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A methodology for evaluating appropriateness of new energy resources in rural applications

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Abstract. In this paper a method to determine the appropriateness of energy resources in rural applications is discussed. Feasible energy resources are comparatively evaluated using eight attributes representing the criteria of appropriateness. 'Appropriateness' is defined as a linear combination of attribute weights multiplied by attribute attainment levels which have been mapped into utility for decision-makers. The uncertainty in data is handled using Monte-Carlo techniques. Sample results indicate a set of dominant energy resources for a particular task. This method can be applied in real-life decision making concerning energy resources for rural applications.

Keywords. Appropriateness index; alternate energy conversion; attribute levels; utility mapping; Monte-Carlo techniques.

1. Introduction

The four-fold increase in the price of oil announced by the Oil Producing and Exporting Countries (OPEC) in 1973 brought into sharp focus the need to consider alternative sources of energy such as biogas, solar energy, wind power, energy from the ocean waves, etc. Many research and development programmes aimed at utilising these energy resources are being pursued in India and elsewhere. Of these renewable energy resources are more attractive in the long run and therefore deserve consideration even if they are more expensive than fossil fuels. An attempt is made in this paper to present a methodology for evaluating the appropriateness of an energy resource in the rural context.

In the last few years, data regarding the Indian rural energy scene has been published (Anon 1974, Makhijani 1976, Revelle 1976, Reddy & Prasad 1977), which provide a general idea on the utilisation of conventional energy resources—both commercial and non-commercial in the rural context. Attempts have also been made to highlight possible applications of newer energy resources, particularly biogas. The report of the US National Academy of Sciences (Anon 1976) presents a state-of-the-art picture of solar energy, wind power, mini-hydel power, Stirling engines and a few other newer energy conversion systems.

However, no one particular conventional energy resource is suitable to meet the total energy demand for all the tasks in the rural sector. For instance, although firewood is used in domestic cooking, it has not yet been made use of for water pumping using external combustion steam engines. Similarly, electricity is only used for irrigation pumpsets or domestic lighting and not for domestic cooking.

Consequently, it has become necessary to examine the appropriateness of an energy resource with particular reference to a task or a group of tasks according to its priority.

2. Identification of task and energy resources

Energy is required in various agricultural operations such as tilling for seedbed preparation, application of fertilisers and insecticides, irrigation, harvesting, grain drying, transportation of the produce, etc. Irrigation, so crucial in agriculture, is gradually being extended to cover a major part of the cultivated land of the country. Ground water roughly covers one third of the water requirement of irrigated land and if this proportion is maintained, the demand for energy to pump ground water is expected to increase. At present electricity in rural areas is mainly used for irrigation pumpsets. However, the high cost of rural electrification is a severe constraint. There is therefore considerable scope for decentralised water-pumping systems based on the newer energy resources.

Small and marginal farmers with land holdings of about one hectare deserve priority in any rural development programme. These farmers cannot afford diesel and electrical pumps and if the government can provide them with water pumps on easier credit terms or subsidies, it would help evaluate appropriateness of conventional and new energy resources so that the support is channelled in the best possible manner. Taking a unit area of 1 hectare and the typical water requirement for irrigation per season for non-rice food crops as 500, mm and assuming a head for water pumping of about 10 m, the total energy requirements amount to 136 kWh per hectare per season or approximately 1 kWh per hectare per day. We must however bear in mind that about 15–20 kWh of energy may be required at a stretch for each irrigation and that about 6–7 such irrigations may be required during a four-month season.

The following water pumping systems can provide a work output equivalent to 1 kWh per day:

(i) bullock-powered traditional waterlifts,
(ii) diesel-powered pumpsets,
(iii) electrical pumpsets,
(iv) biogas generated in family size units (2–3 m^3/day) for energising liquid piston pumps,
(v) biogas generated in large community size plants and utilised in modified diesel engines,
(vi) solar thermal devices driving water pumps,
(vii) solar-pump without moving parts,
(viii) photovoltaic arrays driving electrical pumpsets,
(ix) wind-powered pumps.

While small water wheels, hydraulic ram, Stirling engines, geothermal power, etc. can also be used for smaller applications, the cost and performance data available are rather inadequate yet for our analysis. Moreover, these devices except for Stirling engines run on crop residues can operate only at a few favourable locations.

3. Attributes for evaluating appropriateness

The appropriateness of an energy resource in the rural context can be determined by its relationship with rural development. Rural development can be stated in simple terms as the problem of providing gainful employment to people in villages in the quickest possible time with a reasonable expenditure of resources (including finances) and in a manner consistent with the lifestyle of the people. Viewed from this angle, the following attributes can be identified in order to assess the appropriateness of energy resources:

(i) capital cost of energy conversion devices,
(ii) recurring costs,
(iii) energy technology availability: time factor,
(iv) priority for the use of the resource under consideration in a given application,
(v) organisational and maintenance aspects,
(vi) social acceptance,
(vii) generation of local employment,
(viii) use of locally available fuels or materials.

