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The design of rural energy centres

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Abstract. Need-oriented, self-reliant and environmentally-sound development demands that the design of rural energy centres proceeds step-wises from energy consumption patterns to energy needs to technological options to selection of energy sources and devices to integration of these sources and devices into a system. The procedure is illustrated with Pura village as a concrete example. There is first a description of Pura's energy consumption pattern, and its energy needs and energy resources. In the absence of a rigorous methodology for solving the fundamental problem of designing rural energy centres, *viz.*, given the energy resources and requirements, what is the optimum way of harnessing i energy sources with the aid of j devices to achieve k energy-requiring tasks?, a heuristic approach based on second law efficiencies is used. The result is a design for a rural energy centre for Pura. The first phase of such a centre involves a community-scale biogas plant to meet the energy needs of cooking, domestic electric illumination, and pumping domestic water, in addition to providing organic fertiliser and producing rice husk ash cement. The Pura exercise is used to formulate several principles of rural energy system integration, *viz.*, mixing, cascading and combining of sources, spatial task integration and time-sharing. Finally, the general problem of designing rural energy centres is mathematically formulated. The formulation highlights important data gaps which must be filled before rigorous rural energy system designing can be achieved.

Keywords. Rural energy; village energy consumption; energy planning; rural energy centre; design methodology; second law efficiencies; community biogas plant; energy system integration.

1. Introduction

The growing realisation that the benefits of growth in developing countries have not 'trickled down' to the rural poor has stimulated global interest in technologies for rural development. In particular, problems of rural energy have attracted widespread attention. This attention has focussed on descriptions of the rural energy 'crisis' (Eckholm 1976), guesstimates of rural consumption patterns (Prasad *et al* 1974; Makhijani 1976; Revelle 1976; Reddy & Prasad 1977, Reddy 1978), the formation of centres/groups for village energy studies*, the organisation of seminars/symposia on the subject**, and the design of technological packages for rural energy centres (Anon 1976).

The centre for the Application of Science and Technology to Rural Areas (ASTRA) too has been compelled, from its very inception, to interest itself in rural energy by the constant complaint of the villagers with whom it was in contact that 'fuel' was one of their most pressing problems. Several difficulties, however, came to the fore immediately. Firstly, there was hardly any information at all on energy

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*For example at the Institute of Development Studies, Sussex.
**For example, the Royal Institution Forum, London, 20-22 June 1979.

consumption patterns now prevalent in villages—data was available on UK or USA, but not on villages a few kilometres from the Institute. Secondly, even if the information had been available, a proven methodology for rural energy planning was lacking.

Thus, in the villages in which it is working, ASTRA had to start from 'zero', develop an energy data base and then formulate an energy strategy for implementation. Though ASTRA's work is just entering the implementation phase, its preliminary methodology for rural energy planning is being reported here to provoke scrutiny and refinement.

2. Basic approach

All attempts at external intervention in rural life are inspired, consciously or unconsciously, explicitly or implicitly, by a viewpoint on rural development. ASTRA's perspective (Reddy 1979) has been a rural development which is: (a) need-oriented ('starting from the needs of the neediest'), (b) self-reliant, and (c) environmentally sound.

Such a perspective demands that rural energy planning be based on an approach consisting of the following steps:

(i) elucidation of current rural energy consumption patterns;
(ii) translation of these patterns into a set of energy needs arranged according to priority;
(iii) consideration of the feasible technological options, including the traditional ones, of satisfying these energy needs with the available resources;
(iv) selection of the 'best' option for satisfying each category of need;
(v) integration of the selected options into a system.

This approach has been used for the design of a rural energy centre for Pura village*, and will therefore be described with reference to this concrete case.

3. Pura's energy consumption pattern

With no precedent to follow, the methodology for ASTRA's survey of rural energy consumption patterns was evolved through a 'trial run' in four villages, the lessons of which were used to make a detailed study of six villages including Pura. Whereas the 'trial run' was based wholly on verbal responses to questions from a questionnaire, the detailed study was based, in addition, on observations and measurements.

Since Pura's energy consumption pattern is described in detail elsewhere (Ravindranath *et al* 1979), only those features essential for the design of a rural energy centre for the village are outlined below.

**Pura* (latitude: 12°49′00″ N, longitude: 76°57′49″ E, height above sea level: 670·6 m, average annual rainfall: 50 cm/year, population (in September 1977): 357, households: 56) is one of the villages in a cluster in Kunigal Taluk, Tumkur District, Karnataka State, South India, amidst which ASTRA has established an Extension Centre to generate a grass-roots understanding of rural problems through direct interaction with the people and to elicit their response to technological alternatives.

The energy-utilising activities in Pura are*: (a) agricultural operations (with ragi and rice as the main crops), (b) domestic activities, *viz.*, grazing of livestock, cooking, gathering firewood and fetching water for domestic use including drinking, (c) lighting and (iv) industry (pottery, flour mill and coffee shop). These activities are achieved with the following *direct* sources of energy: human beings, bullocks, firewood, kerosene and electricity.

An aggregated matrix showing how the various energy sources are distributed over the various energy-utilising activities is presented in table 1 in the units appropriate to the sources.

Notwithstanding the methodological and conceptual problems in converting the various sources to a common energy unit (e.g., kilocalories), there are three advantages in doing so: (i) an idea can be obtained of the relative contributions of the various sources to the total energy consumption (ii) a summation over all sources contributing to a particular activity leads to the total magnitude of energy it now utilises (iii) the total magnitudes of energy for the various activities facilitates a ranking of these magnitudes. Using the following conversion factors: 250 kcal/man hour, 200 kcal/woman hour, 120 kcal/child hour, 2300 kcal/bullock hour, 3800 kcal/kg firewood**, 860·4 kcal/kWh electricity, and 8980 kcal/litre kerosene, a source-activity matrix for Pura village has been obtained (table 2).

The matrix yields the following ranking of sources (in order of percentage of annual requirement): (a) fire wood 89% (b) human energy 7% (c) kerosene 2% (d) bullock energy 1% (e) electricity 1%. The ranking of activities is as follows: (a) domestic activities 91% (b) industry 4% (c) agriculture 3% (d) lighting 2%.

Human energy is distributed thus: domestic activities 80% (grazing livestock 37%, cooking 19%, gathering firewood 14%, fetching water 10%), agriculture 12%, and industry 8%. Bullock energy is used wholly for agriculture including transport. Firewood is used to the extent of 96% (cooking 82% and heating bath water 14%) in the domestic sector, and 4% in industry. Kerosene is used predominantly for

Table 1. Energy sources and activities in Pura

	Agriculture	Domestic	Lighting	Industry	Total
Human hours	34848	255506	—	20730	311084
(Man hours)	(19914)	(82376)	—	(16485)	(118775)
(Woman hours)	(14934)	(113928)	—	(4245)	133107
(Child hours)	—	(59202)	—	—	(59202)
Bullock hours	5392	—	—	—	5392
Firewood (kgs)	—	207807	—	8930	216737
Kerosene (litres)	—	—	1938	156	2094
Electricity (kWh)	7264	—	3078	820	11162

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*Transport has been included in agriculture because the only vehicles in Pura are bullock carts and these are used almost solely for agriculture-related activities such as carrying manure from backyard compost pits to the farms and produce from farms to households.

