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N. Vijayamohanan Pillai

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Centre for Development Studies
Thiruvananthapuram

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ABSTRACT

The present paper attempts to analyse the implications of the relationship between reliability and rationing cost involved in a power supply system in the framework of the standard inventory analysis, instead of the conventional marginalist approach of welfare economics. The study is substantiated by fitting a normal distribution to the daily internal maximum demand of the Kerala power system during 1995-96, and also by estimating, based on the techno-economic parameters of different types of power plants, the rationing costs implied in different reliability target criteria.

JEL Classification: C44; L94; Q41.

Key words: Reliability, rationing cost, maximum demand, normal distribution, power supply.

"How weak and little is the light……"

- Edward Thomas (*'Out in the Dark'*)

"Then He commanded the multitudes to sit down on the grass.
And He took the five loaves and the two fish, and looking up to heaven,
He blessed and broke and gave the loaves to the disciples;
and the disciples gave to the multitudes."
- Matthew (14:19)

1. Introduction

Reliability in general terms of a component (or system) equals the probability that the component (or system) does not fail during any given interval (or, equivalently, it implies the probability that the component (or system) is still functioning at any given time). For example, if for a particular system the reliability is given as 0.90, this means that the system, under normal conditions, will be functioning for 90 per cent of the time in any given interval. In a power supply system, reliability refers to the ability of the system to meet the demand for power at any given time. Most of the reliability criteria are measured in terms of the probability of failing to meet the expected demand, thus implying shortage of power.

As in the case of any other good or service, whenever demand exceeds available supply, power shortage is experienced. In addition to random deviations of demand from expectations, several factors (on the supply side, affecting available supply) lead to shortages - insufficient water level in the reservoirs, forced outages of generating units, scheduled preventive maintenance, and generator deratings. When demand (or load, L) exceeds available generating capacity (K), a shortage or 'loss of load' occurs. The probability of shortage, or the expected fraction of time that the available capacity is unable to meet the demand, $P(L > K)$, is known as loss of load probability (LOLP). The expected quantum of energy not served, i.e., energy shortage, as a ratio to mean demand is referred to as loss of energy probability (LOEP). Of these two indices, LOLP is the most commonly used one in planning exercises.

Note that LOLP implies the expected accumulated amount of time in any given period during which load exceeds available capacity. Thus during a one year period, LOLP expressed in terms of days per year is $LOLP = 365 \times P(L > K)$. When expressed as a fraction of time, LOLP gives the probability that there will be a shortage of power (or loss of load) of any magnitude in a given period. Hence the name. It has been a common practice in some of the advanced countries to adopt in electricity supply an arbitrary reliability target, such as a one-day-in-ten-years LOLP. This does not mean a full day of shortages once every 10 years, rather, it refers to the total accumulated time of shortages that should not exceed one day in 10 years, or, equivalently, 0.03 per cent of a day. Telson (1975) has criticized this reliability criterion as too high from an economic standpoint, and suggested a five-day-in-ten-years LOLP (about 0.14 per cent of a day) as more appropriate. In some of the Asian and African countries (e.g., Korea, Hong Kong, Thailand, and Zimbabwe), LOLP criteria are found to vary from 12 to 24 hours per year, equivalent to five to ten days in ten years (Government of India 1997:2).

In India, a reliability target planning criterion of 5 per cent (i.e., 18.25 days a year) was adopted in the First National Power Plan (NPP, 1983) and in the Second NPP (1987). Such a very high level of LOLP target was justified in view of the inability, in terms of funds, to bring in a very large quantum of new capacity additions required for a desirably low target. Later on the general improvement in the technical performance of the generating plants, as also the introduction of new vintage larger size plants with higher efficiency lent sufficient force to decide, during the exercises for evolving the Third NPP (1991), on an LOLP target of 2 per cent (i.e., 7.3 days a year). The same level is now proposed to be retained during the 9th Five Year Plan (FYP) period in the Fourth NPP (1997) also, in view of the unexpected wide gap between the target and the achievement in capacity addition. At the same time, substantial capacity addition in the near future through independent power producers (IPP) has also been expected. It is hence proposed to improve the reliability target planning criterion further to 1 per cent (i.e., 3.65 days a year) LOLP by the end of the 10th FYP. The LOEP, on the other hand, is accepted to be targeted for less than 0.15 per cent.

Random fluctuations in demand imply that a situation may occur where quantity demanded exceeds available capacity. The capacity shortage or excess demand in turn implies that the unserved electricity be rationed among the consumers. The rationing schemes, ranging from simple rotating blackouts to sophisticated load shedding, affect consumers' surplus differently. In addition to surplus loss, rationing involves some administrative costs also. The sum of these two gives the short run social cost of rationing (or outage), the magnitude of which depends on the particular rationing scheme.

The perfect load shedding scheme, proposed originally by Brown and Johnson (1969) assumes costless rationing according to willingness to pay. Taking this as a base case, Crew and Kleindorfer (1976; 1986) defined (incremental) rationing cost as any surplus losses and administrative costs, that are incurred over and above those under the Brown and Johnson scheme, and that depend only on the level of excess demand. Random rationing and rationing in order of lowest willingness to pay are other forms of rationing examined by Visscher (1973) and Carlton (1977). With the former, consumers are served in random order until capacity is exhausted, without incurring any additional penalty costs. Our experiences of load shedding in India corresponds with this scheme. The latter assumes that when consumers have to queue up for service, those with the lowest willingness to pay may be willing to stand in line the longest, leading to rationing in order of lowest willingness to pay until capacity is exhausted, without any social costs. The simplest rationing scheme (with the most convenient, linear, functional form) assumes that each unit demanded but not supplied involves a constant marginal outage cost (Anderson and Turvey 1977: Chapter 14). This can be viewed as a special case of random rationing (Chao 1983).

Though rationing cost is crucial for determining both price and capacity at optimal level, actual numerical estimates of it are very rare. One way of estimating it is from LOLP itself, as a certain level of rationing cost is implied in a given LOLP target (Chao 1983; Pillai 1991). Derived from a maximised expected net social welfare (gross welfare less capital and operating costs less rationing cost), the estimate of the rationing cost is found to vary inversely with the LOLP target chosen, and to depend on the capital and operating costs of a given technology.