The capital cost would be determined from the installed capacity, say, per kilowatt. The cost of the prime-mover, driven loads such as pump and generator, the energy or output storage system (such as batteries and water tank for irrigation) etc. may also have to be included here depending upon the particular energy resource under consideration. Running costs would be determined from depreciation, fuel charges and the cost of operation and maintenance. The running cost can be expressed for one full year or in terms of a fraction of a year, e.g. a crop season. The third attribute concerns the time factor involved in making available to the users a particular energy technology, e.g. energy conversion device. This factor is important because several newer energy resources are at different stages of research and development. The fourth attribute refers to a possible social priority in the use of limited resources in a variety of applications. For instance, if the biogas potential is found to be limited, the society might allot a higher priority for its use in cooking than in irrigation water pumping. In the supply of fuel and the distributing energy, some organisational problems may develop. In addition to this, the maintenance and operation of the devices would also require attention. These aspects are covered in the fifth attribute. The sixth attribute concerns the social acceptance of new energy conversion systems. Such of those energy conversion systems which disturb the lifestyle, which are potentially hazardous and which interfere with religious beliefs are likely to be less acceptable to society. Employment generation in villages for the construction, maintenance and operation of energy conversion systems is the next attribute, which is directly related to rural development. The last attribute relates to the use of locally available fuel, which is highly desirable for a variety of reasons, apart from the low cost and easy and ready accessibility.

The attributes—capital and running costs—can be expressed in rupees. Technology availability can be expressed in years or months and employment generation in terms of mandays. The remaining attributes are qualitative in nature and can be specified in terms of grades like very high, high, medium, low and very low. In numerical terms, these grades can be expressed on a five-point scale ranging, say, from 1 to 5.

4. Appropriateness index

The appropriateness of energy resources can be expressed mathematically as a combination of ratings obtained in respect of each attribute. Thus, the appropriateness index for the jth alternative energy conversion system or resource can be expressed as

$$A_j = \sum_{i=1}^{8} f_{ij}\,(x_i), \tag{1}$$

where the x_i are the attributes and $f_{ij}\,(x_i)$ indicate the scores obtained in respect of each attribute. The expression $f_{ij}\,(x_i)$ includes the following two basic considerations:

(i) all attributes need not be equal and some may be more important than others;
(ii) the value of attaining a certain score in terms of the attribute scales.

These aspects are discussed in the subsequent sections.

5. Relative importance of attributes

The weighting of multiple criteria or attributes is a standard technique in the application of scoring models such as the one given in equation (1). Examples are available in the literature on the application of ranking, rating, paired comparison, the successive comparison method of Churchman, and a few other methods. The authors conducted an opinion poll among eleven participants who were requested to rank the given eight attributes. Of the eleven participants, one was directly involved in rural development, one in energy planning, one from industry, one from R & D

Table 1. Ranks assigned to eight attributes

	Attributes						
	1 & 2*	3	4	5	6	7	8
1	1	3	7	2	4	6	5
2	6	7	5	4	3	1	2
3	3	2	7	1	6	4	5
4	2	4	6	5	1	7	3
5	2	1	5	4	7	3	6
6	2	3	7	4	1	5	6
7	5	1	2	3	6	4	7
8	3	7	1	4	5	6	2
9	2	1	7	5	3	4	6
10	4	7	6	3	5	2	1
11	1	2	6	4	7	3	5

*In the exercise that was carried out, the two costs were combined together.

management, three in R & D on renewable energy resources and four from the academic profession. Ranks were provided from one to eight and this information is presented in table 1. An application of Kendall's (1962) test indicated a low value of concordance; that is, agreement among the participants about rankings was not high enough. At the same time it is not entirely random as found through an application of the Chi-square test.

To rank the attributes, the participants (i.e., decision-makers) were asked to assign values between 1 and 100 in respect of each attribute. These values were normalised and the frequency histograms shown in figure 1 were obtained. The abscissae in figure 1 represents the weight scale ranging from 0 to 1, divided into twenty equal intervals. The frequency of occurrence, that is, the percentage of the number of people who assigned scores falling within a particular weight interval is shown along the ordinate. In figure 1, the expected values for the weights are also shown. The third attribute, technology availability, obtains the highest value (0·17), and priority for use in irrigation obtains the lowest value (0·09). Other attribute weights range from 0·11 to 0·16. These weights appear reasonable and imply that early availability of energy technology and lower costs are surely the most important criteria.

Let the weights given in figure 1 be denoted by w_i where i represents the attribute.