**Based on specimen collection by H I Somashekar and bomb-calorimetry by P Rajabapaiah.

Table 2. Pura energy source-activity matrix (× 10^6 kcals/year)

	Agriculture	Domestic	Lighting	Industry	Total
Human	7·97	50·78	—	4·97	63·72
(Man)	(4·98)	(20·59)	—	(4·12)	(29·69)
(Woman)	(2·99)	(22·79)	—	(0·85)	(26·63)
(Child)	—	(7·40)	—	—	(7·40)
Bullock	12·40	—	—	—	12·40
Firewood	—	789·66	—	33·93	823·59
Kerosene	—	—	17·40	1·40	18·80
Electricity	6·25	—	2·65	0·71	9·61
Total	26·62	840·44	20·05	41·01	928·12

Total energy = 928 × 10^6 kcal/year; = 1·079 × 10^6 kWht/year; = 2955 kWht/day; = 8·28 kWht/day/capita

lighting (93 %), and to a small extent in industry (7 %). Electricity flows to agriculture (65 %), lighting (28 %) and industry (7 %).

There are several features of the pattern of energy consumption in Pura which must be highlighted.

(i) What is conventionally referred to as *commercial* energy, i.e., kerosene and electricity in the case of Pura, accounts for a mere 3 % of the inanimate energy used in the village, the remaining 97 % coming from firewood.* Further, notwithstanding recent doubts (Rudolph & Lenth 1978), firewood must be viewed as a *non-commercial* source since only about 4 % of the total firewood requirement of Pura is purchased as a commodity, the remainder being gathered at zero private cost.

(ii) *Animate* sources, *viz.*, human beings and bullocks, only account for about 8 % of the total energy, but the real significance of this contribution is revealed by the fact that these animate sources represent 77 % of the energy used in Pura's agriculture. In fact, this percentage would have been much higher were it not for the operation of *four* electrical pumpsets in Pura which account for 23 % of the total agricultural energy.

(iii) Virtually all of Pura's energy consumption comes from traditional renewable sources—thus agriculture is largely based on human beings and bullocks, and domestic cooking (which utilises about 80 % of the total inanimate energy) is based entirely on firewood**.

(iv) However, the environmental soundness of this pattern of dependence on renewable resources is achieved at an exhorbitant price: levels of agricultural productivity are very low, and large amounts of human energy are spent on firewood gathering

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*Pura uses about 217 tonnes of firewood per year, i.e., about 0·6 tonnes/day for the village, or 0·6 tonnes/year/capita.

**Unlike some rural areas of India, dung cakes are *not* used as cooking fuel in the Pura region, In situations where agro-wastes (e.g., coconut husk) are *not* abundant, it appears that, if firewood is available within some convenient range (determined by the capacity of head-load transportation), dung cakes are never burnt as fuel; instead dung is used as manure.

(on the average, about 2·6 hr and 4·8 km per day per family to collect about 10 kg of firewood).

(v) Fetching water for domestic consumption also utilises a great deal of human energy (an average of 1·5 hr and 1·6 km per day per household) to achieve an extremely low *per capita* water consumption of 17 litres per day.

(vi) 46% of the human energy is spent on grazing livestock (5·8 hr/day/household) which is a crucial source of supplementary household income.

(vii) Children contribute a crucial 30%, 20% and 34% of the labour for gathering firewood, fetching water and grazing livestock respectively. Their labour contributions are vital to the survival of families, a point often ignored by population and education planners.

(viii) Only 25% of the houses in the 'electrified' village of Pura have acquired domestic connections for electric lighting, the remaining 75% of the houses depend on kerosene lamps, and of these lamps, 78% are of the open-wick type.

(ix) A very small amount of electricity, *viz.*, 30 kWh/day, flows into Pura, and even this is distributed in a highly inegalitarian way—65% of this electricity goes to to the 4 irrigation pumpsets of 3 landowners, 28% to illuminate 14 out of 56 houses, and the remaining 7% for one flour-mill owner.

4. Pura's energy needs

The above pattern of energy consumption constitutes the data base for formulating an energy plan for Pura. This objective is facilitated by representing energy consumption in terms of end-uses or tasks classified with a physics perspective, rather than activities with socio-economic significance. It is also convenient to separate the end-uses of inanimate and animal energy from those of human energy—whereas the former permit the selection of sources and devices appropriate to the energy-utilising tasks, the latter enable a consideration of alternative systems that will improve the quality of life by alleviating or eliminating drudgery. Such an end-use analysis for Pura is shown in table 3, which also contains the output energies taking into account the efficiencies of energy utilisation.

In the first part of the table, the end-uses of inanimate and animal energy (along with indicative temperatures corresponding to these tasks) are ranked in order of decreasing magnitude of energy utilised. This ranking according to magnitude may be considered to provide an *initial* list of priorities for energy planning. For the list to promote development, end-uses which involve satisfaction of the needs of the neediest or the majority can be given an extra weight, e.g., lighting which all homes require can be given a higher weight than power for private pumpsets.

Such an approach leads to the identification of the energy requirement of cooking, i.e., medium-temperature heating (95–250°C), as the first priority in rural energy planning. Unfortunately, this is one requirement which is totally ignored in virtually all current thinking—for example, rural electrification which is being promoted as the answer to rural energy problems does not envisage meeting cooking energy needs even in a remote future.

Once important urgent priorities are met, other items must move up the list. That is, the priority list must change with time. In such a dynamic perspective, end-uses relating to crop production, e.g., water lifting and mobile power for ploughing, to

Table 3. End-uses of energy in Pura
Inanimate and animal energy

	End-use	Input energy/year (kcal/10^6)	Efficiency*	Output energy/year (kcal × 10^6)
1.	Heating (95–250°C)	688·9	5	34·4
2.	Heating (~55°C)	112·4	5	5·6
3.	Heating (~800°C)	23·8	5	1·2
4.	Lighting	20·1	2·5	0·5
4.1.	Lighting (electrical)	(2·7)	10	(0·3)
4.2.	Lighting (kerosene)	(17·4)	1	(0·2)
5.	Mobile power	12·4	20	2·5
6.	Stationary power	7·0	80	5·6
6.1	Water lifting	(6·3)	80	(5·0)
6.2	Flour milling	(0·7)	80	(0·6)
	Total	864·6		49·8

*Estimates

Human energy

	Human activtiy	Human energy expenditure		
		Hours/year	Hours/day/ household	kcal year × 10^6
1.	Domestic	255,506	12·5	50·8
1.1	Livestock grazing	(117,534)	(5·7)	(23·4)
1.2	Cooking	(58,766)	(2·9)	(11·7)
1.3	Firewood gathering	(45,991)	(2·3)	(9·1)
1.4	Fetching water	(33,215)	(1·6)	6·6
2.	Agriculture	34,848	1·7	8·0
3.	Industry	20,730	1·0	5·0
	Total	311,084	15·2	63·8

post-harvest operations, and to village industries should quickly take high priority.