In this paper we seek to establish a relationship between LOLP and LOEP on the one hand, and based on this relationship, we derive an estimator of rationing cost in general, and also in terms of the actual power demand distribution, found to be normal. We deviate from the conventional comparative static analysis of welfare economics, involving long and tedious derivations, and, instead, make use of the simple results on reliability from the standard inventory analysis - a novel approach, that surprisingly and most assuredly yields the same results on rationing cost as the former method. The relationship thus estimated is also analysed for its implications for the peak load pricing rule under uncertainty.

In the next section, we discuss the most common reliability indices of LOLP and LOEP in the framework of the standard results of inventory analysis, and bring out the relationship between them; and in section 3, we apply these rules/results to power system reliability. Section 4 seeks to establish a relationship among the two reliability criteria and outage cost. Some numerical examples are given to illustrate the implications of the relationship for different technologies based on the techno-economic parameters of some representative power plants. The final section is a brief summary.

2. Reliability Indices

The excess demand situation in the case of any good or service is a major problem. If demand were uniform, it would be just enough to gear supply or stock to the expected demand. However, random fluctuations in demand (L) about its mean value [$E(L) \equiv \mu$, where E is the expectation operator] involve some chances of shortage and necessitate a further safety margin or buffer or reserve (R). Thus the standard inventory analysis posits the supply or stock (S) at

$$S = \mu + R \qquad \ldots\ldots (1)$$

The value of the reserves determines the reliability of service. If R is too small, excess shortages result; if R is too large, excessive holding costs have to be borne. Hence the significance of an optimum level of reserves.

The simplest and the most frequently used approximation of reserve levels is based only on the mean (μ) and the standard deviation (σ) of the demand distribution. Here R is equated to the demand deviation from its mean, $(L - \mu)$, which in turn is set equal to some value Z_s times the standard deviation, i.e., $R = L - \mu = Z_s\sigma$; the value of Z_s is chosen such as to fix at some predetermined level, the probability that demand exceeds supply. Thus for the normal distribution, one σ demand deviation, ($Z_s = 1$) results in the expected demand exceeding supply for 15.9 per cent of the time; and 2σ deviation ($Z_s = 2$), for 2.3 per cent of the time only. In other words, if demand deviates from its mean by one σ point, then for 84.1 per cent of the time, we are confident, supply is sure to meet demand. The risks, however, are different, sometimes substantially, for other distributions. For instance, when $Z_s = 1$, the risk of the expected demand exceeding supply is 13.5 per cent for exponential distribution, and 21.1 per cent for uniform distribution; when $Z_s = 2$, the risks are 5 per cent and 6.7 per cent respectively.

Thus the reserve margin required is defined to be equal to $Z_s\sigma$, and (1) becomes

$$S = \mu + R = \mu + Z_s \sigma. \qquad \text{..... (2)}$$

The probability of shortage (or LOLP) and hence the reliability of service vary with demand distribution. Let the demand for a good follow a probability function f(L), the probability that the demand lies between L and (L + dL). Then the probability of shortage, i.e., the probability that demand (L) will exceed available supply (S), is given by

$$\text{LOLP} = P(L > S) = \int_S^\infty f(L)dL \qquad \text{.....(3)}$$

and the expected quantum of shortage (Q) is

$$Q = E(L - S) = \int_{S}^{\infty} (L - S) f(L) dL \qquad \text{….. (4)}$$

The reliability of service, (ρ), can be defined as the ratio of mean value of supply to mean value of demand, and is given by

$$\rho = (\mu - Q)/\mu = 1 - (Q/\mu) = 1 - \text{LOEP}, \qquad \text{….. (5)}$$

where LOEP is the loss of energy probability (also called shortage factor)[1] in power system reliability analysis, defined as $\text{LOEP} = E(L - S)/E(L) \equiv Q/\mu$.

From (4) and (5), we have an inverse relationship at the margin between shortage/LOEP and available supply expressed through LOLP:

$$\frac{\partial Q}{\partial S} = \mu \frac{\partial}{\partial S}(\text{LOEP}) = -\int_{S}^{\infty} f(L) dL = -\text{LOLP}. \qquad \text{…..(6)}$$

Noting that $\dfrac{\partial Q}{\partial S}$ is negative,

$$\left|\frac{\partial Q}{\partial S}\right| = \left|\mu \frac{\partial}{\partial S}(\text{LOEP})\right| = \text{LOLP}. \qquad \text{….. (7)}$$

Using (2), we can also express (7) as

$$\left|\frac{\partial}{\partial Z_S}(\text{LOEP})\right| = \text{LOLP}\,\sigma/\mu = \text{LOLP}\,\nu, \qquad \text{…..(8)}$$

where $\nu = \sigma/\mu$ is the coefficient of variation (CV) of demand.

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1 This roughly corresponds to unit loss function in inventory analysis. Usually it is given as Q/σ rather than as Q/μ, that refers to our LOEP. Unit loss function Q/σ, appears more as a convenient formulation, than as a definitional one, as for example, the unit loss function under the normal distribution can thus be made equal to the term within the parentheses of equation (14), that is, independent of ν, the demand variability, as σ is cancelled out in the formulation.

Thus, LOLP may be defined as a marginal rise in shortage for a one unit fall in supply. This leads to two (equivalent) implications. i) It implies from (7) that LOLP may also be expressed as a fraction of the expected demand, the fraction being determined by the marginal change in LOEP for a unit change in the available supply; it also shows, for example, for a 10 per cent LOLP, that the marginal rise in LOEP associated with a one unit fall in supply is equivalent to 10 per cent of the inverse of the expected demand. ii) LOLP may also be interpreted [from (8)] as a fraction of demand variability, the fraction being determined by the marginal change in LOEP with respect to the standardised supply; it also follows that for a 10 per cent LOLP, the marginal rise in LOEP for a unit fall in standardized supply corresponds to 10 per cent of the coefficient of variation of demand. The second implication is significant, as it establishes a direct relationship between LOLP and marginal change in shortage factor (LOEP) in terms of demand variability; and we will make use of it in the estimation of rationing cost in Section 4.

