Distribution functions to describe the variation of the present per capita electricity consumption in India and future needs with respect to the population

S. P. Sukhatme

The present mean annual per capita consumption of electricity in India is only around 800 to 900 kWh. This is a low value and it is accepted that it will have to increase in the future to a mean value which could range from 1840 to 4000 kWh. This article is concerned with an aspect which has not received attention so far, viz. the nature of distribution of the consumption around the mean with respect to the population. Since no direct data are available, an attempt is made to deduce the present distribution in India from data available for the world as a whole. It is shown that the present variation can be approximated to be a Poisson-like Weibull distribution which is highly inequitable. The study also suggests a distribution for the future in which not only is the mean annual per capita value higher, but the variation can be approximated by a Gaussian-like Weibull distribution which is more equitable.

Keywords: Distribution function, equitable distribution, future electricity needs, per capita electricity consumption.

IN 2011–12, India consumed about 1000 TWh of electricity equivalent to a mean value of 800–900 kWh/person-year. In contrast, USA consumed about 12,000 kWh/person-year, whereas other economically developed countries like Germany and France had mean per capita values between 7000 and 8000 kWh/year. It is agreed that the present consumption in India is low. It is also generally accepted that the consumption in USA is high and wasteful. High consumption is harmful because one is using up non-renewable energy resources unnecessarily and also because of the consequent increase in greenhouse gas emissions. Thus, the question which is often asked from the point of view of energy policy and planning is: what per capita mean value should India aim for in the future? The question is particularly appropriate when one recognizes that on a per capita basis, India is not that well endowed with natural resources. The word 'future' as used here refers to a date about 50 or 60 years from today when the country will be economically developed and the mean annual per capita consumption/need for electricity (MACE) would have more or less stabilized. Obviously, the value we suggest should be adequate for providing a good standard of living for most of our people. At the same time, it should not lead to unnecessary wastage.

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An increase in the value of MACE over the years is a necessary condition for a better quality of life in India. However, having a high enough value of MACE is in itself not sufficient. One needs to know how the annual per capita consumption of electricity (ACE) is distributed amongst the people and ask whether the distribution is equitable or not. The purpose of this article is to suggest the shape of such distributions. Till now, this aspect has not received the attention it deserves. Its link with the future mean value which India should aim for has also not been studied. This study helps deduce the present distribution of ACE for India and shows that it is inequitable. This will be done with the help of data available for the world as a whole. Then, we proceed to suggest a distribution for the future in which not only is the value of MACE higher, but the distribution is also more equitable.

Mean annual per capita needs of electricity in the future

Two approaches have been adopted in the literature for estimating the value of MACE required in a country as it seeks to become a developed country in the future.

In the first approach, one considers the electrical energy inputs required in various sectors like manufacturing, transportation, mining, agriculture, commercial, construction, etc., which provide the goods, services, food, infrastructure, etc. needed in daily life. Data on these inputs are collected in numerous locations and countries. These are averaged and converted into per capita values. To these values are added the electricity needs of the residential sector. Goldemberg *et al.*[1,2] carried out such pioneering studies in the 1980s by collecting and analysing data in four countries – Brazil, Sweden, India and USA. The main result obtained from their studies was that in a country like India, a mean value of 1840 kWh/person-year would be adequate for providing a good, but frugal standard of living. The estimate was based on the assumption that sound energy conservation measures would be adopted and energy-efficient devices would be used. Since the work of Goldemberg and his co-workers was conducted more than 20 years ago, it can be criticized on the grounds that more efficient electrical devices are available today and that the required value of MACE should have decreased a little. On the other hand, it can also be argued that electricity is used in more applications today than was the case earlier and that consequently, the required value of MACE should have increased. Since there is no better estimate available in the literature based on the procedure adopted by Goldemberg *et al.*[1,2], we will accept 1840 kWh/person-year as a credible value.