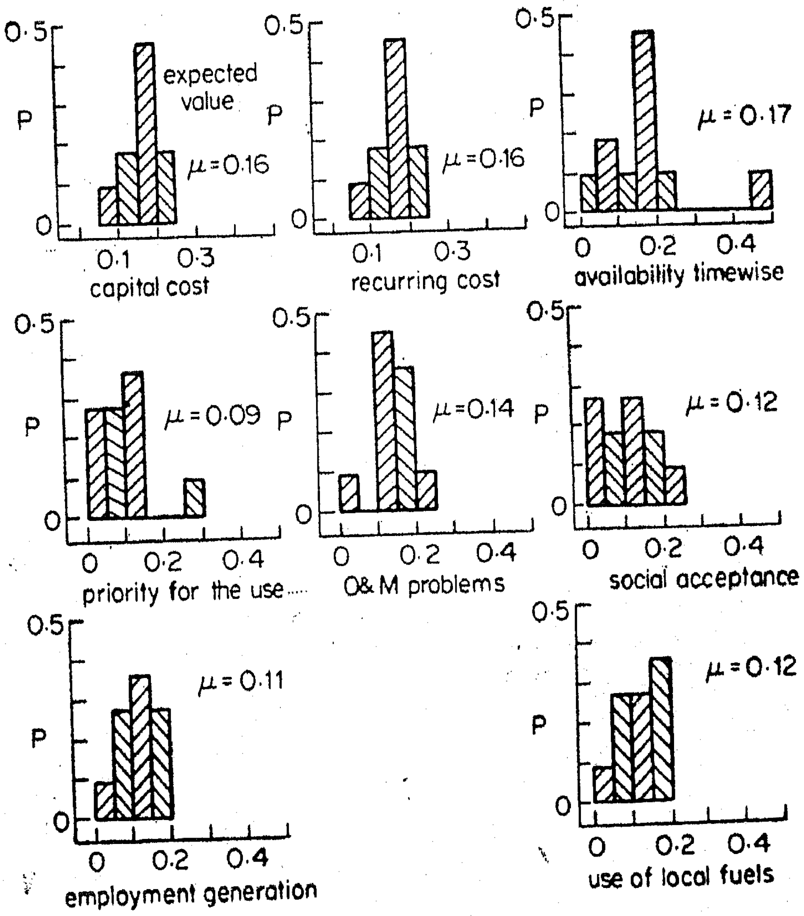

Figure 1. Frequency histograms for attribute weights.

6. Attribute levels

In our present decision-making problem, the attributes have two characteristics. The first is that these attributes appear with scales of attainment and not as goals which are either achieved or not achieved. The second characteristic is that each attribute for a given energy resource appears with a range of values rather than with one fixed value. To be specific, consider wind-powered pumps. To provide 1 kWh per hectare per day on an average, during the *rabi* season (the main irrigation season from November to February), the swept rotor diameter may have to be of the order of 10 m providing an equivalent swept area of 78·5 m^2. Prototype windmills having swept areas ranging from 8 m^2 to 78·5 m^2 have been reported (Govindaraju & Narasimha 1979; Vilstern 1978; Sherman 1976; Smith 1976; Tyabji 1977; Tewari *et al* 1979). From the information available on these designs, one might assume that the capital cost for our wind-powered pumps will range from Rs 5,500 to Rs 13,500. This range would accommodate such variables as windspeeds, choice of construction material, design and fabrication techniques, labour charges, etc. Further, it would be reasonable to assume that the probability of the cost being either Rs 5,500 or

