrained to occur during the hours of darkness, and the service cannot be supplied without electricity. Thus an outage which affects public illumination imposes a cost in the form of reduced community well-being since some of the benefits of public illumination, e.g. security, improved motoring safety, etc., are foregone. The exact value of such foregone benefits is difficult to determine, but one can argue that these foregone benefits are worth at least as much as the net supply cost which the community would have incurred for public illumination during the outage periods 1/. For example, during a one hour outage such a minimum estimate of net cost would equal the annuitized value of capital equipment and routine maintenance expenditures per hour of use of the particular street lights affected by the outage; electricity costs are not included since they are not incurred during outages.

Hospitals essentially provide health services; but, because of the lack of knowledge of the production process and the difficulty of measuring outputs, the measurement of outage costs is more difficult and less exact than in the case of industrial firms discussed earlier. Two hospitals (80 beds and 200 beds) were surveyed to estimate the opportunity costs of both productive factors which are made idle (e.g. electricity using equipment, labor, etc.) and intermediate products, such as blood and medicines, which

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1/ It is unlikely that the decisions concerning marginal investments on public illumination would be made on the basis of explicit cost-benefit analyses. However, if street lighting is either much too inadequate, resulting in reduced security for citizens at night, or conversely far too extensive, leading to increased costs and municipal taxes, etc., then there will be public pressure on the city government to rectify the situation.

might spoil because of outages. 1/ The principal outage costs were found to occur during the night period (i.e. 1900-0600 hours), due to idle labor and capital. The average cost was estimated to be Cr$0.67 per hospital bed per hour of outage.

Outage costs for government offices and commercial customers were found to be minimal because, in most cases, work could continue by daylight. Furthermore, there was sufficient slack during the normal hours of work for jobs delayed by any outage to be made up. Supermarkets and hotels reported minor amounts of spoilage for long outages, i.e., over five hours; however, such outages are extremely rare. The KWH consumption of rural consumers in the vicinity of Cascavel was less than 1% of the total in 1974, and their share of demand is unlikely to exceed 5% of the total even by 1996. Therefore, this category of consumer will not be considered in detail here. In general, large mechanized farming operations which are more electricity intensive, may be treated like large industries, whereas small farmers and hired workers could be treated more like residential consumers. In estimating farm incomes and effective wage rages, the importance of auto-consumption would have to be recognized, especially for farmers close to the subsistence level.

III. The Optimization Model

Let the measure R characterize the reliability level of the electric power system, over the time horizon being considered, and let D be the corresponding demand for the service assuming a given price level. We wish to

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1/ Estimating the costs resulting from possible losses of life is a task exceeding the scope of this study; and therefore, such costs are not considered here. The existence of standby batteries for operating, intensive care, and surgical equipment suggests that loss of life will be avoided in most cases; the cost of these batteries is very small.

determine whether a change in R will provide a net economic benefit to society. A simple expression for the net benefit of electricity consumption at given levels of reliability R, demand D, and assuming fixed tariffs, may be written: NB(R,D) = TB(D) - OC(R,D) - SC(R,D); where TB(D) = total benefit from consumption at the level of demand D, if there were no outages; OC(R,D) = outage costs 1/; and SC(R,D) = supply costs.

$$\therefore \frac{d(NB)}{dR} = -\frac{\partial(OC+SC)}{\partial R} + \frac{\partial D}{\partial R} \cdot \frac{\partial}{\partial D}(TB-OC-SC)$$

For purposes of the simulations carried out in this study, we make the simplying assumption that $\partial D/\partial R = 0$, i.e. for the range of reliability levels considered here, variations in R will have negligible effects on predicted demand. Also, it is assumed that variations in R do not significantly affect consumers' expectations of reliability. Then the effects of an increase in reliability $|\Delta R|$ on net benefits may be written:

$$\Delta NB = -\Delta OC - \Delta SC = |\Delta OC| - |\Delta SC|$$

where $\Delta OC = \frac{\partial OC}{\partial R} \cdot \Delta R$ and so on, and use has been made of the fact that $\frac{\partial OC}{\partial R} < 0$ and $\partial SC/\partial R > 0$. Therefore, in order to maximize the net economic benefits of supplying electricity to society, the reliability level should be increased as long as the corresponding decrease in outage costs exceeds the increase in