A second approach adopted for determining the desirable value of MACE is to plot the human development index (HDI) of a country against its MACE value[3]. HDI of a country is a composite index which combines indices regarding life expectancy, school education and gross national income in that country. By definition, the value of HDI ranges between 0 and 1. The plot obtained using data for all countries of the world shows that there is a fairly good correlation between the two quantities. It is seen that the value of HDI increases as the value of MACE increases and that HDI reaches a value around 0.9 when MACE is about 4000 kWh/person-year. Thereafter, the value of HDI levels of around 0.9 even if the electricity use goes on increasing. Based on this information, it has been argued that it would be desirable to provide an average of 4000 kWh/person-year to meet the future needs of electricity in India.

Thus we have two values, 1840 and 4000 kWh/person-year, for consideration. In an earlier paper[4], I had suggested that 'keeping in mind the need for frugality in energy usage', we should opt for a value of 1840 kWh/person-year. At the same time, it was stated that 'the projected per capita value needs to be distributed more equitably amongst all sections of the society'.

Finally, we should also note that values outside the range 1840–4000 have been suggested by other researchers. Shankar Sharma[5] feels that a per capita consumption of just 800 to 1000 kWh/year can lead to an 'adequate level of HDI if efficient and responsible usage of electricity is ensured'. He estimates that 420 kWh/person-year would be needed on the average for residential purposes, leaving a balance of 380–580 kWh/person-year for all other activities (commercial, transportation, manufacturing, etc.). No data are presented to show how this amount would be adequate. On the other hand, Kakodkar[6] has used the plot of HDI versus MACE mentioned earlier to suggest that India should target a value of 5000 kWh/person-year for the future. Presumably, this suggestion is made to take account of the scatter and uncertainty in the data available for the countries of the world.

The Weibull distribution

After studying various distributions, we opt to use the Weibull distribution function to describe the variation of the present electricity consumption as well as the future need with respect to the population. The density function for the Weibull distribution is given by

$$f(x) = (k/c)(x/c)^{(k-1)} \exp[-(x/c)^k], \tag{1}$$

where x is the electricity consumption/future need per person per year (ACE). k and c are parameters in the distribution, k being a shape parameter and c a scale parameter. The Weibull distribution has the advantage of being flexible in its shape. For values of k between 0 and 1, it has a Poisson-like shape, while for values of k greater than 1, it has a Gaussian-like shape. The fraction of the population, $F(x)$, covered in the distribution from 0 to x is obtained by integrating eq. (1) from 0 to x, which yields the expression

$$F(x) = 1 - \exp[-(x/c)^k]. \tag{2}$$

Present distribution in India

We now focus our attention on the present distribution of the annual per capita value with respect to the population for India. There are no field data based on studies made in this regard. Some data are available on the distribution of annual per capita consumption of electricity in residences. However, that component is only a part of the total. For this reason, the approach followed here will be to use worldwide data for the electricity consumption and the population of each country of the world and derive a continuous distribution from the discrete data available. About 70% of the world's countries (having 80% of the population) are classified as developing countries. Thus it would be fair to assume that the world as a whole would have a distribution with a shape corresponding to that for a developing country like India. We will make this reasonable assumption and thereby derive the present distribution for India by simply scaling the distribution for the world appropriately.

From the *CIA World Factbook*[7], data for the average ACE and population are available for each country of the world. In this reference, the data from different