To evaluate the reliability criteria, we need to consider the actual demand distribution, since the risks are different for different distributions, as we have already seen. For illustration, we take up the distribution of the daily maximum (peak) demand for electricity on the Kerala power system during 1995-96, presented in Table 1. When the demand series is distributed in suitable class intervals, the tail (lower and higher) values are found to be fewer in frequency, and hence we have tried to explore whether the data fit a normal distribution well. We have found that this closely approximates a normal distribution with mean = 1425 MW and standard deviation = 97.7 MW, giving a coefficient of variation (CV) of 6.86 per cent.[2] Hence below we consider the relevant properties of the reliability criteria in the context of the normal distribution.

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2 For a long time, Kerala has been reeling under severe power shortage, and power cut/load shedding has become the rule of the day. The very low variability in the maximum demand distribution obtained here might be a reflection of the ironed-out pattern of the supply-constrained demand.

Table 1 Distribution of the daily maximum demand for electricity on the Kerala power system during 1995-96

Maximum Demand (MW)	Actual Frequency	Theoretical Frequency
1150 – 1200	3	4
1200 – 1250	10	10
1250 – 1300	26	23
1300 – 1350	49	45
1350 – 1400	57	65
1400 – 1450	71	72
1450 – 1500	59	65
1500 - 1550	52	45
1550 – 1600	32	23
1600 – 1650	6	10
1650 - 1700	1	4

Mean = 1425 MW

Standard Deviation = 97.72 MW

Chi Square value = 11.01

Chi Square Critical value for 10 degrees of freedom at 5 per cent level = 18.31

Hence we cannot reject the null hypothesis that the data fit the theoretical distribution well.

Normal (Gaussian) distribution

We have the normal distribution

$$f(L)\,dL = \left(\sigma\sqrt{2\pi}\right)^{-1} \exp\left[\left(-1/2\sigma^2\right).\left(L-\mu\right)^2\right] dL. \quad \ldots\ldots \quad (9)$$

Defining $Z = (L - \mu)/\sigma$, ….. (10)

we find that the probability of shortage (LOLP) is

Thus the very reliability of the data is in question, but we use the same just for illustration.

$$\text{LOLP} = P(L > S) = \left(\sqrt{2\pi}\right)^{-1} \int_{Z_S}^{\infty} \exp\left(-Z^2/2\right)\, dZ = \phi\,(Z_s), \quad \ldots\ldots (11)$$

which is a well-tabulated function.

The expected shortage is given by

$$Q = \sigma\left(\sqrt{2\pi}\right)^{-1} \exp\left(-Z_S{}^2/2\right) - \sigma Z_S \left(\sqrt{2\pi}\right)^{-1} \int_{Z_S}^{\infty} \exp\left(-Z_S{}^2/2\right)\, dZ$$

$$= \sigma\,[\Psi(Z_s) - Z_s\ (\text{LOLP})], \quad \ldots\ldots (12)$$

where $\Psi(Z_s) = \left(\sqrt{2\pi}\right)^{-1} \exp\left[-Z_s^2/2\right]$ ..... (13)

is the standard normal distribution N(0, 1), again a well-tabulated function; and LOLP = $\phi\,(Z_s)$.

The shortage factor (LOEP), expressed in terms of LOLP, is

$$\text{LOEP} = \nu\,[\Psi(Z_s) - Z_s\ (\text{LOLP})], \quad \ldots\ldots (14)$$

where $\nu = \sigma/\mu$ is the CV of demand distribution.[3] Note that LOEP < LOLP, and falls with demand variability. Thus, given the normally distributed maximum demand, we can estimate LOLP and LOEP for the corresponding standard variate, Z_s.[4] But how shall we determine Z_s in the context of a power system? The next section discusses our method of estimation of Z_s.

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3 Also see (8).

4 See the Appendix 1 for the results on other two distributions, viz., exponential and uniform, presented only for comparative illustration of the relationship between LOLP and LOEP.

3. Application to Power System Reliability

Now we turn to applying the above results from the standard inventory analysis to the reliability analysis of a power system. Sufficient redundancy and excess capacity throughout the system designed to meet contingent exigencies are the major safeguards against power supply shortages. At the generation level, excess capacity is expressed in the form of buffer or reserve margins. In determining the capacity to be installed to meet an expected maximum demand (peak load), due account is taken of the possible fluctuations in load from its expectation (μ). If demand were uniform, installed capacity could correspond just to the expected maximum demand. However, the random deviations of demand as well as the day-to-day variations in the available capacity necessitate some reserve margin to account for them. Thus installed capacity required in a power supply system is determined in relation to the expected maximum demand with due considerations for a certain reserve margin to ensure reliability in meeting the contingent demand deviations. Thus with 10 per cent reserve margin (PRM), installed capacity (K) equals 1.1 times the expected maximum demand (μ). That is,

$$K = \mu + R = \mu(1 + PRM). \qquad \text{….. (15)}$$

Now comparing (15) with (2), we find that

$$\mu \; PRM = Z_k \, \sigma,$$

$$\text{or} \quad Z_k = PRM \, \mu/\sigma \; = \; PRM/\nu, \qquad \text{…… (16)}$$

where $\nu = \sigma/\mu$ is the CV of maximum demand.

Thus the standardized variate, Z_k, that determines LOLP and reliability, as shown above, is in turn determined, in the reliability analysis of a power system, by both demand and supply fators, i.e., demand variability and PRM. Here we consider three possible cases:[5]

i) If PRM is just enough to contain demand variability, i.e., PRM = ν, then $Z_k = 1$, and for the normal distribution, installed capacity falls short of the expected maximum demand only for 15.9 per cent of the time; i.e., LOLP = 0.159 [from (11)], LOEP = 0.083 times CV [from (14)], and the reliability of service is $\rho = 1 - 0.083\nu$. For example, for the Kerala power system with $\nu = 6.9$ per cent as in 1995-96, assuming PRM = ν, we have LOEP = 0.01 and $\rho = 0.99$, so that the expected peak power shortage (with $\mu = 1425$ MW) is 14.25 MW only [from (12)]. It can also be seen that for every one unit drop in available supply, LOEP increases by 0.01 per cent [from (7)].

ii) With PRM > ν, we have $Z_k > 1$, that reduces the chances of shortage and raises the service reliability. Thus, considering the overall reserve margin of the Kerala power system in 1995-96 (including the Central share of capacity, provided the Kerala system has undisturbed access to its share of Central allocation) of about 44 per cent of the mean maximum demand (1425 MW), we get $Z_k = 6.35$, and hence LOLP and LOEP are just nil – evidently, the largesse of a very low demand variability.