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1/ Note that OC also depends on consumers' expectations of reliability which are related to the actual reliability level.

supply costs, and vice versa. Equivalently, since TB is assumed to be independent of the reliability level R, the net benefit NB is maximized at the value of R where total costs TC = OC + SC are a minimum.

We define the measure of reliability of electricity supply to any group of consumers in year t as follows: 1/

$$R_t = 1 - OE_t/TE_t$$

where OE_t = electric energy not supplied because of outages in year t.

TE_t = total electric energy that would have been supplied in year t if there were no outages.

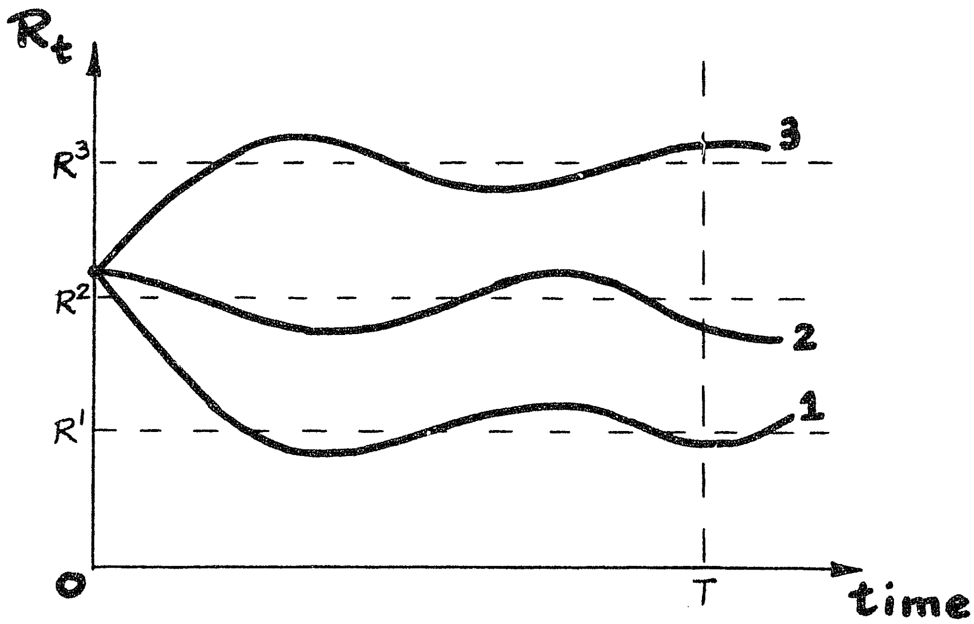

Figure 1: Characterization of alternative expansion paths according to the reliability level.

1/ This measure is analogous to the loss of energy probability (LOEP) criterion used in generation system planning.

Consider Figure 1, which shows three possible evolutionary paths of system reliability for the given demand forecast starting from a relatively high level and extending over some planning time horizon; i.e. 0 to T. Path 2 represents the case in which expenditures on the power system are sufficient to maintain the medium level of reliability R^2. In paths 1 and 3 the reliability is adjusted to two different target levels, i.e., R^1 and R^2. The paths vary about the trend line because of the lumpy nature of the investments corresponding to each system expansion plan.

Now, let the annual stream of future system supply costs (i.e. investment, maintenance, etc.) and outage costs, net of marginal generation costs of KWH not supplied due to outages, associated with expansion path i be denoted by SC_t^i and OC_t^i for $t = 0, \ldots\ldots\ldots, T$.