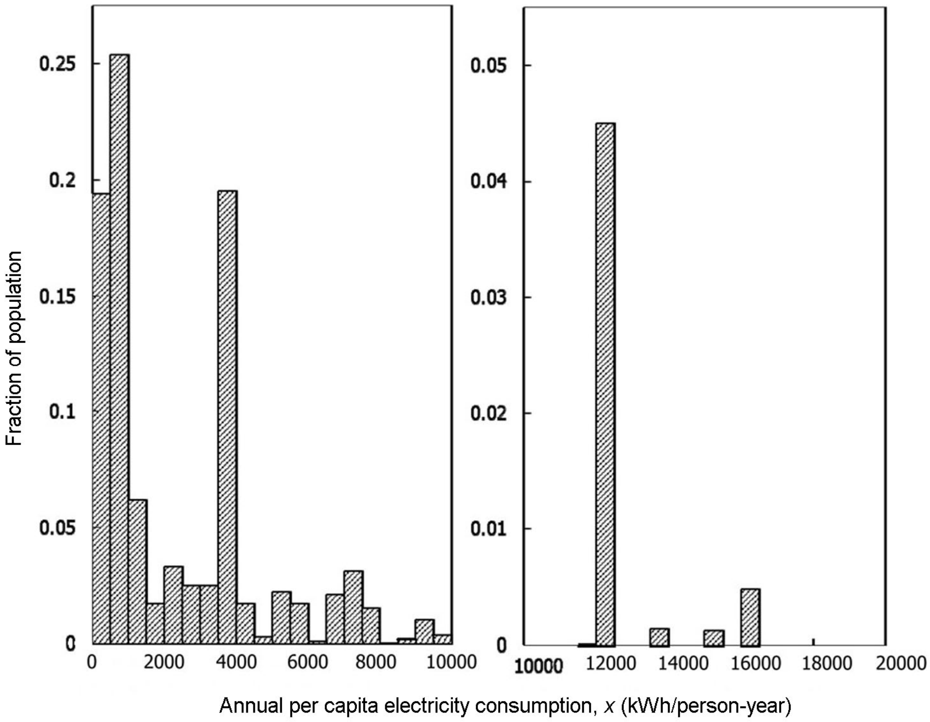

Figure 1. Bar chart of annual per capita electricity consumption in the world vs fraction of world's population. (Scale on y-axis for values of x from 10,000 to 20,000 is five times the scale from 0 to 10,000.) Mean = 2938 kWh/person-year.

countries are not for the same year, but lies over a small period from 2008 to 2012. It may also be a little inconsistent because it is compiled from various sources. Nevertheless, it should be adequate for the present purpose where one is trying to determine the shape of the distribution approximately.

We bunch all countries in blocks of 500 kWh/year. Thus, countries having an annual per capita consumption from 0 to 500 kWh/year are included in one group, those having a consumption from 500 to 1000 kWh/year in the next group and so on. Out of a total number of 212 countries, we have 58 countries having a total population of 1,354,230,152 (which is 19.36% of the total) in the first group; 18 countries with a population of 1,777,526,228 (25.41%) in the second group and so on. The calculated values are plotted as a bar chart in Figure 1. While there are spikes and dips in the bar chart, the overall trend is of a sharply decreasing value of the fraction of the population when plotted against the annual per capita electricity consumption. It is to be noted that the two big spikes in the 500–1000 and 3500–4000 kWh/year ranges are caused by the presence of India and China in these groups. India has a mean value of 868.8 kWh/person-year, whereas China has a mean value of 3874.3 kWh/person-year.

We will now fit a Weibull distribution to the bar chart plotted in Figure 1. Since a continuous distribution is to be obtained and blocks of 500 kWh/year have been used in generating the bar chart, values of the function $f(x)$ in eq. (1) are obtained by dividing the fraction of the population in Figure 1 by 500 kWh/person-year. The fitting is done with the constraint that the mean matches the mean of 2938 kWh/person-year for the world data. The Weibull distribution thus obtained is shown in Figure 2. It merges asymptotically with the x- and y-axes as the values of x and y tend to infinity. The two parameters, k and c, of the distribution have the values of 0.87 and 2739 kWh/person-year respectively. It is to be noted that k has a value between 0 and 1.

In order to obtain the distribution for India, we assume that the value of the shape parameter is the same as obtained for the world and adjust only the value of the scale parameter c using the ratio of the mean annual per capita electricity consumption for India and the world. Thus

$$c_{\text{India}} = c_{\text{World}}\,[868.8/2938], \quad (3)$$

where 868.8 kWh/person-year is the mean annual per capita value for India as given in *CIA World Factbook*[7] and 2938 kWh/person-year is the mean value for the world. The distribution thus obtained for India is shown in Figure 3 ($k = 0.870$; $c = 810$ kWh/person-year). It is seen that the distribution is highly skewed. About 65.5% of the population has access to a per capita value less than the mean and 15.0% consumes less than

100 kWh/year. Thus in India today, in addition to the mean value being low, the distribution is highly inequitable.