iii) On the other hand, if the reserves are inadequate in relation to demand variability, i.e., PRM < ν, then $Z_k < 1$, and the probability of demand exceeding available supply increases and reliability decreases. In this case, disregarding the Central share, Kerala's own installed capacity in 1995-96 (1505.5 MW), in relation to the mean maximum demand, gives a PRM of only 5.65 per cent, whereas the annual internal maximum

5 See Appendix 2 for sensitivity results on LOLP and LOEP (as also the multiplier for the capacity charge component of the rationing cost) for different values of PRM and ν, under the three distributions of normal, exponential and uniform.

demand (1651 MW, maximum of the daily peak loads), stood about 16 per cent above the mean maximum demand (and about 9 per cent below the installed capacity). This necessitates that the Kerala system in 1995-96 must have a PRM of at least 20 per cent to meet the maximum demand with an available capacity of about 2000 MW, implying $Z_k = 2.90$ and very high reliability (LOLP = 0.0019 and LOEP = 0.00004). If, on the other hand, the PRM were only 16 per cent, just enough to cover the peak load (of 1651 MW), then the implied LOLP would be 1 per cent (i.e., 0.0104, for $Z_k = 2.31$). However, in the actual situation, in relation to the annual maximum demand, we have $Z_k = -1.29$, and hence LOLP = 0.901 and LOEP = 0.092. Though the LOLP is very high, the reliability of service turns out to be higher (0.908), thanks to the very low demand variability. (If the CV were 25 per cent, LOEP would be about 33 per cent.) The significance of our formulation of the relationship (16) is very much evident from this discussion.

4. Reliability and Rationing Cost

Now that we have determined LOLP and LOEP, as also Z_k, in terms of PRM and ν, required in their estimation in the context of a normally distributed maximum demand in a power supply system, we now derive a relationship among rationing cost, and reliability (LOLP, LOEP) in electricity supply in the event of excess (maximum) demand. Instead of the conventional marginalist approach of analysing the expected net social welfare, we seek to minimise the total cost made up of costs of capacity, output (generation) and shortage that yields exactly the same result as does the former. We assume the simplest rationing scheme, with a constant marginal penalty cost of excess demand, that is a special case of random rationing, that we usually experience in our country. Thus the rationing costs we estimate later at the end of this section approximate the reality. For sake of simplicity, again, we dispense with subscripts and symbols for diverse technology and periods.

From the preceding sections, we have the fraction of expected energy shortage, LOEP, as $LOEP = Q/\mu$, giving the availability factor as $(1 - LOEP)$. During the length[6] (θ) of a certain period (i.e., peak period), the energy shortage is $\theta\, Q = \theta\, \mu\, LOEP$ units, involving a penalty price of 'r' per unit short. The energy available for supply, then, is $\theta\, \mu\, (1 - LOEP)$ units with an operating cost of 'b' per unit. The capacity cost is 'β' per kW of capacity, K. Thus the total cost is:

$$TC = \beta K + b\, \theta\, \mu\, (1 - LOEP) + r\, \theta\, \mu\ LOEP. \qquad \ldots\ldots (17)$$

Minimising the total cost,

$$\frac{\partial TC}{\partial K} = 0 = \beta + (r - b)\, \theta\, \mu\, \frac{\partial}{\partial K} LOEP \qquad \ldots\ldots (18)$$

Now, using (10),

$$Z = (L - \mu)/\sigma \ \rightarrow\ (K - \mu)/\sigma = Z_k, \qquad \ldots\ldots (19)$$

we can rewrite (18) as

$$\beta + (r - b) \ = \ \frac{\theta}{\upsilon} \frac{\partial}{\partial Z_k} LOEP \ = \ 0, \qquad \ldots\ldots (20)$$

where $\nu = \sigma/\mu$.

$\frac{\partial}{\partial Z_k} LOEP$, the rate of change in LOEP with respect to standardized capacity, depends on the particular demand distribution. Using (8) and the definition of LOLP in (11), we obtain for normally distributed demand:

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6 The analysis can be extended to multiple period case also; for example, shortage and non-shortage periods as well as peak and off-peak periods. Only during the shortage duration (in peak period) is the third term in (17), $r\ \theta\ \mu$ LOEP, active; and this is the only case we consider here.

$$\frac{\partial}{\partial Z_k} \text{LOEP} = -\nu \text{LOLP} = -\nu \phi (Z_k). \qquad \text{..... (21)}$$

Now, from (20) and (21), we get LOLP as

$$\text{LOLP} = \phi(Z_k) = \beta/\theta(r - b). \qquad \text{..... (22)}$$

Equation (22) presents a number of significant implications:

The denominator in (22) represents the net expected social cost of shortage. Each unit of power cut imposes a penalty of 'r', but saves a marginal operating cost of 'b'. As the net social cost of rationing increases, LOLP falls. The rationale for this is clear. As (non-price) rationing (in the event of excess demand) becomes more inefficient, rationing cost increases; this necessitates to place more reliance on price rationing (price rise) to reduce excess demand, which in turn leads to increased profits and capacity expansion. Thus reliability also increases. Equation (22) shows that for any given LOLP target criterion, a certain level of rationing cost is implied in it. This then provides an estimate of rationing cost:

in general,

$$r = b + \beta/\theta \text{LOLP}, \qquad \text{..... (23)}$$

or, in particular,[7] for

normally distributed demand: $r = \beta + \theta/\phi\,(Z_k)$, ...(24)

where $Z_k = \text{PRM}/\nu$.

The general expression, (23), for 'r' that explicitly states the relationship between the rationing cost and LOLP, is a significant result

7 See the Appendix 1 for the results on other two distributions, viz., exponential and uniform.

in that it brings out an economic justification in setting an outage cost vis-à-vis an optimal reliability target planning criterion (LOLP); it also marks the effects on this reliability criterion of the assumptions of capital costs, generation costs and rationing costs (see Chao 1983; Pillai 1991).