Next we define the present discounted values:

$$R^i = 1 - \left[\sum_{t=0}^{T} \frac{OE_t^i}{(1+r)^t} \Big/ \sum_{t=0}^{T} \frac{TE_t^i}{(1+r)^t}\right]; \quad SC^i = \sum_{t=0}^{T} \frac{SC_t^i}{(1+r)^t}; \quad OC^i = \sum_{t=0}^{T} \frac{OC_t^i}{(1+r)^t};$$

and, total costs: $TC^i = OC^i + SC^i$.

The expansion path i which minimizes TC^i also yields the optimum reliability level R^m. In practice, because the system design process involves discrete jumps in R rather than continuous variations, it is better to consider of a band of optimum reliability levels around R^m, rather than a unique value. Furthermore, the impact of the new reliability lends on price and demand should be examined iteratively, as discussed earlier. In this formulation, the measure R^i is an aggregate scalar quantity used for convenience to simply characterize a given system expansion path i. The process of choosing the optimum system design is carried out on the basis of an economic cost benefit analysis, and is quite independent of the actual measure of reliability.

The above cost-benefit simulation model is sufficiently general to optimize any part of a power system, i.e. at the generation, transmission or distribution levels. However, in the illustrative case study presented next, only the distribution network is varied, whereas the reliability of power delivered to the sub-station is exogenously fixed (i.e., generation and transmission reliability are held constant). Therefore, incremental generation and transmission costs do not enter into the calculation, except for KW and KWH losses in the distribution system, which may be valued at the marginal supply cost. A given improvement in reliability may, of course, be realized more economically by strengthening generation and transmission rather than distribution, but this is outside the scope of the case study.

IV. The Case Study

The case study involves the optimization of the electric power distribution system servicing the Cascavel urban area, by comparing the costs and benefits of changes in the reliability level. The analysis is characterized by the high level of disaggregation required for distribution system planning. 20 categories of consumers are identified: 4 residential income classes, 10 industrial sectors, 3 commercial categories (including government offices), public illumination, hospitals and schools. The city is overlaid with a rectangular grid which divides up the urban area into 247 distinct cells (0.5 x 0.5 km^2), and the planning time horizon spans a 21 year period

(1976-1996). The technical and engineering considerations by which the supply side costs were determined are briefly summarized below. 1/

First a demand forecast is made assuming a constant future real price level, disaggregated by consumer category, by geographic cell, and by year, over the plan period. For each consumer type, electricity consumption is correlated with one or more other explanatory variables which are relatively easy to predict. For residential consumers, the relationship between KWH use and household income is used together with the projected growth of population and income, to forecast electricity consumption. In each industrial sector, the future load is based on the value added per KWH, and projected growth of value added. Similarly, the key relationships for commercial users, hospitals and schools are KWH consumption per unit area of floor space, per hospital bed, and per student respectively. These loads are allocated among the different geographic cells, for the plan period, starting with the existing pattern of consumers in 1976 available from the billing records of the local electric utility company, and using the Cascavel long range urban development plan 2/ and zoning regulations to determine the future distribution of demand. The results of the demand forecasts for various categories of consumers are summarized in Table 2. Also, information on population, percent of the population served with electricity, household income and consumption of electricity, and value-added per KWH is summarized in this table.

1/ For details, see M. Munasinghe and W. Scott, "The Optimum Economic Reliability Level and Long Range Distribution System Planning", Proceedings of the IEEE Power Engineering Society Conference, Summer 1978, Los Angeles.

2/ Plano Diretor the Desenvolvimento, Prefeitura Municipal de Cascavel, Parana, Brazil, 1975.