The second part of table 3 represents the end-uses of human energy in Pura. It is obvious that the inhabitants of Pura suffer burdens which have been largely eliminated in urban settings by the deployment of inanimate energy. For example, gathering firewood and fetching water can be eliminated by the supply of cooking fuel and water respectively. Thus, energy planning for Pura must scrutinise the expenditures of human energy to see whether they involve necessary employment, meaningful work or avoidable drudgery. This exercise will lead to important additional priorities in an energy plan for Pura. These priorities must include the supply of cooking fuel to Pura's homes, the provision of a convenient water supply, and the production of fodder and feed for livestock. Unfortunately, improvements in the quality of life through an alteration in the pattern of expenditure of human energy rarely form part of the agenda of rural energy planning. However, great caution must be exercised with regard to human energy in agriculture and industry to ensure that inanimate energy inputs do not aggravate the human condition, for example, by increasing total unemployment.

5. Pura's energy resources

Pura's energy resource position must next be examined. Pura, like most Indian villages, has no fossil fuel resources. Even if it had, the use of irreplaceable fossil fuels for energy is debatable. Pura's only internal energy sources are those arising directly, or indirectly, from photosynthesis. Though, in principle, all biomass can be harnessed for energy purposes (if necessary, after suitable processing), the materials which are immediately usable in Pura are firewood, crop wastes (e.g., rice husk) and animal wastes.

The present pattern of firewood usage is unsustainable for more than a few years—firewood is a rapidly dwindling resource. For firewood to become a dependable resource (instead of a liability), it must be harvested from efficiently managed ' energy forests ' where fast-growing trees are grown specifically for their firewood output. In such an alternative pattern of firewood usage, the resource position depends upon the particular species that are grown, and of course on the land made available for the energy forest. A yield of about 50 tonnes of dry wood per hectare per year can be assumed for species such as *Casuarina* or *Leucaena leucocephala* (Seshadri 1978). Thus, about 5 hectares will yield Pura's present firewood consumption of 217 tonnes per year. The firewood from an energy forest can either be used directly or after conversion to charcoal or methanol. Notwithstanding these attractive features, energy forests are associated with long gestation times of 3–5 years, and cannot therefore be part of an immediate solution.

In perhaps the same category is ethanol production which can be established in a few years. One hectare of land yields annually about 100 tonnes of sugarcane and therefore 4·4 tonnes of molasses from which about 870 litres of ethyl alcohol fuel can be obtained (Prasad *et al* 1979).

One important difference between fuel-wood forests and ethanol from sugarcane plantations is that the latter requires ' good ' agricultural land suitable for foodgrain production, in contrast to the former which can make do with non-arable land. Thus, the development of these two types of fuel resources must be part of an optimum land-use planning. In so far as the land under forest cover is far below the 30% declared as optimum, the development of energy forests should perhaps be preferred.

In contrast to the relatively long gestation times associated with the growth of energy forests and the development of ethanol production, animal wastes are a major resource which can be tapped within a year. The energy survey indicated that Pura's cattle population of 143 yields about 1·02 tonnes of wet dung per day from overnight droppings alone.* This minimum of 370 tonnes of wet dung per year is basically a cellulosic material which can be anaerobically fermented in a biogas plant to yield at

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*Based on weight measurements made in the houses at dawn.

least* 35 m^3 per day or 12,775 m^3 per year of biogas (60–70% CH_4 and 30–40% CO_2) with a calorific value of 5340–6230 kcal/m^3.

The two renewable energy inputs flowing into Pura spontaneously are solar and wind energy. Measurements of solar insolation at Pura have not been made, but the data from Bangalore indicates an average solar power of about 0·8 kW/m^2. Of course, the diffuse character of solar energy, and its restriction to about one-third of a day are well-known. Wind data have been obtained at the ASTRA Extension Centre, about 2 km from Pura. Though the average wind speed is about 15 km/hour, it can go as high as 30–40 km/hour for 1–2 hr intervals. But, there is a marked seasonality in the wind, with about 80% of the annual wind energy of about 6000 kWh/hectare being available in about four months of the year (Shrinivasa *et al* 1978).

Electricity and kerosene are both energy sources which are imported into Pura. At present, Pura consumes an average of 30 kWh/day of electricity. This low figure is primarily because the present demand is from the relatively rich of Pura who are very few in number—only 25% of the homes have electric lights and a mere 5% own irrigation pumpsets. But, even if this demand were to increase markedly, there are major difficulties in making the supply from the grid keep pace. Firstly, the growth of electricity generation has fallen far short of the rise of nation-wide demand, even though the rural share is less than 20%. Secondly, increasing the capacity of lines to villages implies increased transmission and distribution costs which are already above Rs. 3000/kW. These constraints on generation and transmission mean that grid electricity must be viewed as a *limited* resource even if the generation is from renewable sources, e.g., hydel generation.

The situation is quite similar with kerosene. 40% of the country's 3·4 million tonnes consumption in 1977-78 was imported from abroad, and domestic lighting accounts for almost 60% of the total consumption (Shah 1979). With jet aircraft being strong competitors for the supply, it is clear that Pura cannot count on imported kerosene as an energy resource for long, i.e., Pura must find a substitute for kerosene as rapidly as possible.

6. Selection of sources and technologies to meet Pura's energy needs

The fundamental problem of rural energy planning, and of the design of rural energy centres, can be stated thus: given the energy resources and requirements, what is the optimum way of harnessing i energy sources with the aid of j devices to achieve k energy-requiring tasks subject to l constraints? In other words, if ijk is designated as an *energy path* by which a source i is utilised with the aid of a device j to fulfil an energy task k, what is the optimum set of energy paths, and the optimum energy flow along each one of this set, to meet the energy needs with the available resources? An immediate solution is required to meet present needs, but it is also essential to anticipate change, and to develop solutions which cater to the contours of future needs.

A rigorous methodology for solving the fundamental problem posed above has yet to be developed. Pending such an achievement, a heuristic approach has been adopted for Pura's energy needs.

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*The figures are based on the performance of the unheated biogas plant at the Institute (Rajabapaiah *et al* 1979).

In the case of Pura, the energy-requiring tasks have been listed in table 3, from which it may be seen that $k = 6$, *viz.*, medium-temperature heating (95–250°C), low-temperature heating (~55°C), lighting (~2000°C), stationary power, mobile power and high-temperature heating (~800°C). The inanimate energy sources available in Pura now or in the very near future are: energy forests, ethanol, biogas, solar energy, wind energy, grid electricity and kerosene; i.e., $i = 7$. Despite the limited number of tasks and of sources, a very large number of energy paths can be considered while going from sources to tasks. Even excluding multiple paths between particular sources and particular tasks (e.g., biogas → mantle lamp, and biogas engine → generator → electric bulb), the number of conceivable paths can be as many as 42 in the Pura case.