The future distribution in India

We have discussed earlier that for the future, mean values have been suggested based on two different approaches. A mean value of 1840 kWh/person-year based on frugal living is obtained by adding up electrical energy requirements for various activities which contribute to our daily living, while an estimate of 4000 kWh/person-year is based on the good correlation obtained between HDI and MACE for data based on all the countries of the world.

We will first examine the distribution obtained by simply scaling up the present distribution deduced for India from a mean value of 868.8 to 4000 kWh/person-year. This is drawn as curve 1 ($k = 0.87$; $c = 3729$ kWh/person-year) in Figure 4. Since it is a scaled version of Figure 3, again 65.5% of the population has access to per capita values less than the mean of 4000 kWh/person-year. In addition, calculations show that for $x = 1840$ kWh/person-year, $F(x) = 0.418$. Thus, 41.8% of the population consumes less than 1840 kWh/person-year, which has been identified as a desirable frugal value. This is a large percentage and is indicative of an inequitable and unacceptable situation.

It follows that in suggesting a distribution for the future, we need to specify not only a mean for India, but also another factor which will lead to a more equitable distribution. We will do so by constructing a Weibull distribution in which the mean is 4000 kWh/person-year and the percentage of the population consuming less than 1840 kWh/person-year lies between 10 and 20, say

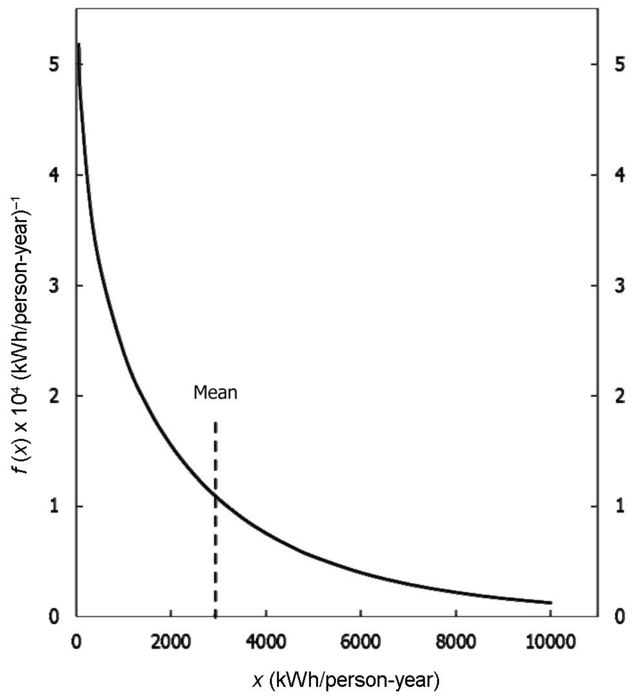

Figure 2. Weibull distribution for world derived from bar chart of Figure 1. $k = 0.870$; $c = 2739$ kWh/person-year; mean = 2938 kWh/person-year.

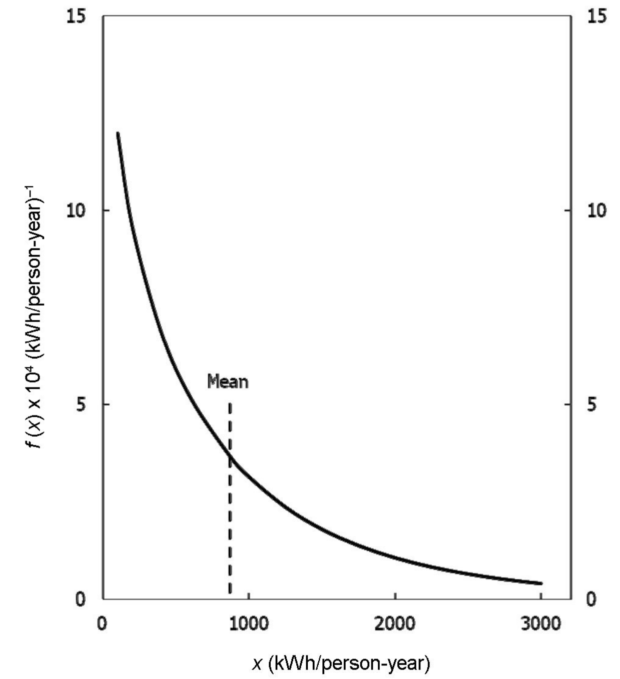

Figure 3. Present distribution in India (deduced from world distribution). $k = 0.870$; $c = 810$ kWh/person-year; mean = 868.8 kWh/person-year.