Equation (22) is significant again in that it sets the optimal marginal capacity cost as a fraction (equal to LOLP) of the net social cost of rationing implied in that level of LOLP. That is, for a 10 per cent LOLP, the marginal capacity cost corresponds to 10 percent of the net rationing cost. Thus we obtain an optimal investment rule in shortage period. The denominator in (22) may also be interpreted as the net expected benefits from a unit increase in capacity. Each unit increase in capacity implies that with each unit of power cut avoided, a rationing cost of 'r' is escaped, but a marginal operating cost of 'b' is incurred. Thus the investment rule in (22) states that the marginal capacity cost (β/θ) equals the net expected benefits from a unit increase in capacity in shortage period times the probability of that period, i.e., (r – b)LOLP (Turvey and Anderson 1977: Chapter 14).

Another significant implication of (22) is its potential in yielding the stochastic equivalent of the deterministic peak load pricing rule, whereby peak period price equals $b + \beta/\theta$. Now substituting here for β/θ from (22), we have the stochastic pricing rule:

$$P = b(1 - \text{LOLP}) + r\text{LOLP}, \qquad \ldots\ldots (26)$$

a probability-weighted average of the marginal operating cost and the marginal rationing cost (Turvey and Anderson 1977: Chapter 14). Since (1 – LOLP) is the probability of meeting demand and LOLP, that of power cut, the average price is applicable to both the situations. This is in contrast to the deterministic pricing rule that charges the off-peak customers only the marginal operating cost (b).

Compared with the peak-period price, rationing cost is much higher through the effect of LOLP on the unit capacity cost. If, for example, PRM is just sufficient to meet demand variability (ν) such that $Z_k = 1$, then as we have already seen, LOLP for normal distribution is 0.159; for exponential distribution, it is 0.135 and for uniform distribution, 0.211. Then from (23), we find that the capacity charge component of the rationing cost is about (1/0.159 =) 6.3 times higher than that of peak-load tariff rate if demand follows normal distribution; it is about 7.4 times higher, if demand is exponentially distributed, and about 4.7 times higher for uniformly distributed demand. If PRM > ν, then LOLP falls, with a much higher implied rationing cost; and if PRM < ν, reliability falls, with a lower implied rationing cost. [8]

Some numerical examples will illustrate the implications of the relationship between LOLP and rationing cost. Let us consider the following parameters of different power plants, and estimate the outage costs for different LOLP targets, as well as peak- and off-peak-period prices (representing generation cost only, and assuming a peak period of 3.5 hours a day, i.e., from 6 to 9.30 in the evening). The basic data (as in 1996) are taken from International Energy Initiative (1998).

I A Coal-Based Thermal Power Plant of 350 MW Capacity:

(a) Capital cost : Rs. 1310 crores

Annuitised capital cost (at 12 per cent discount rate and for 25 years of plant life) : Rs. 4772.14/kW/year

Marginal capital cost at peak demand (with 10 per cent transmission and distribution loss and 20 per cent reserve margin) : Rs. 6299.23/kW/year.

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8 See foot note 5.

(b)	Fuel costs	
	Coal consumption norm	: 3192 kg./kW
	Price of coal	: Rs. 1000/tonne
	Oil consumption norm	: 72000 ml./kW
	Price of oil	: Rs. 6396/kl.
	Total fuel cost	: Rs. 3652.5/kW
(c)	Operation and maintenance cost	
	(2.5 per cent of capital cost)	: Rs. 935.7/kW
(d)	Total operating cost (off-peak price)	: Rs. 0.524/kWh
(e)	Peak period price	: Rs. 5.45/kWh
(f)	Average (accounting) price	: Rs. 1.24/kWh.
(g)	Rationing cost (Rs./kWh) with	
	10 per cent LOLP	: 49.83
	5 per cent LOLP	: 99.14
	2 per cent LOLP	: 247.07
	Five-day-in-ten-years LOLP	: 3600.08
	One-day-in-ten-years LOLP	: 17998.32

II A Diesel-Based Thermal Power Plant of 5 MW Capacity

(a)	Capital cost	: Rs. 7.5 crores
	Annuitised capital cost (at 12 per cent discount rate and for 25 years of plant life)	: Rs. 1912.5/kW/year
	Marginal capital cost at peak demand (with 10 per cent transmission and distribution loss and 20 per cent reserve margin)	: Rs. 2524.5/kW/year.
(b)	Fuel costs	
	Oil consumption norm	: 438 litres/kW
	Price of oil	: Rs. 7/litre
	Total fuel cost	: Rs. 3066/kW
(c)	Operation and maintenance cost	
	(4.5 per cent of capital cost)	: Rs. 675/kW

(d) Total operating cost (off-peak price) : Rs. 0.427/kWh

(e) Peak period price : Rs. 2.40/kWh

(f) Average (accounting) price : Rs. 0.72/kWh

(g) Rationing cost (Rs./kWh) with

10 per cent LOLP : 20.19

5 per cent LOLP : 39.95

2 per cent LOLP : 99.23

Five-day-in-ten-years LOLP : 1443.0

One-day-in-ten-years LOLP : 7213.28

III A Gas-Based Thermal Power Plant of 300 MW Capacity

(a) Capital cost : Rs. 900 crores

Annuitised capital cost (at 12 per cent discount rate and for 25 years of plant life) : Rs. 3825/kW/year

Marginal capital cost at peak demand (with 10 per cent transmission and distribution loss and 20 per cent reserve margin) : Rs. 5049/kW/year.

(b) Fuel costs

Gas consumption norm : 1740.3 gms./kW

Price of gas : Rs. 3.2/gm.

Total fuel cost : Rs. 5569/kW

(c) Operation and maintenance cost

(4.5 per cent of capital cost) : Rs. 1350/kW

(d) Total operating cost (off-peak price) : Rs. 0.7898/kWh

(e) Peak period price : Rs. 4.74/kWh

(f) Average (accounting) price : Rs. 1.37/kWh

(g) Rationing cost (Rs./kWh) with

10 per cent LOLP : 40.31

5 per cent LOLP : 79.83

2 per cent LOLP	: 198.40
Five-day-in-ten-years LOLP	: 2885.93
One-day-in-ten-years LOLP	: 14426.50

IV. A Hydro-Electric Power Plant of 120 MW Capacity

(a) Capital cost : Rs. 180 crores

Annuitised capital cost (at 12 per cent discount rate and for 25 years of plant life) : Rs. 1912.5/kW/year

Marginal capital cost at peak demand (with 10 per cent transmission and distribution loss and 20 per cent reserve margin)
: Rs. 2524.5/kW/year.