In this context, guidance can be sought from the second law of thermodynamics, and in particular, the concept of second law efficiencies. This concept has been elaborately discussed in a report sponsored by the American Physical Society (Anon 1975), and therefore, only its important implications will be cited here:

(i) Every energy source must be associated with a grade or quality, which may be determined by its temperature or the temperature it can produce. Low temperature heat is the lowest grade (or quality) energy, electrical and mechanical energy (which correspond to infinite temperatures) are the highest quality energy, and chemical fuels (coal, oil, biogas) come in between.

(ii) The second law efficiency is the ratio of the actual useful work/heat transferred with a given source and device to the *maximum* possible work/heat transferable by *any* source and device for the same task. Thus, the second-law efficiency sets up an ideal or norm for a particular task k. It permits a screening of various energy paths ijk for the achievement of that task k, and the selection of the path with the highest second-law efficiency. Whereas the first-law efficiency, which is the ratio of the actual useful work/heat output of a given source and device in the performance of the task to the energy input, reveals how well the *given* source and device is performing, the second law efficiency shows which (of a number of alternative sources and devices) is the best source and device for achieving the task.

(iii) For a given task, it is the maximisation of second law efficiencies that determines the minimisation of fuel consumption in the case of consumable fuels, and of capital costs in the case of renewable sources.

(iv) The maximisation of second law efficiencies implies that sources and devices must be *matched* to the task. This matching is facilitated by two thumb-rules: (a) 'Do not use a higher quality source than the task deserves!', and (b) 'For the matched source, choose the device which transfers the most useful work/heat!'

Thus, second law efficiencies are a powerful heuristic for selecting the technically 'best' energy technologies (sources and devices) for the various tasks that need to be performed. Unfortunately, the values of second-law efficiencies have not been tabulated for all paths ijk to various tasks k. In the case of paths for which second-law efficiencies are not available, a programme of determining them must be launched.† Pending the establishment of a complete table of second-law efficiencies, the thumb rules can be used.

Table 4. Selection of sources and devices for Pura.

task	alternatives	
	sources	devices
(1) medium-temperature heating	$\boxed{\text{biogas}}$	$\boxed{\text{gas burner}}$
	energy forests	wood/charcoal stoves
(2) low-temperature heating	waste heat	wood/charcoal stoves
	solar	solar water-heater/solar dryer
(3) lighting	$\boxed{\text{electricity}}$	$\boxed{\text{incandescent lamps}\ \text{fluorescent tubes}}$
(4) stationary power	draught animals	animal-powered devices
	human labour	pedal-powered devices
	wind	wind mills
	$\boxed{\text{biogas}}$	$\boxed{\text{biogas engine}}$
	energy forests	producer-gas engine
	ethanol	internal combustion engine
	electricity	electric motor
(5) mobile power	draught animals	animal-powered devices
	human labour	pedal-powered devices
	ethanol	internal combustion engine
	energy forests	producer-gas engine
	$\boxed{\text{biogas}}$	$\boxed{\text{biogas engine}}$
(6) high-temperature heating	biogas	furnace
	charcoal	furnace

* The sources and devices within boxes correspond to those proposed for phase I of rural energy centre for Pura.

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†For example, it can be shown that the second law efficiency for raising water from room temperature up to boiling point (a process which accounts for about two-thirds of Pura's energy requirement for cooking rice) by burning biogas fuel is double the second-law efficiency when an electrical immersion heater is used. This factor of 2 is for *thermally* produced electricity.

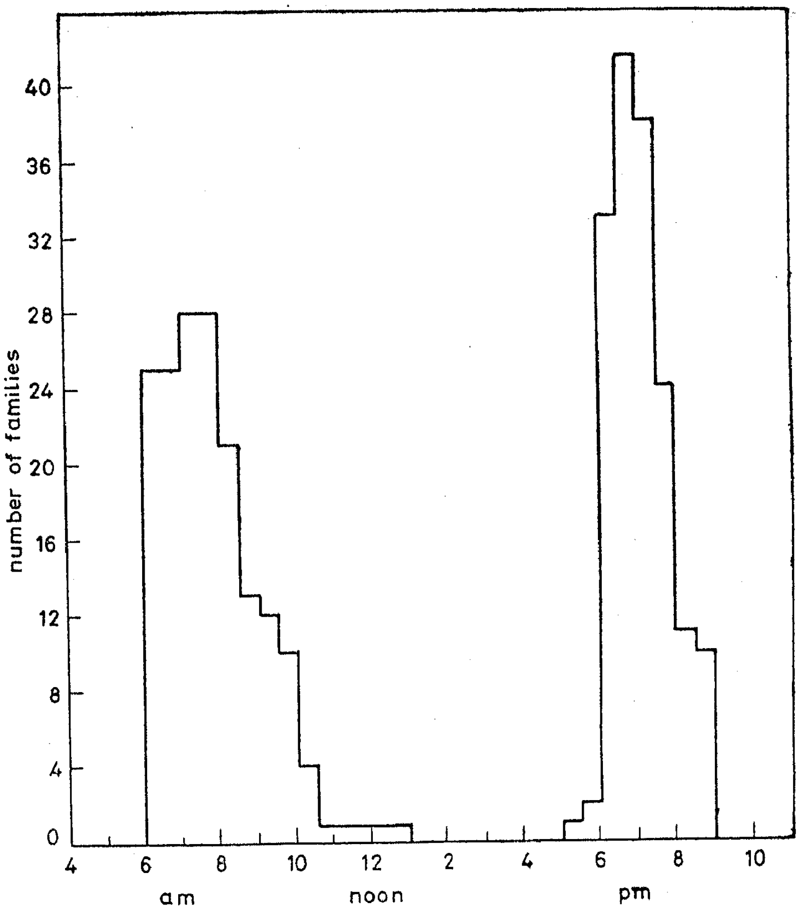

Figure 1. Cooking hours in Pura

The use of the thumb rules leads in the case of Pura to the selection of a very limited set of energy paths, i.e., sources and devices to achieve the tasks corresponding to the energy needs of Pura (table 4).

To restrict the alternatives further, additional constraints must be imposed.

The first additional constraint is the necessity of matching the time-dependence of the energy-utilising task (the load curve for the task) with the time-variation, if any, of the supply of energy from the chosen source. If energy from this source is not available when it is needed, then storage of energy becomes imperative. But, storage implies a new path $ij'k$ different from ijk in the absence of storage, and therefore a new second-law efficiency which may not be as high.