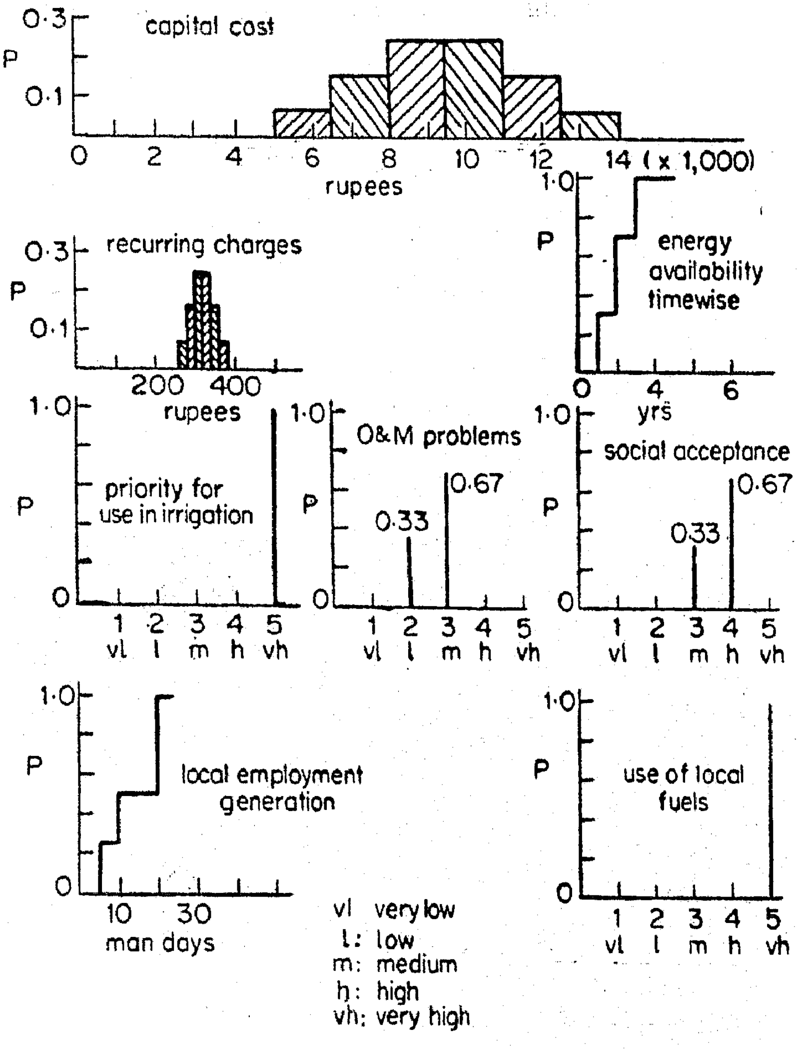

Figure 2. Attribute attainment levels for wind-powered pumps.

Table 2. Attribute attainment levels.

Alternatives (energy conversion systems)	Attributes (probabilities shown in brackets)							
	Capital cost (Rs) (normal distribution)	Recurring charges (Rs) (normal distribution)	Technology availability —timewise (years) (linear distribution)	Priority for use	O & M problems	Social acceptance	Local employment generation (man-days)	Use of local fuels
1. Bullock-powered waterlifts	1,250– 2,750	140–210 + 450–900	½	H (67%) VH (33%)	VL (67%) L (33%)	VH	3	VH
2. Electrical pumpset	8,000–19,000	14– 70 + 125–325	0 (32%) 12 (100%)	H (67%) VH (33%)	M (50%) H (50%)	VH	12	VL
3. Diesel-powered pumpsets	3,550– 5,500	110–190 + 210–330	½	M (50%) H (50%)	H (33%) VH (67%)	VH	2	VL
4. Family-size biogas plant energising liquid piston pumps	2,800– 3,800	250–290	1½ (0%) 3½ (100%)	L (33%) M (67%)	L (33%) M (67%)	L (50%) M (50%)	6	VH
5. Community-size biogas plant energising modified diesel pumpsets	600– 1,200 + 3,500– 5,500	160–220	1½ (0%) 3 (100%)	L (33%) M (67%)	H (33%) VH (67%)	M (50%) H (50%)	6	VH
6. Solar-thermal devices	16,000–28,000	490–690	2½ (0%) 5 (100%)	VH	H (33%) VH (67%)	H (33%) VH (67%)	6	VH
7. Solar-pump without moving parts	27,000–51,000	550–960	3½ (0%) 6 (100%)	VH	M (33%) H (67%)	VH	6	VH
8. Photovoltaic systems	9,000–13,000 (assuming US D.O.E. goals of $1 per peak watt are achieved by mid 80s.	100–140	4 (0%) 9 (100%)	VH	VL (67%) L (33%)	VH	0	VH
9. Wind-powered pumps	5,500–13,500	2603–80	⅛ (0%) 2 (100%)	VH	L M	M H	10–20	VH

O & M = operation and maintenance
VH, very high; H, high; M, medium; L, low; VL, very low

Rs 13,500, the two extreme values, would be very small compared to the cost being around Rs 9,000 (the mean value). In other words, for the capital cost, one may assume the probability distribution curve to be normal, as shown in figure 2(a). Similarly, for the same energy converter (i.e., wind-powered pumps), one may determine the probability distribution functions regarding the other attributes also. These are shown in figure 2. Similar analyses can be made for the other energy resources also. In this paper, the details regarding these resources are not given, but the methodology is similar to the one just discussed. The details can be found in Tewari (1978). However table 2 briefly gives these details.

7. Utility mapping

The appropriateness of an energy resource was earlier defined as a combination of scores in respect of the eight attributes. However, the measures of these attributes are not all the same. While capital and operating costs are measured in rupees, the availability of technology is measured in years and social acceptance purely in qualitative terms. Consequently, the scores cannot be combined simply as in equation (1). But if the scores are expressed in terms of some common measure, then one can apply equation (1). One such common measure is the degree of satisfaction to a decision-maker or a group of decision-makers. Following the definition of utility provided by Starr & Zeleny (1977), if the outward aspects of the preferences of decision-makers are quantified then this artifact called 'utility' can be handled mathematically.