(b) Operation and maintenance cost
(10 per cent of capital cost) : Rs. 1500/kW

(c) Total operating cost (off-peak price) : Rs. 0.171/kWh

(d) Peak period price : Rs. 2.15/kWh

(e) Average (accounting) price : Rs. 0.46/kWh

(f) Rationing cost (Rs./kWh) with

10 per cent LOLP	: 19.93
5 per cent LOLP	: 39.69
2 per cent LOLP	: 98.98
Five-day-in-ten-years LOLP	: 1442.74
One-day-in-ten-years LOLP	: 7213.03

5. Conclusion

The present paper employs a novel approach to power system reliability study by utilising the results on reliability in the standard inventory analysis, making use of particular (normal) demand distribution for the daily internal maximum (peak) demand of the Kerala power system during 1995-96. Thus the concepts of buffer stock, shortage probability and unit loss function are extended to power system reliability in terms of percentage reserve margin, LOLP and LOEP respectively. We find that the inverse relationship at the margin between LOEP and available supply corresponds to LOLP weighted by the inverse of the expected demand. It is found that in the case of normally distributed demand, LOEP < LOLP, and falls with demand variability.

Rationing cost involved in power shortage includes loss of consumers' surplus and cost of administering a certain rationing scheme. Minimising the total cost incurred in power supply in a shortage period yields a significant inverse relationship between LOLP and rationing cost along with other (capacity and operating) cost components. Various implications of this relationship are examined, for optimal investment rule, stochastic version of peak load pricing, etc. Rationing cost implied in different LOLP target criteria are also estimated, based on the techno-economic parameters of different types of power plants. The assumption in our model of a random rationing scheme brings these estimates up as representing the actual penalty costs of the excess demand for power, that we exert on the system in India. It is found that the rationing cost, as also the peak-period price (representing generation cost only), associated with a hydro-electric power plant is lower than that with thermal plants.

References

Brown, G., and Johnson, M. B. (1969) 'Public Utility Pricing and Output under Risk', *American Economic Review*, Vol. 59, March: 119 - 128.

Carlton, D. W. (1977) 'Peak Load Pricing with Stochastic Demand', *American Economic Review,* Vol. 67, December: 1006 - 1010.

Chao, Hung-po (1983) 'Peak Load Pricing and Capacity Planning with Demand and Supply Uncertainty', *Bell Journal of Economics*, Vol. 14, Spring: 179 - 190.

Crew, M. A., and Kleindorfer, P. R. (1976) 'Peak Load Pricing with a Diverse Technology', *Bell Journal of Economics*, Vol. 7, Spring: 207 - 231.

Crew, M. A., and Kleindorfer, P. R. (1986) *The Economics of Public Utility Regulation*, Macmillan Press.

Government of India (1997) *Fourth National Power Plan 1997 - 2012*, Central Electricity Authority, New Delhi, March.

International Energy Initiative (1998). *Least Cost Planning Exercise for Kerala State Electricity Board, Draft Report*. Bangalore, March..

Pillai, N. Vijayamohanan (1991) *Seasonal Time-of-Day Pricing of Electricity under Uncertainty: A Marginalist Approach to Kerala Power System*. Unpublished Ph. D. Thesis, University of Madras, Chennai.

Telson, M. L. (1975) 'The Economics of Alternative Levels of Reliability for Electric Power Generation System', *Bell Journal of Economics*, Vol. 5, Autumn: 679 - 694.

Turvey, R., and Anderson, D. (1977) *Electricity Economics - Essays and Case Studies*. John Hopkin's University Press, Baltimore.

Visscher, M. L. (1973) 'Welfare-Maximising Price and Output with Stochastic Demand: Comment', *American Economic Review*, Vol. 63, March: 224 - 229.

APPENDIX 1

In this appendix we present, for comparative illustration, the results on the relationship between LOLP and LOEP as also that between the reliability indices and rationing cost in the case of exponential and uniform distributions.

Exponential distribution

The exponential distribution is

$$f(L)dL = \lambda \exp(-\lambda L)dL, \qquad \text{..... (A1)}$$

where $\lambda = 1/\mu$, and standard deviation, σ, = μ (= $1/\lambda$). .....(A2)

Here the shortage probability (LOLP) is

$$LOLP = P(L > S) = \exp(-\lambda S). \qquad \text{..... (A3)}$$

Now from (2) and (A2), we get

$$LOLP = P(L > S) = \exp(-\lambda S) = \exp[-(1 + Z_s)], \qquad \text{..... (A4)}$$

and the expected shortage,

$$Q = \sigma \exp[-(1 + Z_s)]. \qquad \text{..... (A5)}$$

Thence the LOEP is

$$LOEP = \nu \exp[-(1 + Z_s)] = \nu\, LOLP = LOLP, \qquad \text{..... (A6)}$$

since ν =1; hence the reliability of service is not influenced by CV and LOEP = LOLP, unlike in the case of normal distribution.

For exponential distribution, we have from (8) and (A4):

$$\frac{\partial}{\partial Z_k} LOEP = -LOLP = -\exp[-(1 + Z_k)];$$

hence the rationing cost: $r = b + \beta/\theta \exp[-(1 + Z_k)]$.

Uniform (Rectangular) distribution

The uniform distribution is

$$f(L)dL = 1/(L_1 - L_0), \ L_0 < L < L_1$$

$$= 0 \ \text{otherwise}. \qquad \text{.....(A7)}$$

We have

$\mu = (L_1 + L_0)/2$, and

$\sigma = (L_1 - L_0)/2\sqrt{3}$

and the limits on the distribution are

$$L_0 = \left(\mu - \sigma\sqrt{3}\right)$$

and

$$L_1 = \left(\mu + \sigma\sqrt{3}\right)$$

Considering the definition of Z_s implied in (2), we get

$$\text{LOLP} = P(L > S) = \frac{\sqrt{3} - Z_s}{2\sqrt{3}}$$

and directly from (2)

$$\text{LOLP} = P(L > S) = \frac{1}{2\sigma\sqrt{3}}(L_1 - S) \qquad \text{…..(A8)}$$

Note that LOLP is not defined for values of Zs greater than the square root of 3.