Cooking with solar energy is an excellent illustration of the point under discussion. Figure 1 shows clearly that Pura families cook during those hours when the sun is not shining strongly. Hence, for solar cookers to be useful, either these families must change their cooking hours, and therefore living patterns, or solar energy must be stored. The former option may result in women losing employment, and the latter requires expensive storage systems.

Wind energy must also be examined from the point of view of whether the water-lifting needs of agriculture occur during the months of May to September when the winds are strongest. Superficial observation indicates that the maximum water-lifting needs are during these pre-monsoon windy months, but much more in-depth study is required of both cropping and wind patterns.

The second additional constraint concerns the development criterion of self-reliance. Imports of energy into the village can be ruled out in the first iteration, and permitted only when it is found that internal energy sources and those coming into the system 'free' (solar, wind, flowing water) cannot meet the energy needs. In other words, local resources must be chosen, unless they are inadequate to satisfy the needs.

The third additional constraint arises from the development criterion of environmental soundness. To sustain development over the long run, renewable sources of energy must be chosen. Hence, depletable sources (fossil fuels) must be excluded.

The fourth additional constraint is that of *power*. This constraint becomes relevant whenever a task k must be completed within a certain time t_k, e.g., ploughing or harvesting or grain drying. Then, if the task requires the expenditure of energy E_k, its power requirement is $P_k = E_k/t_k$. This means that all paths involving sources i and devices j which deliver *less* power than is required for the task, i.e., $P_{ijk} < P_k$, are unacceptable; only those which satisfy the condition* $P_{ijk} \geqslant P_k$, can fulfil the task**.

The fifth additional constraint is that of availability of the technologies. Some energy paths (sources and devices for tasks) may be very attractive, but unavailable right now. Hence, immediate choices must be tentative, and when attractive options appear 'on the shelf', they can be incorporated into the solution later.

The additional constraints described above narrow down the choice drastically. In the case of Pura***, the choice gets restricted to: (i) biogas and biogas burners for medium-temperature heating, (ii) electricity and incandescent lamps (or fluorescent tubes) for lighting, (iii) wind (whenever available) and windmills for stationary power (particularly water-lifting), (iv) biogas and biogas engines for stationary power (including water-lifting at sites close to biogas plant). In the case of low-temperature heating, mobile power, high-temperature heating and water-lifting for agriculture at sites which are not convenient either for wind or biogas energy, further technology development and/or analysis is required before definite choices are made to replace or supplement currently used sources and devices.

With regard to those energy-utilising tasks in Pura which now involve expenditures of human energy (table 3), gathering firewood and fetching water are directly related to cooking fuel and water supply respectively. Hence, by meeting the energy needs of medium-temperature heating and stationary power for domestic water-lifting, the expenditure of human energy on gathering firewood and fetching water can be wholly or partly reduced. The activity of free grazing of livestock is associated with the problem of fodder which must be solved in association with the fuel problem through two-tier *fodder-cum-fuel* forests. The question of human energy in agriculture and industry is part of the larger issue of employment generation and productivity increase and involves major socio-economic considerations which will not be dealt with here.

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*In fact, P_k may be a range of values. Further, the choice may not be a yes-no matter, and if $P_{ijk} < P_k$, the path ijk may still be used, but penalties will be paid, e.g., by way of decreased efficiency or output.

**This distinction between energy and power is often completely ignored in discussions on animal energy.

***Detailed consideration of the choice of technologies for each of the energy-utilising tasks in Pura is contained in a report of the Karnataka State Council for Science and Technology (Reddy *et al* 1979).

7. A rural energy centre for Pura

Notwithstanding the technical attractiveness of establishing a complete rural energy centre as a ' one-shot affair ', there is an important sociological reason why technological innovations must be introduced a few at a time and not all at once. Each innovation constitutes a perturbation imposed upon the village system which is forced to go into a transient response before settling down to a new state of equilibrium. It is the finite relaxation time of the village system which demands that new innovations be introduced only after the system has recovered from the previous ones. In other words, because the technology sub-system must fit into the larger socio-economic and cultural system of the village, it follows that a rural energy centre must *grow* in a phased manner; it must not be externally imposed as one massive perturbation which throws the village system into an instability from which it can save itself only by rejecting altogether the technological ' fix '. The phased growth of a rural energy centre also facilitates the mid-phase and inter-phase modifications of total system design which are certain to become necessary because of inadequate *a priori* understanding of villages and/or complex energy systems.

With this perspective, a community biogas system is envisaged as Phase I of the proposed rural energy centre for Pura. Biogas has been the first choice because it addresses itself to the first priority energy task in Pura, *viz.*, medium-temperature heating (95–250°C) for cooking. Further, individual family-size plants have been rejected for three reasons: (a) Only about 71% of Pura's families own cattle and therefore have the raw material for biogas plants. (2) Even if all the families have cattle, only a few can afford biogas plants—roughly the same number (i.e., three) as now own pumpsets, because family-size biogas plants are about 60–80% of the cost of pumpsets. (3) Biogas plants show clear-cut economies of scale—a community-size plant for 56 families is only 6·3 times the cost of a plant for one family.

The utilisation of the output of the community biogas plant is shown in figure 2. The design of the system has been guided by the fact that, even assuming a minimum yield of 0·034 m^3/kg fresh dung, a 42·5 m^3/day plant can provide a *surplus* of 11 m^3/day of biogas after meeting all the cooking energy needs of all the households in Pura. This means that the surplus gas must be utilised to yield economic returns which can completely subsidise the ' free supply ' of non-metered piped biogas to all the houses between fixed hours determined from present cooking patterns (figure 1).

It is proposed that the excess gas will be used to run a 5 HP biogas engine, and that the 5⅓ hr engine time will (a) pump the daily water requirements of the biogas plant, and thereafter, the domestic needs of the village—20 min; (b) drive a generator to supply electricity between fixed hours—3 hr/day—to illuminate the non-electrified houses*; (c) provide motive power for a ball mill to grind for 2 hr/day rice husk ash (a waste product) and lime and produce saleable cement.

In addition, the plant will yield every day 1960 kg of liquid slurry which dries out with a nitrogen content of 1·9% which is double the nitrogen content of fresh dung dried in the open air.

Thus, in the first phase, it is proposed to: (a) pipe cooking fuel to all the homes in Pura, (b) provide electric lighting to the presently non-electrified homes and (c) pump

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*This electricity will be charged for at the usual electricity board rates. Despite this, the households will have to spend only about 60% of what they now spend on kerosene lamps.