TABLE 2

Summary of Economic and Load Forecasts

	1976	1996
Number of Persons ('000)	90	399
% of Population Served with Electricity	55.8	91.5

	Total Annual Electricity Consumption (GWH)		Average Net Income/household (1976 $Cr x 10^3)		Average Elect. Consumption/Household (KWH)	
	1976	1996	1976	1996	1976	1996
I Residential						
Lower:	0.3	8.6	18.4	40.3	307	680
Lower Medium:	3.5	50.7	47.7	94.7	794	1570
Upper Medium:	5.9	61.7	97.5	191.1	1631	2860
Upper:	4.4	30.8	228.6	386.3	3233	4820
TOTAL	14.1	151.8				
II. Industrial			Value-Added/KWH (1976 Cr$)			
			1976			
Main:						
Metallurgy and Mech.	.25	4.17	23.5			
Non-Metalic Minerals	.80	13.16	14.9			
Wood	4.33	13.91	32.3			
Oils	5.42	52.28	19.6			
Food and Beverages	3.26	31.51	19.9			
Other	1.23	11.94	14.1			
TOTAL	15.29	126.96	124.3			
Service:						
Telephone	.46	5.42	25.1			
Water and Sewage	2.80	22.57	5.1			
Metallurgy and Mech.	.25	4.17	23.5			
Other	3.50	57.28	--			
TOTAL	7.01	89.44	54.1			
TOTAL	22.30	216.40	232.5			
III. Commercial	13.5	164.5				
IV. Public Illumination	3.0	13.5				
V. Hospitals and Schools	0.6	2.8				
VI. TOTALS	53.5	549.0				

Next, several alternative distribution systems are designed to meet this load, each using a different target reliability criterion. Thus we distinguish four basic system designs to be called the low, medium A, medium B and high reliability plans respectively. Finally, the engineering analysis leads to a determination of the total supply costs, and the expected annual frequency and duration of outages (over the plan period), corresponding to each basic system plan.

The chief global (or city-wide) characteristics of the basic alternative system plan are summarized in Table 3. Initially, confining our attention to the four basic system designs, as the overall reliability level (R) increases, outage costs (OC) decline steadily, whereas supply costs (SC) remain fairly stable until there is a sharp rise in SC between the medium B and high reliability plans. 1/ Outage costs per KWH lost (OCK) tend to rise with increasing system reliability.

As discussed in Section II, the four types of electricity use for which outage costs were significant are: residential, industrial, public lighting and hospitals. Table 4 indicates that the first two categories are the dominant ones, in terms of total energy use (TE) and outage costs. For the range of reliability levels considered in this study, the main industrial group appears to be the one most affected by outages, in terms of OCK, followed by residential, service industrial, hospitals, and public illumination. OCK for the main industrial category tends to increase as reliability increases (and the average outage duration decreases), whereas OCK does not vary much with system reliability for the other categories of users.

1/ Plan 2B is slightly cheaper although more reliable than Plan 2A, because of better design optimization. However, for this range of reliability SC may be considered essentially constant.

Table 3 - Global Characteristics of the Alternative Distribution System Plans[1/]

System Plan	Reliability:R	Outage Rate: OR[2/] (%)	Outage Cost: OC (10^6 Cr$)	Supply Cost: SC (10^6 Cr$)	Total Cost:OC+SC (10^6 Cr$)	Outage Cost/KWH Lost: OCK(Cr$/KWH)
Basic Designs						
1 (Low Rel.)	0.9935	0.650	150.1	57.5	207.6	14.0
2A (Med. Rel.)	0.9969	0.314	77.2	58.6	135.8	14.9
2B (Med. Rel.)	0.9981	0.191	49.5	57.8	107.3	15.7
3 (High Rel.)	0.9988	0.116	28.4	76.9	105.3	14.8
Hybrid Designs						
4 (Med./High Rel.)	0.9982	0.184	44.5	59.9	104.4	14.6
5 (Med./High Rel.)	0.9983	0.166	44.3	65.2	109.5	16.1
6. (Med./High Rel.)	0.9984	0.159	39.3	67.4	106.7	14.9

1/ Present discounted values of quantities, over the period 1976-2006 as defined in Section III; discount rate= 12%.