Take for example the capital cost. It is obvious that any decision maker—farmer or a policy planner—would surely prefer a lower capital cost. Moreover, a capital cost higher than a reasonable value would be much less preferred. The highest capital

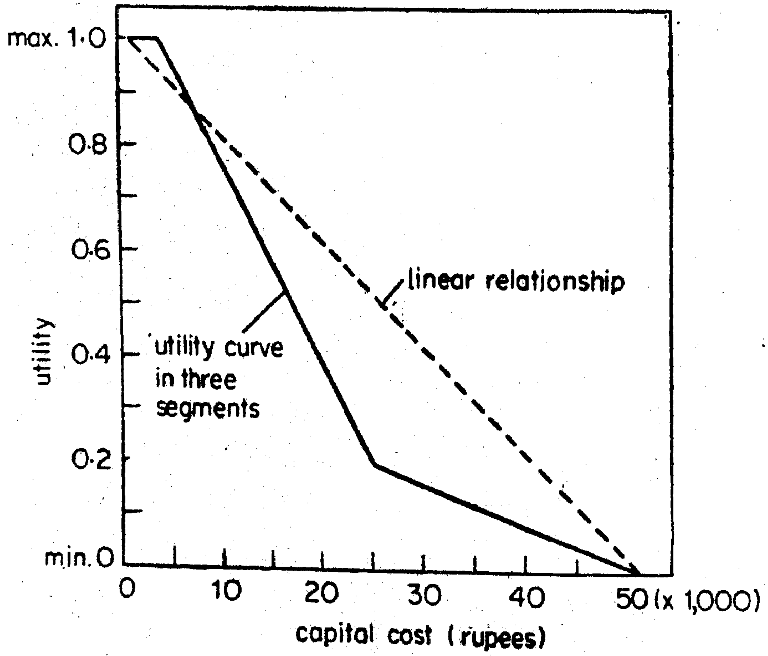

Figure 3. Utility-attribute relationship.

cost encountered among the nine energy resources identified in this study was found to be Rs 51,000 (corresponding to solar pumps without moving parts) and the lowest value was Rs 1,000 (corresponding to bullock-powered waterlifts) (Tewari 1978). Let us define the maximum possible utility as 1 and the lowest possible value as 0. Then we can state that a capital cost of Rs 1,000 amounts to the highest utility (1) and a capital cost of Rs 51,000 obtains the lowest utility (zero). Now, the simplest relationship between utility and attribute-attainment levels would be a straight line joining the extreme ends of the two scales, as shown in figure 3. But, a decision-maker might accord a fairly high utility, higher than that given by the straight line, for capital cost, as long as it remains within what he considers a reasonable value say, Rs 4,000. Thereafter, utility may drop significantly. Beyond a cost of Rs 25,000, which itself is highly undesirable, the utility may slowly decrease to zero. This logic is graphically displayed by means of the three-segmented curve shown in figure 3.

Following the above logic which represents one approach, variations can be expected depending upon the preferences and views of decision-makers. An exercise of this procedure in actual practice could include interviews of decision-makers and