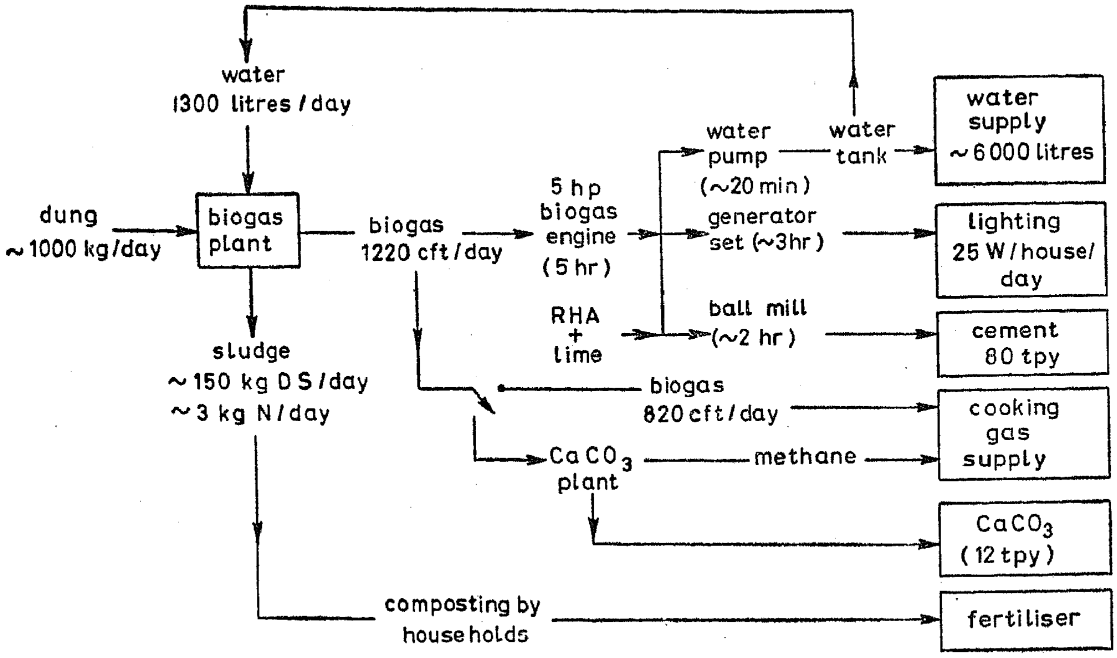

Figure 2. Community plant for Pura village

the domestic water requirements of the village to an overhead storage tank. In this process, the drudgery of firewood gathering for cooking fuel needs will be eliminated completely, and that of obtaining water will be alleviated.

The feasibility report (Reddy *et al* 1979) discusses in detail the commercial viability and social costs and benefits of this first phase of the rural energy centre for Pura. In brief, the capital cost of the entire Phase I system, i.e., biogas plant, gas distribution, biogas engine, generator, electricity distribution, pumpset, overhead water storage tank, ball mill for cement production, building and miscellaneous items, will be about Rs. 70,000. On this investment, the revenues on electricity and cement are envisaged to bring a return of 22% corresponding to an undiscounted pay-back period of 4·5 years.

The subsequent phases of the rural energy centre for Pura are being considered. Phase II may attempt to meet the total energy needs for low-temperature heating (of water for bathing) and partial needs of water lifting with windmills. In addition, the initiation of an energy forest will be considered. Phase III will seek to address itself to motive power needs perhaps through biogas, producer-gas and/or ethanol engines. However, far more analysis and hardware development is necessary before the designs of the subsequent phases are ‘ frozen ’.

8. Integration of sources and devices into a system

The heuristic design of a rural energy centre for Pura has revealed a few general principles for the integration of energy sources and devices into a system for achieving the required tasks. Since such principles have not been stated hitherto, a brief attempt is made here to indicate them.

The maximisation of second-law efficiencies requires the deployment of low-grade energy sources for low-grade tasks, and high-grade sources for high-grade tasks. So, as long as there are several grades of tasks to be performed, it follows that energy sources of different grades should be used. Hence, system integration must involve the *principle of mixing sources to match tasks*—in general*, an optimised rural energy system should be based on a *mix* of energy sources *i*, where the *i*s refer to the sources energising the set of devices that accomplish the required tasks. These sources *i* may be *primary* in the sense that they are inputs to the system (e.g., solar or wind energy), or they may be *intermediate* sources which are produced inside the system from primary sources (e.g., electricity from wind energy) or from other intermediate sources (e.g., exhaust heat from an engine driven by producer gas obtained from firewood).

One possibility is a mix in which all the energy sources *i* are primary sources. If, in addition, all the devices are of the single-source single-task category, then the result is a system with virtually no element of integration. The system is simply a juxtaposition of separate sources, devices and tasks. Such a system can be represented by the network in figure 3a, from which it can be seen that the paths from sources through devices to tasks are quite separate and unconnected.

But, there are other possibilities. For instance, during the course of performing a task, a device can produce as ' waste ' a lower grade of energy than that which drives the device. The use of this waste energy to drive another device which performs a lower-grade task (figure 3b) illustrates *the principle of cascading*, according to which, ' as energy passes from a high-quality form to its impotent final form as ambient-temperature heat ' (Anon 1975), it performs a series of tasks of lower and lower grade. For example, one can think of a series of heat engines each one running on the waste heat from the previous one. A common example is where the waste heat from an engine is used to carry out a heating task, e.g., heating water.

Another approach to integration involves *the principle of combining energy sources* according to which two or more energy sources act in conjunction to perform a task (figure 3c). Thus, two energy sources can supplement each other's contribution in heating a fluid, e.g., solar pre-heated water can be used for cooking rice with biogas fuel. The merit of this principle of integration is that the higher grade energy only needs to complete the task which is partially accomplished by the lower grade energy.

The two principles of cascading and of combining energy sources can be used simultaneously. This requires the ' waste ' energy from one device, i.e., an intermediate source, being used to supplement the efforts of another energy source in another device, or even the same device (figure 3d). For example, exhaust heat from an engine can be used as a supplementary heat source along with a fuel; or the waste heat from a sugar-cane juice evaporator using bagasse fuel can be used to pre-heat the juice.

Instead of introducing integration at the source-end of devices, the integration can also be carried at the task-end.

This *principle of spatial task integration* is displayed by hybrid devices which perform more than one task (figure 3e). For example, when the roof of a biogas plant gas holder is made to serve as the absorber of a solar water-heater, the result is a hybrid multi-task device, *viz.*, biogas plant-cum-solar water-heater. In fact, the integral nature of the design can be extended one step further by providing a slope to the transparent greenhouse roof of the solar water heater ' riding piggy-back ' on the

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*The special case is the rare type of system which has only one task to perform,