2/ $OR= 100 * (1-R) = 100 * \frac{OE}{TE}$.

Table 4 - Energy Use and Outage Costs by Major Consumer Category[1]

Consumer Category	Total Energy:TE (GWH)	Outage Cost:OC (10^6 Cr$)				Outage Cost/KWH Lost: OCK (Cr$/KWH)			
		Plan 1	Plan 2A	Plan 2B	Plan 3	Plan 1	Plan 2A	Plan 2B	Plan 3
Residential	484.1	68.2	34.8	20.5	9.9	17.9	18.2	18.6	17.5
Main Industrial	371.8	77.4	40.6	27.8	17.8	31.4	33.5	30.0	26.5
Service Industrial	224.7	4.1	1.6	1.0	0.6	3.4	3.2	3.8	3.6
Public Lighting	60.4	0.2	0.1	-	-	0.4	0.4	0.4	0.4
Hospitals	11.7	0.3	0.1	-	-	5.9	5.9	5.9	5.9

1/ Present discounted values of quantities over the period 1976-2006, as defined in Section III ; discount rate=12%.

A more detailed breakdown of outage costs for the two dominant categories, residential and main industrial, is presented in Table 5. As expected, OC increases with the outage rate (OR) for all consumer types. For any given class of residential consumer, the outage cost per KWH lost is relatively unaffected by the reliability level; but for a given system plan, residential OCK rises a little with income level. The values of industrial OCK reflect the nature of the respective outage cost functions given in Table 1. 1/

In summary, residential consumers suffer outage costs of about Cr$16-22 per KWH lost, over the range of reliability levels considered. Industrial sub-category A.3 is the most sensitive (approximate range Cr$35 to 75 per KWH lost), especially to outages of shorter duration, whereas OCK is lower for the remaining sectors (Cr$12-35 per KWH lost). The outage cost results for industrial consumers are consistent with results from other studies 2/, but our residential outage costs are much larger because in previous studies the value of foregone leisure was ignored 3/. Within the

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1/ In the case of A.1 and A.2, the intercept term is small so that the linear OC function practically passes through the origin. Therefore, since both OC and OE are linearly proportional to outage duration, their ratio OCK is constant and unaffected by reliability level. For A.3 and A.6, the respective OC functions have a large intercept and a logarithmic form, leading to an increase in the values of OCK as OR (and the mean outage duration) decrease. The discontinuities in the OC functions of A.4 and A.5 due to large spoilage costs for outage duration d>0.5 hours, dictate the values of OCK in these cases.

2/ A range of values US$0-7 per KWH lost have been reported for different industries by others. However, because of the wide variations in methodology, different countries of application and timing of these studies, the results are not strictly comparable.

3/ Except for the study by the Swedish Committee on Supply Interruption Costs (op.cit.) which gave values of residential outage costs similar to ours; once again the results are not directly comparable.

Table 5 - Disaggregate Energy Use and Outage Costs of Residential and Main Industrial Consumers 1/