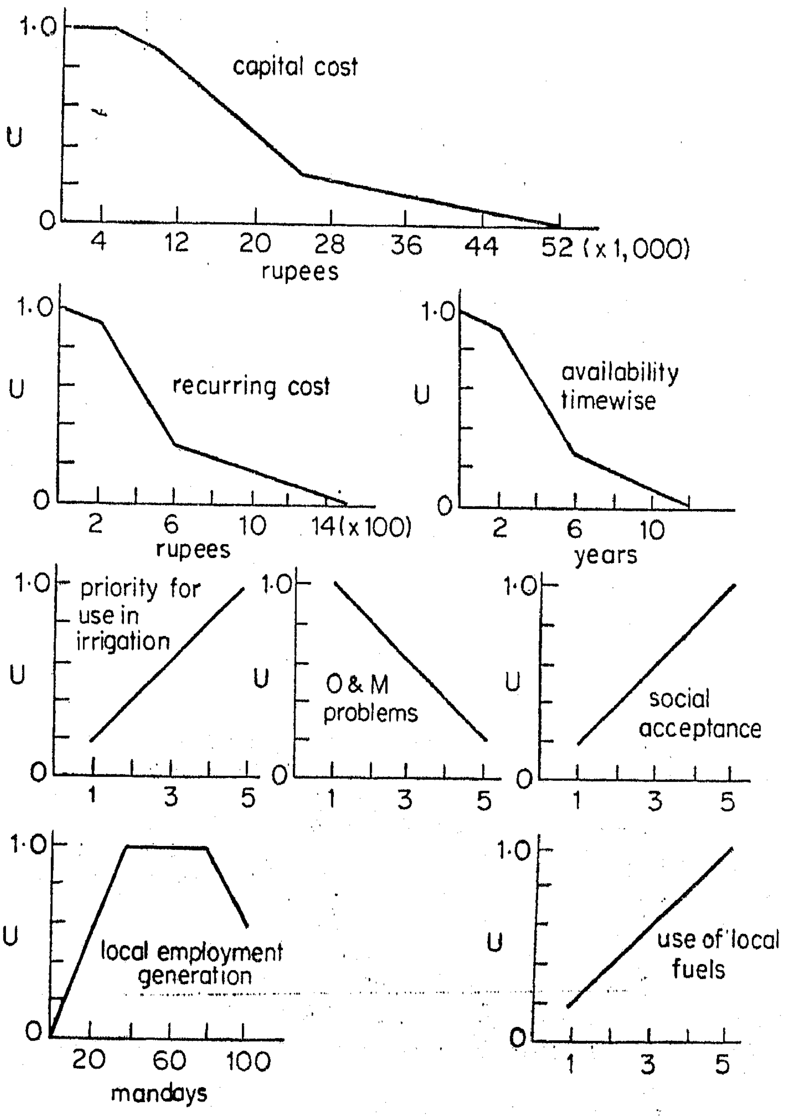

Figure 4. Utility-attribute curves

conducting group discussions. Several techniques have been discussed in the literature such as Keeney's (1972) N & M lottery method, Miller's (1970) method and the direct technique of Edward (1977). The technique discussed here is based on Edward's method, which was applied by him in several examples of social decision-making.

Similar utility-attribute curves can be drawn for the other attributes. These are given in figure 4. In the case of qualitative attributes, the relationship is shown as a straight line. This is expected to be sufficient here since precise quantification of the attribute itself is not possible and therefore any further refinement in utility curves would be a mere exercise.

At this stage, we have two important sets of information. One is regarding the probability distribution versus attribute level for a given energy resource and for each attribute. For a wind-powered pumpset, this information is as shown in figure 2. The second deals with the attribute attainment level versus utility, as just discussed in the above sections. This information is shown in figure 4, and applies to all energy resources under consideration. These two sets of information can be combined into one. This resultant set refers to the mapping of utility versus probability curves for each attribute-energy pair. This transformation mapping is simple, since the attribute level is a common variable in both figures 2 and 4. Figure 5 illustrates

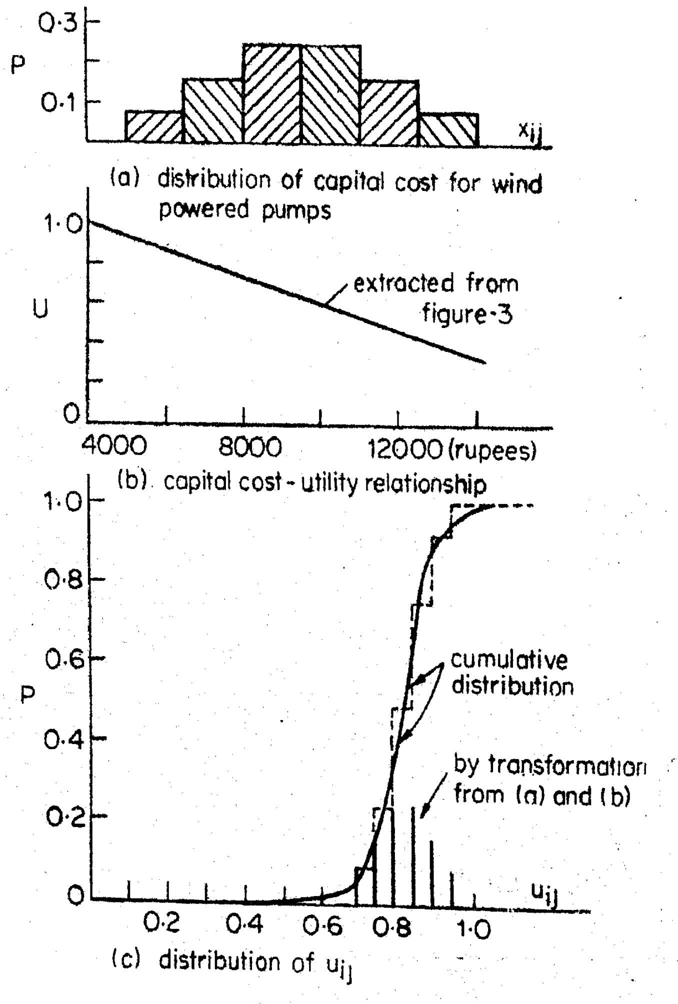

Figure 5. Mapping of attribute levels into utility.

this mapping for the first attribute, *viz.* capital cost and for the energy resource, wind-powered pumpset. The resultant mapping is shown in figure 5(c). If u_{ij} represents the utility of the attribute i for the jth alternative energy resource, then figure 5(c) shows a plot of u_{ij} versus probability distribution.