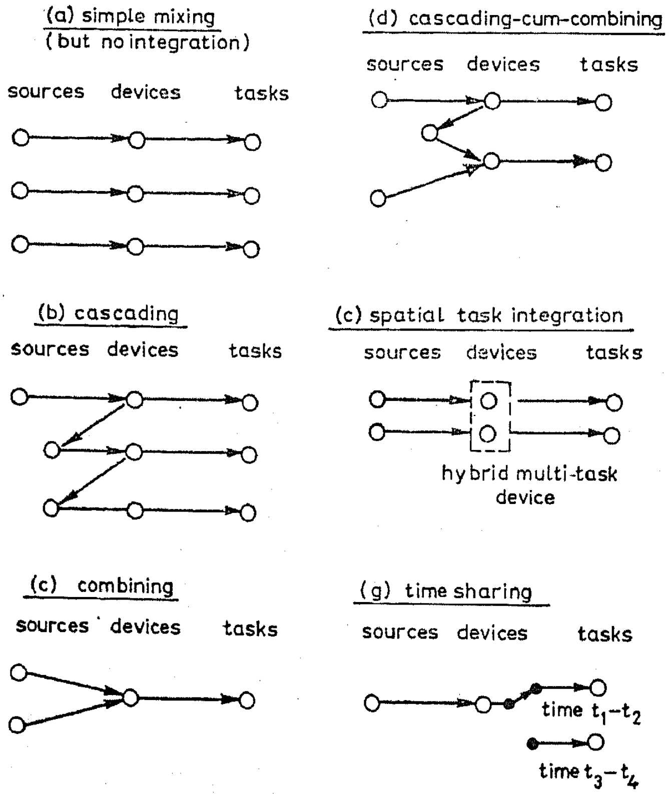

Figure 3. Principles of integration

biogas plant and by collecting the solar-distilled water from a gutter built into the side of solar water-heater (Reddy *et al* 1979).

Spatial integration of tasks in hybrid devices is not the only possibility; the *principle of time-sharing of devices* also represents a form of integration (figure 3f). For example, an engine or motor can be shared between tasks which required to be performed at different times, or a supply pipeline can be time-shared between biogas for cooking and water for domestic consumption (Reddy 1976).

These principles of assembling sources and devices into an energy system may prove useful in preventing current attempts to impose upon the village scene packages of hardware items which are not really integrated in the sense described above. The caution is against juxtaposing gadgets which have not been specifically designed for integration into the system, but instead the gadgets have a system deliberately designed for their promotion (Anon 1979). Another caution is against systems which convert all the primary sources into electricity which is then used to perform the required tasks. This all-electric type of rural energy system violates the principle of a mix of sources to match tasks, and the penalty for this disregard of second-law efficiencies is in the form of extremely high capital costs for the system (Anon 1976).

9. Towards a mathematical approach to rural energy centres

The case study of Pura has been used as an illustrative exercise to reveal the nature and complexity of the problem of rural energy centres and to indicate a heuristic approach. Like all villages, Pura is both unique and typical. Along with 60% of

India's villages, it has a population of under 500. Like a large part of India, Pura is in a dry and backward area, and shows little impact of modernisation. Another typical feature of Pura is its human-to-cattle ratio of 2:3 which is not very different from the all-India average of 2. But, the energy problem of Pura is bound to be fundamentally different from the problems of a village in the cold mountains, windy coasts, forests or deserts.

To handle this variety of villages, and therefore of rural energy problems, it would be advantageous to develop a mathematical approach to rural energy systems. Towards this end, a preliminary attempt at a mathematical formulation of the problem of rural energy centres is indicated below.

As stated earlier, the fundamental problem of designing a rural energy centre for a particular village is to find the optimum way of using its m accessible sources in n possible devices to perform the p tasks corresponding to its energy needs.

The first constraint is that the total energy supplied by the sources should be equal to the requirements of the tasks. Defining A_k as the total energy requirement (e.g., in kcal) of the kth task and A_{ijk} as the quantity of energy obtained when source i is used *via* device j to perform this kth task, the condition is that

$$A_k = \sum_{i=1}^{m} \sum_{j=1}^{n} A_{ijk} = \sum_{i=1}^{m} \sum_{j=1}^{n} r_i \, \eta_{ijk} \, x_{ijk}, \tag{1}$$

$$k = 1, 2, \ldots, p,$$

where r_i is the energy equivalent (e.g., kcal/kg, kcal/m^3, etc.) of the source i, η_{ijk} is the first law efficiency* for the path ijk defining the ratio of the energy output to the energy input, and x_{ijk} the quantity (in kg, m^3, etc.) of resource i used *via* device j for task k.

The second constraint is that there is an upper limit for all local energy sources. Defining R_i as the maximum energy *locally* available per annum from the ith energy source ($i = 1, 2, \ldots m'$, where the m' local energy sources are a sub-set of the set m of all energy sources), the condition is that

$$R_i \geqslant \sum_{j=1}^{n} \sum_{k=1}^{p} r_i \, x_{ijk} \geqslant r_i \sum_{j=1}^{n} \sum_{k=1}^{p} x_{ijk}, \tag{2}$$

$$i = 1, 2, \ldots m'.$$

The third constraint is that some tasks have definite power requirements, i.e., they demand that the requisite energy be supplied within a certain time. If P_k is the maximum power required by the *individual* user of a device performing the kth task and P_{ijk} is the maximum power available for this task from a source i *via* device j, the condition can be written thus:

$$x_{ijk} = 0 \text{ if } P_{ijk} < P_k. \tag{3}$$

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*η_{ijk} is assumed here to be independent of x_{ijk}, i.e. there are no efficiencies of scale. This assumpion is reasonable if (a) devices are used whose number is proportional to the energy input (e.g., one device per household), and (b) the scale of devices used in villages is in a range within which the efficiency is almost constant.

Thus, the power condition can be used *a priori* to eliminate those source-device combinations which cannot yield adequate power for the task. In case there is a possibility of combining sources in devices, the above condition must be written for the combined power of the sources, i.e.,

$$x_{ijk} = 0 \text{ if } \sum_i P_{ijk} < P_k. \tag{4}$$

It is also essential that the sum of the power *outputs* of the *i*th energy source through all the paths *ijk* should not exceed the maximum power $P_i^{\max}$ which this source can develop, i.e., the condition is

$$P_i^{\max} \geqslant \sum_{j=1}^{n} \sum_{k=1}^{p} P_{ijk} \text{ (output)}. \tag{5}$$

But P_{ijk} is the contribution of the power *output* from the *i*th source *via* the *j*th device to the total power required by the *k*th task; hence

$$P_{ijk} \text{ (output)} = (A_{ijk}/A_k)\, P_k = (r_i\, \eta_{ijk}\, x_{ijk}/A_k)\, P_k. \tag{6}$$

The corresponding power *input* from the *i*th source must reckon with the efficiency η_{ijk} of power conversion*, i.e.,

$$P_{ijk} \text{ (input)} = (r_i\, \eta_{ijk}\, x_{ijk}/A_k)\, (P_k)\, (1/\eta_{ijk}). \tag{7}$$

Hence, the total power *input* required of the *i*th source is

$$P_i \text{ (input)} = r_i \sum_{k=1}^{p} (P_k/A_k) \sum_{j=1}^{n} x_{ijk}. \tag{8}$$

If there is a possibility of the loads corresponding to the various tasks occurring at different times, it is also necessary to introduce a diversity factor for each source:

$$d_i = \frac{\text{sum of individual maximum loads at a given time}}{\text{total maximum load}}. \tag{9}$$