Consumer Category	Total Energy:TE (GWH)	Outage Cost: OC (10^6 Cr$)				Outage Cost/KWH Lost:OCK (Cr$/KWH)				Outage Rate (OR) (%)			
		Plan				Plan				Plan			
		1	2A	2B	3	1	2A	2B	3	1	2A	2B	3
Residential 2/													
L	19.9	2.85	1.36	0.83	0.38	16.5	16.8	17.2	16.2	0.870	0.406	0.243	0.117
LM	152.3	20.11	10.02	5.98	2.87	16.6	16.8	17.3	16.2	0.798	0.391	0.228	0.117
UM	198.9	27.47	14.00	8.27	4.01	17.6	17.9	18.3	17.2	0.783	0.394	0.227	0.117
U	113.1	17.72	9.43	5.46	2.65	20.6	20.8	21.4	20.0	0.760	0.401	0.226	0.117
Main Ind. 3/													
A.1	9.7	0.61	0.26	0.14	0.10	24.9	24.9	24.9	25.0	0.269	0.106	0.056	0.041
A.2	30.5	1.11	0.48	0.27	0.19	13.6	12.8	11.9	11.8	0.251	0.124	0.074	0.054
A.3	63.9	9.45	5.29	3.92	2.84	36.7	48.0	73.1	75.5	0.403	0.173	0.084	0.059
A.4	146.2	44.13	22.18	15.54	8.73	31.8	35.2	31.9	25.2	0.948	0.431	0.334	0.237
A.5	88.1	19.40	10.07	5.92	4.40	35.0	32.0	21.9	22.1	0.630	0.357	0.306	0.226
A.6	33.4	26.70	2.28	2.03	1.52	16.6	21.2	22.8	22.8	0.482	0.322	0.267	0.200

1/ Present discounted values of quantities over the period 1976-2006, as defined in Section III ; discount rate=12%.

2/, 3/ Residential and main industrial sub-categories as described in Section III, and Table 2.

residential consumer category, and for a given system plan, OR is quite stable. However, there are significant differences among values of OR for the different industrial sub-categories, because of variations in production hours, restart times, etc.

The results of the distribution system optimization procedure described in Section IV may be clarified from Table 3 and Figure 2, on a city-wide basis, where it is convenient to plot the outage rate $OR^i = OE^i/TE^i = 100 * (1 - R^i)$ instead of R^i, because most values of R^i lie between 0.98 and 1.0. As discussed earlier, we find that in progressing from Plan 1 to Plan 3, there is a steady improvement in overall reliability, a corresponding decrease in global outage costs (OC) and a sharp increase in the distribution system supply costs (SC) between Plans 2B and 3. As a first approximation, the minimum value of the total economic cost to society, i.e., the combined outage and distribution supply costs (OC+SC), will be most likely to occur somewhere in the region of Plans 2B and 3.

In the next stage of optimization, it is possible to refine the procedure by examining outage and supply costs for specific areas of the city. The results of disaggregate outage costs and outage cost per KWH cost at the cell level indicate that the high population density areas in the city centre, and the area zoned for main industrial activity suffer the highest outage costs. Therefore, we consider several hybrid distribution system designs, by varying the levels of reliability for different neighborhoods.

In hybrid Plan 4, the reliability of service to the main industrial zone is maintained at the same level as in the high reliability Plan 3, whereas the distribution system for all other areas is designed according to the medium reliability Plan 2B. Plans 1 and 2A are ruled out as viable