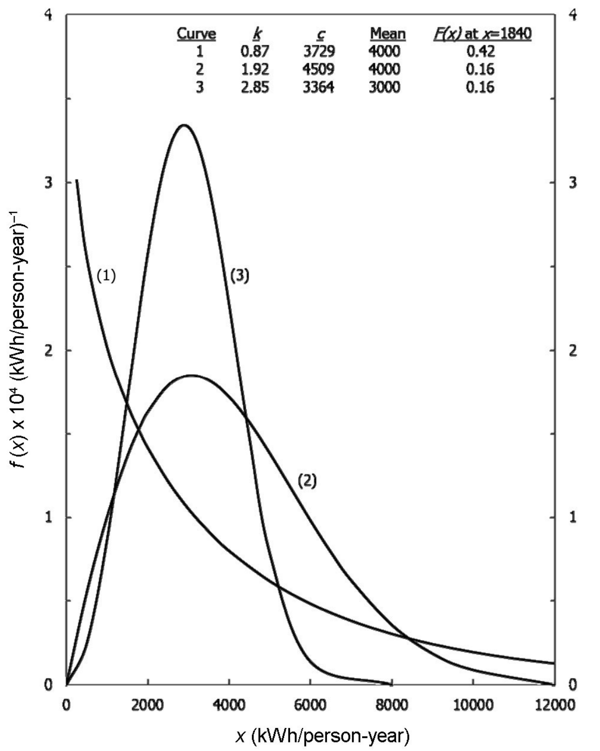

Figure 4. Possible future distributions in India. Curve 1, inequitable; curves 2 and 3, equitable.

around 15. The distribution thus obtained is curve 2 in Figure 4, the values of the parameters, k and c, being $k = 1.92$ and $c = 4509$ kWh/person-year respectively. It will be noted that unlike the distribution shown in curve 1, the value of k is now greater than 1 and the distribution is more Gaussian-like in its shape. As expected, this distribution is much more equitable. The percentage of the population consuming less than 1840 kWh/person-year turns out to be 16.4, which is acceptable. Even the percentage of the population below the mean is reduced from the value of 65.5 in curve 1 to 54.8 in curve 2.

Curve 2 is an indication of the shape of the distribution India should strive for in the future while simultaneously raising the value of the mean. In order to emphasize that it is not a unique solution, we will construct one more Weibull distribution with a similar Gaussian-like shape. In this case, we will specify that the mean is 3000 kWh/person-year, but the percentage of the population below 1840 kWh/person-year is still the same as in curve 2, viz. 16.4. The distribution obtained is shown as curve 3 in Figure 4. The values of the parameters k and c which satisfy the above specifications are obtained as 2.85 and 3364 kWh/person-year respectively. Curve 3 is a more equitable distribution than curve 2. The percentage of the population below the mean is 51.4. However, as seen in Figure 4, it has a sharper peak than curve 2.

Concluding remarks

This article focuses on the importance of knowing the variation of the annual per capita consumption of electricity in a country with respect to the population of the country rather than just knowing the mean value. It is deduced that the present distribution in India is a Poisson-like Weibull distribution ($k < 1$), which is highly inequitable. It is also shown that while it is necessary to increase the value of the mean over the years, it will also be necessary to make a transition to a Gaussian-like Weibull distribution ($k > 1$), which is more equitable. Strong policy measures have to be introduced in order to achieve this objective. Otherwise, the gains achieved with mean values of 3000 kWh/person-year or more will not benefit a large percentage of our population.

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