The expected quantum of shortage is

$$Q = \frac{1}{4\sigma\sqrt{3}}(L_1 - S)^2 = \frac{\sigma}{4\sqrt{3}}\left(\sqrt{3} - Z_s\right)^2$$

so that LOEP is

$$\text{LOEP} = \frac{\upsilon}{4\sqrt{3}}\left(\sqrt{3} - Z_s\right)^2 = \frac{\upsilon}{2}\left(\sqrt{3} - Z_s\right)\text{LOLP}$$

Like the normal distribution, LOEP < LOLP, and falls with demand variability.

Using the definition of LOLP in (A8), we have the rationing cost as

$$r = b + \frac{\beta}{\theta}\frac{2\sqrt{3}}{\left(\sqrt{3} - Z_k\right)}$$

Again, r also is *not* defined for values of Z_s greater than the square root of 3.

APPENDIX 2

In this Appendix we present the sensitivity results for LOLP, LOEP and multiplier for the capacity charge component of the rationing cost for different values of percentage reserve margin (PRM) and coefficient of variation (ν), when demand is assumed to follow different distributions, viz., normal, exponential, and uniform

When Demand is Normally Distributed

1. Loss of Load Probability (LOEP)

		Coefficient of Variation									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Percent Reserve Margin	10	0.15866	0.30854	0.3707	0.40129	0.42074	0.43251	0.44433	0.44828	0.4562	0.46017
	20	0.02275	0.15866	0.25143	0.30854	0.34458	0.3707	0.38591	0.40129	0.41294	0.42074
	30	0.0013499	0.066807	0.15866	0.22663	0.27425	0.30854	0.3336	0.35197	0.3707	0.38209
	40	0.000031671	0.02275	0.091759	0.15866	0.21186	0.25143	0.28434	0.30854	0.32997	0.34458
	50	0.0000003	0.0062097	0.04746	0.10565	0.15866	0.20327	0.23885	0.26435	0.28774	0.30854
	60	0	0.0013499	0.02275	0.066807	0.11507	0.15866	0.19489	0.22663	0.25143	0.27425
	70	0	0.00023263	0.0099031	0.040059	0.080757	0.121	0.15866	0.18943	0.2177	0.24196
	80	0	0.000031671	0.0037926	0.02275	0.054799	0.091759	0.12714	0.15866	0.18673	0.21186
	90	0	3.3977E-06	0.0013499	0.012224	0.03593	0.066807	0.098525	0.12924	0.15866	0.18406
	100	0	0.00000025	0.00043423	0.0062097	0.02275	0.04746	0.076359	0.10565	0.1335	0.15866

2. Loss of Energy Probability (LOLP)

		Coefficient of Variation									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Percent Reserve Margin	10	0.008326204	0.039544899	0.076122191	0.11450713	0.153408	0.1927653	0.2319359	0.271778	0.311147	0.350856
	20	0.00084801	0.016652409	0.045529121	0.0790898	0.115182	0.1522444	0.1908548	0.229014	0.267633	0.306816
	30	3.81257E-05	0.005856208	0.024978613	0.05244174	0.0843038	0.1186347	0.1546245	0.191833	0.228367	0.266684
	40	7.1193E-07	0.001696021	0.012489523	0.03330482	0.0600726	0.0910582	0.1234098	0.15818	0.193228	0.230364
	50	2.3642E-08	0.000400105	0.006107138	0.02021994	0.041631	0.0674781	0.0969123	0.130301	0.163771	0.197724
	60	6.07466E-10	7.62514E-05	0.002544031	0.01171242	0.0280315	0.0499572	0.0764337	0.104883	0.136587	0.168608
	70	9.13288E-13	1.16604E-05	0.000932814	0.00646268	0.0183188	0.0364748	0.0582834	0.084999	0.11289	0.142819
	80	5.05125E-16	1.42386E-06	0.000384028	0.00339204	0.0116101	0.024979	0.0435994	0.06661	0.092436	0.120145
	90	1.02777E-19	1.38175E-07	0.000114377	0.00169171	0.0071301	0.0175686	0.0334971	0.053151	0.074936	0.100378
	100	7.69305E-24	0.00000005	2.83606E-05	0.00080021	0.0042401	0.0122143	0.0242793	0.04044	0.060134	0.083262

3. Multiplier for the Capacity Charge Component of the Rationing Cost

		Coefficient of Variation									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
	10	6.303	3.241	2.698	2.492	2.377	2.312	2.251	2.231	2.192	2.173
	20	43.956	6.303	3.977	3.241	2.902	2.698	2.591	2.492	2.422	2.377
	30	740.796	14.968	6.303	4.412	3.646	3.241	2.998	2.841	2.698	2.617
Percent	40	31574.627	43.956	10.898	6.303	4.720	3.977	3.517	3.241	3.031	2.902
Reserve	50	4000000.000	161.038	21.070	9.465	6.303	4.920	4.187	3.783	3.475	3.241
Margin	60	Not Defined	740.796	43.956	14.968	8.690	6.303	5.131	4.412	3.977	3.646
	70	Not Defined	4298.672	100.978	24.963	12.383	8.264	6.303	5.279	4.593	4.133
	80	Not Defined	31574.627	263.671	43.956	18.249	10.898	7.865	6.303	5.355	4.720
	90	Not Defined	294316.744	740.796	81.806	27.832	14.968	10.150	7.738	6.303	5.433
	100	Not Defined	4000000.000	2302.927	161.038	43.956	21.070	13.096	9.465	7.491	6.303