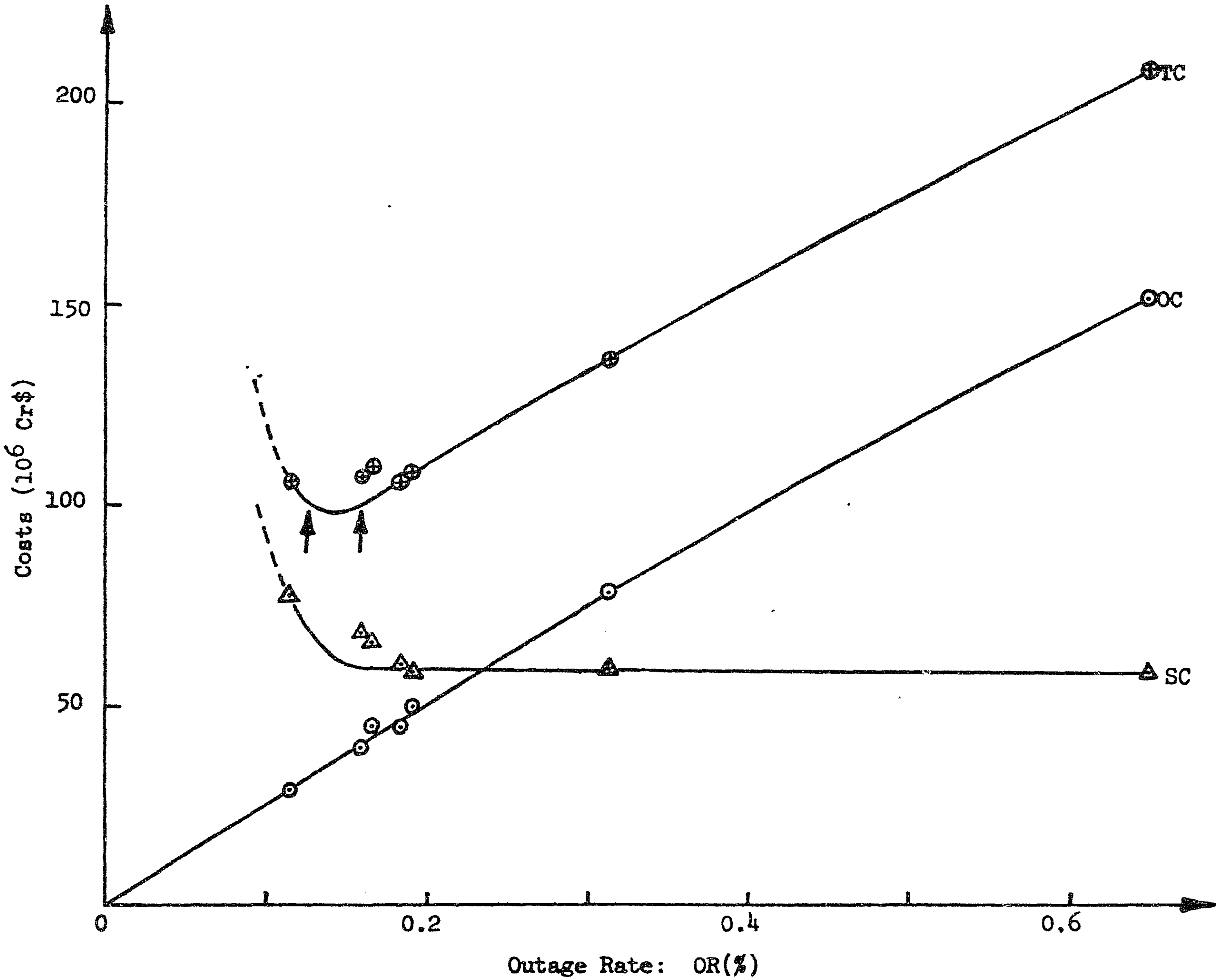

Figure 2 - Optimization of the distribution system: costs versus outage rate

alternatives for any specific area, because the potential saving in reducing SC by changing from a higher reliability design to either of these two plans is generally much smaller than the corresponding increase in OC. In Plan 5, the city center areas are provided with a high reliability distribution system, and the rest of the city gets medium B reliability service. Finally, in Plan 6 both the city center and the main industrial zone are supplied at high reliability, while all other areas obtain medium B reliability service. The results for the hybrid plans indicate that Plan 4 has the lowest total costs. 1/ Clearly, further fine tuning of the optimization procedure is possible by examining different parts of the city in greater detail and varying the design of the distribution system in these areas. However, for the purposes of this study, which is to demonstrate the application of the new methodology, we go no further than to identify an approximate range of reliability levels 0.13<OR<0.16 (see arrows in Figure 2) within which the optimum distribution system plan should lie. In fact, since the greatest potential savings in OC would be realized by the main industrial consumers, the possibilities for improving reliability in the industrial zone, even beyond the high level of Plan 3, should be examined. The optimum system design corresponding to the minimum of the TC curve would probably provide very high reliability service for the main industrial consumers, a slightly lower level of reliability (e.g. a design lying between Plan types 2B and 3) for the city center, and reliability of service corresponding to Plan 2B elsewhere in the city.