8. Computation of appropriateness—Monte-Carlo technique

In equation (1), the overall appropriateness or worth of an energy resource is defined as a linear combination of appropriateness in terms of each attribute. The latter denoted by $f_{ij}(x_i)$ consists of two parts, one regarding the importance weights of the attribute themselves that is w_i, and the other connected with attribute attainment levels. To facilitate the combination of quantities with different scales of measurement, we had introduced the mapping of attribute attainment levels into a non-dimensional parameter 'utility'. We recall that u_{ij} represents the utility of the attribute i for the jth energy resource. Therefore we may write

$$f_{ij}(x_i) = w_i u_{ij}. \tag{2}$$

Substituting the above in equation (1), we get for the appropriateness A_j of the jth energy resource

$$A_j = \Sigma_i \, w_i u_{ij}. \tag{3}$$

One difficulty is encountered in computing A_j according to (3). w_i and u_{ij} are not definite quantities, but they appear with their probability distributions. Defining A_j as a quantity jointly distributed over w_i and u_{ij}, which indeed is the case according to (2), the computation can be carried out using the Monte-Carlo technique. According to this technique, random numbers are generated in pairs and their values determine particular values of w_i and u_{ij} to be multiplied. In figure 6, the cumulative distribution of a pair of w_i and u_{ij} corresponding to capital cost for wind-powered pumps ($i=1, j=9$) is shown. The probability scales are partitioned into intervals to match the steps in the probability curve. Supposing, the random numbers drawn are 0·23 and 0·45; then the values of w_i and u_{ij} read from figures 6(a) and 6(b) are 0·15 and 0·78 respectively. These two are multiplied and stored. The process is repeated eight times corresponding to eight attributes, that is $i = 1 \ldots 8$, but with the same value of j corresponding to wind-powered water pumps. The value of A_j is obtained by adding the results of eight w_i and u_{ij} multiplications. This value of A_j is stored. Next, an additional sixteen random numbers corresponding to eight u_{ij} and eight w_i are generated and the resulting A_j is stored. Supposing this process is repeated 100 times, then 100 values of A_j are obtained, each with equal probability. This information can be readily converted into a frequency histogram and subsequently into cumulative distribution of the type shown in figure 6(c).

The justification for the above procedure in which estimation of A_j is made by using draws of random numbers is based on the law of large numbers. Following Mihram (1972) if $x_1, x_2 \ldots x_n$ are independent random variables from a probability distribution function $f(x)$ having mean μ and variance σ then, for sufficiently large

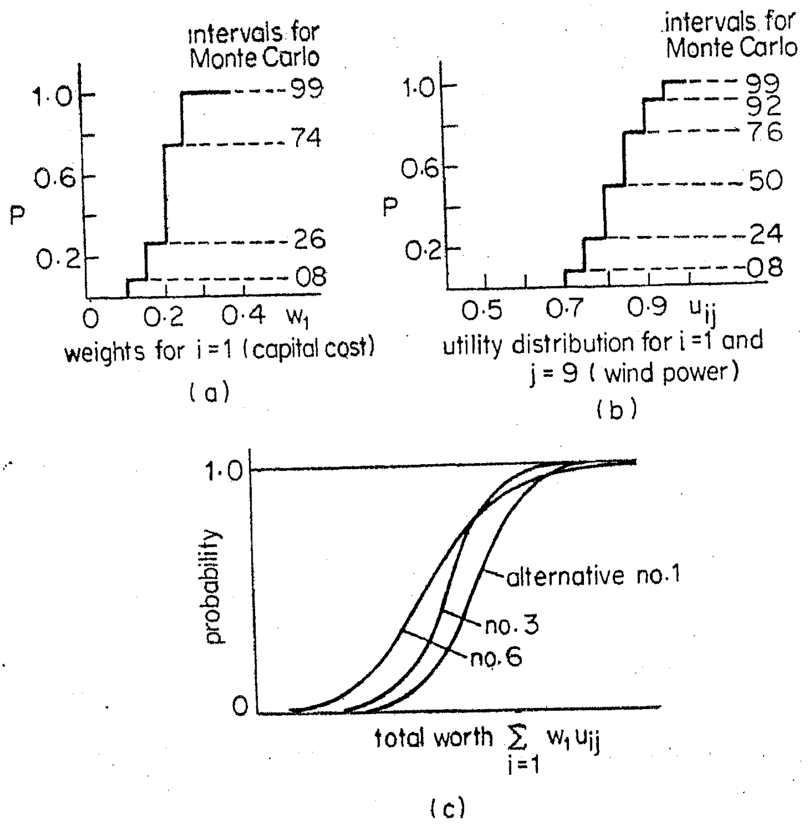

Figure 6. Labelling of random numbers for the application of Monte-Carlo technique

N, their arithmetic mean

$$X_N = N^{-1} \sum_{i=1}^{N} X_i, \tag{4}$$

will in all probability approach μ as the limiting value. In this manner, the mean value of an arbitrary distribution A_j can be estimated by sampling for each w_i and u_{ij} and multiplying the two values each time. By repeating this experiment a large number of times the value so calculated can be deemed to approach the arithmetic mean of the combined distribution $(w_i u_{ij})$.