When Demand is Exponentially Distributed

1. Loss of Load Probability (LOLP) = Loss of Energy Probability (LOEP)

		Coefficient of Variation									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
	10	0.13534	0.22313	0.26360	0.28650	0.30119	0.31140	0.31891	0.32465	0.32919	0.33287
	20	0.04979	0.13534	0.18888	0.22313	0.24660	0.26360	0.27645	0.28650	0.29457	0.30119
	30	0.01832	0.08208	0.13534	0.17377	0.20190	0.22313	0.23965	0.25284	0.26360	0.27253
Percent Reserve Margin	40	0.00674	0.04979	0.09697	0.13534	0.16530	0.18888	0.20775	0.22313	0.23588	0.24660
	50	0.00248	0.03020	0.06948	0.10540	0.13534	0.15988	0.18009	0.19691	0.21107	0.22313
	60	0.000912	0.01832	0.04979	0.08208	0.11080	0.13534	0.15612	0.17377	0.18888	0.20190
	70	0.000335	0.01111	0.03567	0.06393	0.09072	0.11456	0.13534	0.15335	0.16901	0.18268
	80	0.000123	0.00674	0.02556	0.04979	0.07427	0.09697	0.11732	0.13534	0.15124	0.16530
	90	4.5400E-05	0.00409	0.01832	0.03877	0.06081	0.08208	0.10170	0.11943	0.13534	0.14957
	100	1.6702E-05	0.00248	0.01312	0.03020	0.04979	0.06948	0.08816	0.10540	0.12110	0.13534

2. Multiplier for the Capacity Charge Component of the Rationing Cost

		Coefficient of Variation									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
	10	7.389	4.482	3.794	3.490	3.320	3.211	3.136	3.080	3.038	3.004
	20	20.086	7.389	5.294	4.482	4.055	3.794	3.617	3.490	3.395	3.320
	30	54.598	12.182	7.389	5.755	4.953	4.482	4.173	3.955	3.794	3.669
Percent Reserve Margin	40	148.413	20.086	10.312	7.389	6.050	5.294	4.814	4.482	4.239	4.055
	50	403.429	33.115	14.392	9.488	7.389	6.255	5.553	5.078	4.738	4.482
	60	1096.633	54.598	20.086	12.182	9.025	7.389	6.405	5.755	5.294	4.953
	70	2980.958	90.017	28.032	15.643	11.023	8.729	7.389	6.521	5.917	5.474
	80	8103.084	148.413	39.121	20.086	13.464	10.312	8.524	7.389	6.612	6.050
	90	22026.466	244.692	54.598	25.790	16.445	12.182	9.833	8.373	7.389	6.686
	100	59874.142	403.429	76.198	33.115	20.086	14.392	11.343	9.488	8.257	7.389

When Demand is Uniformly Distributed

1. Loss of Load Probability (LOLP)

		Coefficient of Variation									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
	10	0.21132	0.3557	0.4038	0.4278	0.4423	0.4519	0.4588	0.4639	0.4679	0.4711
	20	Not Defined	0.2113	0.3075	0.3557	0.3845	0.4038	0.4175	0.4278	0.4358	0.4423
	30	Not Defined	0.0670	0.2113	0.2835	0.3268	0.3557	0.3763	0.3917	0.4038	0.4134
Percent	40	Not Defined	Not Defined	0.1151	0.2113	0.2691	0.3075	0.3350	0.3557	0.3717	0.3845
Reserve	50	Not Defined	Not Defined	0.0189	0.1392	0.2113	0.2594	0.2938	0.3196	0.3396	0.3557
Margin	60	Not Defined	Not Defined	Not Defined	0.0670	0.1536	0.2113	0.2526	0.2835	0.3075	0.3268
	70	Not Defined	Not Defined	Not Defined	Not Defined	0.0959	0.1632	0.2113	0.2474	0.2755	0.2979
	80	Not Defined	Not Defined	Not Defined	Not Defined	0.0381	0.1151	0.1701	0.2113	0.2434	0.2691
	90	Not Defined	Not Defined	Not Defined	Not Defined	Not Defined	0.0670	0.1288	0.1752	0.2113	0.2402
	100	Not Defined	Not Defined	Not Defined	Not Defined	Not Defined	0.0189	0.0876	0.1392	0.1792	0.2113

2. Loss of Energy Probability (LOEP)

		Coefficient of Variation									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
	10	0.00774	0.04382	0.08472	0.12681	0.16939	0.2122	0.2552	0.2982	0.3413	0.3845
	20	0.00104	0.01547	0.04915	0.08764	0.12805	0.1694	0.2114	0.2536	0.2961	0.3388
	30	0.02321	0.00155	0.02321	0.05568	0.09249	0.1315	0.1717	0.2126	0.2541	0.296
Percent	40	0.07424	0.00207	0.00688	0.03094	0.06269	0.0983	0.1361	0.1753	0.2154	0.2561
Reserve	50	0.15415	0.01702	0.00019	0.01342	0.03868	0.0699	0.1047	0.1415	0.1798	0.2191
Margin	60	0.26292	0.04641	0.00311	0.00311	0.02043	0.0464	0.0773	0.1114	0.1474	0.185
	70	0.40056	0.09023	0.01566	0.00002	0.00796	0.0277	0.0541	0.0848	0.1183	0.1537
	80	0.56706	0.14848	0.03782	0.00415	0.00126	0.0138	0.0351	0.0619	0.0924	0.1254
	90	0.76244	0.22117	0.06962	0.01549	0.00033	0.0047	0.0201	0.0426	0.0696	0.0999
	100	0.98668	0.30829	0.11103	0.034049	0.00518	0.0004	0.0093	0.0268	0.0501	0.0774

3. Multiplier for the Capacity Charge Component of the Rationing Cost

		Coefficient of Variation									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Percent Reserve Margin	10	4.732	2.812	2.477	2.337	2.261	2.213	2.180	2.156	2.137	2.123
	20	Not Defined	4.732	3.252	2.812	2.601	2.477	2.395	2.337	2.294	2.261
	30	Not Defined	14.928	4.732	3.527	3.060	2.812	2.658	2.553	2.477	2.419
	40	Not Defined	Not Defined	8.688	4.732	3.717	3.252	2.985	2.812	2.690	2.601
	50	Not Defined	Not Defined	52.981	7.186	4.732	3.854	3.404	3.129	2.944	2.812
	60	Not Defined	Not Defined	Not Defined	14.928	6.511	4.732	3.959	3.527	3.252	3.060
	70	Not Defined	Not Defined	Not Defined	Not Defined	10.432	6.127	4.732	4.042	3.630	3.357
	80	Not Defined	Not Defined	Not Defined	Not Defined	26.233	8.688	5.879	4.732	4.108	3.717
	90	Not Defined	Not Defined	Not Defined	Not Defined	Not Defined	14.928	7.761	5.706	4.732	4.163
	100	Not Defined	Not Defined	Not Defined	Not Defined	Not Defined	52.981	11.415	7.186	5.579	4.732

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