1/ Note that the plotted data points for hybrid plans 5 and 6 are off the trend line of TC for optimally designed systems.

The results are relatively insensitive to a 10% change in the demand forecast, e.g. Plan 4 remains the best one tested. A range of discount rates between 8% and 14% were also tried, but these changes also did not have much impact on the main conclusions (except for different values of PDV, etc.). Finally, the results were not significantly affected by variations in the shadow pricing parameters. 1/

VII. Conclusions

The study demonstrates that it is possible to optimize the design of a long range distribution system so as to minimize the total costs (i.e. sum of outage and system costs) to society. Since the economic methodology is quite general, it would be possible to treat generation and transmission system reliability in the same way; i.e. optimize the design of the whole electric power system.

The principal outage costs are incurred by industrial and residential consumers, and this fact would be reflected in the optimum design of the distribution system, with the high population density core city area and the industrial zone receiving the highest reliability service. The medium reliability type B service is preferable to lower reliability designs for other areas, because the difference in system costs between these alternatives is small compared to the difference in outage costs. Further fine tuning of the system is possible by varying the design in specific areas to obtain a better optimum. The results are relatively unaffected over the range of variations in the demand forecast, discount rate and shadow prices considered in the study.

1/ The principle parameters varied were: the shadow exchange rate $1<SER<1.25$; the shadow wage rate $1>SER>0.8$; and the ratio of overtime to normal wage rate $1<\frac{\bar{w}}{w}<1.5$.

The explicit analysis of residential outage costs, confirmed by an empirical survey of the consumers' willingness-to-pay to avoid outages, indicates that the net household income earning rate is a reasonable estimate for such outage costs incurred during the leisure hours. Industrial outage costs by major sector have also been analyzed in terms of spoilage, idle factors of production, and the making up of lost production during both regular working hours and overtime. The analysis is helpful in identifying those industries which are very sensitive to outages; this information would be most useful in the context of load shedding e.g. to rank industries in terms of outage cost per KWH lost.

If the optimum plan corresponding to the minimum TC (about Cr$98 million in Figure 2) is adopted, it would result in a net saving of about Cr$ 8 million (US$0.65 million) in present value terms for Cascavel, over the next 30 years, assuming that the alternative would have been Plan 3 in which the existing high level of reliability was maintained into the future, over the whole city. Of this net saving, Cr$15 million would be the reduction in system costs, whereas outage costs would increase by Cr$7 million. If electricity revenues were reduced by Cr$15 million, we find that the consumers living in the medium reliability areas would pay on the average at least Cr$0.01 less per KWH consumed 1/ than with Plan 3. This change in the mean

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1/ Assuming that the system cost saving of Cr$15 million is allocated to the 1,340 GWH (in present discounted value terms) consumed by users outside the industrial zone. If the tariff of main industrial consumers within the industrial zone was raised to reflect their higher reliability level, the average tariff for other areas of the city could be reduced further.

price due to reliability level optimization alone is small compared, for example, to the average 1976 residential tariff of about Cr$0.82 per KWH consumed, i.e. a reduction of about 1%; and therefore, we need not consider the feedback effects of the revised price level on the demand forecast.

The methodology is quite straightforward, using data (most of which may be obtained without much difficulty, e.g. from the local electric utility company) as inputs to three basic computerized models, which help to determine: (a) the demand forecast; (b) the alternative distribution system designs; and (c) the corresponding system costs and outage costs. Special features of the analysis include the combined use of economic and engineering criteria to optimize long range distribution system planning, and the high level of disaggregation in planning: by consumer category, by geographic area (cells of 500 x 500 m^2 each), and by year (over a 20-year period).

Because every city has its specific characteristics, the results of the Cascavel case study cannot be used to draw wide ranging conclusions regarding generally desirable, distribution system reliability levels for other cities in the developing countries. However, the methodology remains valid and could be applied elsewhere.

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