Pseudo random numbers, sufficient for all practical purposes, can be generated using the mixed congruential method, according to which the kth random number is calculated from

$$U_k = (aU_{k-1} + c) \ (\text{mod } m), \tag{5}$$

where U_{k-1} is the $(k-1)$th random number (generated earlier), c is an additive constant, and mod m means that the value $(aU_{k-1} + c)$ is divided by m, the remainder being the value of U_k.

In the functional subroutine RANDU the values of the constants are:

$$a = 65\,539, \ m = 2^{31}, \ c = 2^{32} + 1.$$

With this arrangement, the cycle length, that is, the period after which the chain of random numbers is repeated is quite large. The repetition would occur after generating 2^{30} random numbers. In our case, if we carry out 500 sampling experiments for each A_j, then the total number required to be generated is just 8,000. So, for all practical purposes the subroutine provides acceptable random numbers for our computation.

9. Illustrative results

The methodology was applied in the case of the task identified in § 2 and the data discussed in § 6. As mentioned earlier, due to limitation of space, it has not been possible to provide details of the analysis of the attribute attainment levels in this paper. The emphasis in this paper is on the methodology and for clarity, some results are provided in figure 7. Without going into the accuracy of the conclusions likely to be inferred from figure 7, the important fact to observe is that in spite of considerable uncertainty in the available data, it is possible to find a clearer pattern of the dominant alternatives.

It is believed that if the exercise is carried out with a group of decision-makers using the latest data and fairly reliable figures, the methodology is likely to be of considerable help in the decision-making process.

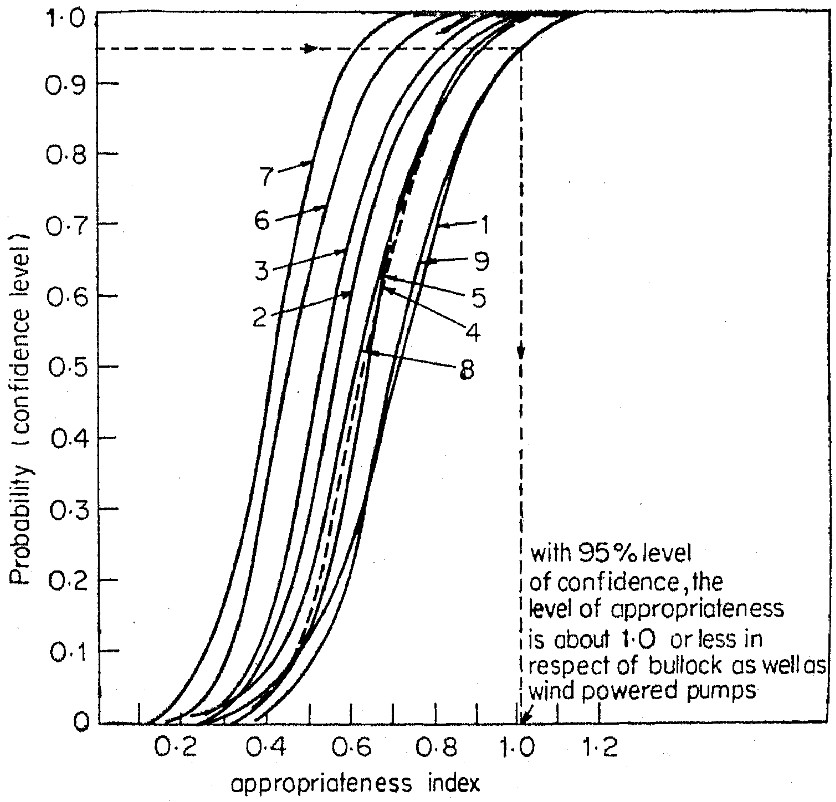

Figure 7. Relative appropriateness of various energy conversion systems. 1. Bullock-powered traditional waterlifts. 2. Diesel-powered pumpsets. 3. Electrical pumpsets. 4. Biogas generated in family size units (2–3 m^3/day) for energising liquid piston pumps. 5. Biogas generated in large community size plants and utilised in modified diesel engines. 6. Solar thermal devices driving water pumps. 7. Solar pump without moving parts. 8. Photovoltaic arrays driving electrical pumpsets. 9. Wind-powered pumps.

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