Hence, the condition is

$$P_i^{\max} \geqslant (r_i/d_i) \sum_{k=1}^{p} (P_k/A_k) \sum_{j=1}^{n} x_{ijk}. \tag{10}$$

The design of the rural energy centre can be based on several objectives. The obvious one is minimisation of the total annual cost *C* of the rural energy centre. If *C* (cap) and *C* (op) are the annual charges arising from the capital investment and

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*If the averages of output and input power are considered, η_{ijk} is both the power efficiency as well as the energy efficiency.

operational requirements respectively, then the objective function which has to be minimised is

$$C = C\,(\text{cap}) + C\,(\text{op}). \tag{11}$$

As a first approximation†, the annual costs arising from the capital investment and operational charges for source i can both be assumed to be proportional to the quantity of source i which is utilised, i.e.,

$$C\,(\text{cap}) = \sum_{i=1}^{m} C_i\,(\text{cap}) = \sum_i \sum_j \sum_k a_{ijk}\, x_{ijk}, \tag{12}$$

and

$$C\,(\text{op}) = \sum_{i=1}^{m} C_i\,(\text{op}) = \sum_i \sum_j \sum_k b_{ijk}\, x_{ijk}, \tag{13}$$

where the constants of proportionality, a_{ijk} and b_{ijk}, represent the annual capital charges and operational costs respectively per unit quantity of source i used *via* device j to accomplish task k.

The constants implicitly involve second-law efficiencies, but this feature can be brought out explicitly since it can be shown that

$$a_{ijk} = \frac{\theta_i\,(\text{cap})\, u_{i^*j^*}\,(\text{cap})}{\eta_{i^*j^*k}\ \epsilon_k\ \eta_{ijk}} \quad \text{and} \quad b_{ijk} = \frac{\theta_i\,(\text{op})\, u_{i^*j^*}\,(\text{op})}{\eta_{i^*j^*k}\ \epsilon_k\ \eta_{ijk}}, \tag{14}$$

$$a_{ijk} = (a'_{ijk}/\epsilon_k) \text{ and } b_{ijk} = (b'_{ijk}/\epsilon_k), \tag{15}$$

where the θs represent the ratio of the costs of using the sources and devices i and j to the costs of using the ideal source and device i^* and j^*, the $u_{i^*j^*}$s, the costs of using the ideal source and device i^* and j^* per unit quantity of source used, the ηs are the first-law efficiencies and ϵ_k the second-law efficiency for the kth task.

The preference for local, renewable sources can be introduced by using multipliers thus: $\alpha_i \geqslant 1$ for non-local sources and $\beta_i \geqslant 1$ for non-renewable sources. That is,

$$C\,(\text{cap}) = \sum_{i=1}^{m} \alpha_i\, \beta_i \sum_{j=1}^{n} \sum_{k=1}^{p} a_{ijk}\, x_{ijk}. \tag{16}$$

The fundamental problem of rural energy system design can now be stated††:

Minimise C where

$$C = \sum_{i=1}^{m} \alpha_i\, \beta_i \sum_{j=1}^{n} \sum_{k=1}^{p} \frac{a'_{ijk}}{\epsilon_k}\, x_{ijk} + \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=1}^{p} \frac{b'_{ijk}}{\epsilon_k}\, x_{ijk}. \tag{17}$$

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†The approximation is completely valid when the annual capital and operational costs arise from devices whose number is proportional to the quantity of energy source used, e.g., when there is one device per family. It is also valid when the scale of devices used in villages is in a range within which there are hardly any economies.

††Other formulations of the problem are also being considered, e.g., maximising task satisfaction subject to limitations on the availability of energy sources.

Subject to the following conditions:

$$\text{(i)} \quad \sum_{i=1}^{m} r_i \sum_{j=1}^{n} \eta_{ijk}\, x_{ijk} = A_k \qquad \text{(needs satisfaction),} \qquad (1)$$

$$k = 1, 2, \ldots, \text{p},$$

$$\text{(ii)} \quad r_i \sum_{j=1}^{n} \sum_{k=1}^{p} x_{ijk} \leqslant R_i \qquad \text{(resource availability),} \qquad (2)$$

$$i = 1, 2, \ldots, m' \leqslant m,$$

$$\text{(iii)} \quad \frac{r_i}{d_i} \sum_{k=1}^{p} \frac{P_k}{A_k} \sum_{j=1}^{n} x_{ijk} \leqslant P_i^{\max} \quad \text{(total power availability),} \; (10)$$

$$\text{(iv)} \quad x_{ijk} \geqslant 0 \text{ for all } i, j \text{ and } k. \qquad (18)$$

The following set of conditions:

$$x_{ijk} = 0 \text{ if } P_{ijk} < P_k \text{ (power availability for individual devices),} \qquad (19\text{a})$$

$$\eta_{ijk} = 0 \text{ if periods of source supply and demand do not overlap,} \qquad (20\text{a})$$

can be introduced into the problem as an *a priori* check and by setting the values of the corresponding x_{ijk}'s and η_{ijk}'s equal to zero. Or, the objective function can be modified by adding multipliers γ_{ik} and δ_{ik}

$$\gamma_{ik} = 1 \quad \text{if } P_{ijk} \geqslant P_k,$$

$$\gg 1 \quad \text{if } P_{ijk} < P_k, \qquad (19\text{b})$$

and

$$\delta_{ik} = 1 \text{ if periods of source supply and task demand overlap,}$$

$$\delta_{ik} \gg 1 \text{ if supply and demand periods do not overlap.} \qquad (20\text{b})$$

The above approximation of the general problem has a linear objective function (costs) and linear constraints. Further, the variables are non-negative. Hence, it is a linear programming problem* which can be solved by simplex or revised simplex procedures. It is in fact a three-dimensional transportation problem.

Despite the reduction in complexity in the 'linear' version of the general problem, a solution is possible only after a large amount of data is available. The merit of the mathematical formulation of the problem presented here is that it has identified what information is required for the optimal design of rural energy systems or centres.

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*If, however, there are marked economies and efficiencies of scale even for the scales of devices reasonable for villages, then the linear approximations are no longer valid, and the problem becomes a non-linear programming exercise.

It has highlighted the importance of quantifying, with respect to magnitude and time, the energy requirements of all the tasks and the availability of energy sources—all these are region-specific and location-specific. It has also emphasised the importance of data on the first-law efficiencies of all feasible devices, the second-law efficiencies of all tasks, the unit costs of source utilisation, and the power requirements of various tasks—these are technology-specific and cost-specific.

10. Acceptability of rural energy centres

However technically perfect the design of a rural energy centre may be, there is no guarantee that the system is consistent with development objectives. To ensure this consistency, additional criteria must be used, e.g., whether the rural energy centre satisfies the energy component of basic needs, particularly the needs of the neediest, and fulfils the desire for local self-reliance. The problem of assessing designs for rural energy systems from the standpoint of the wider social perspective is far more complex, and the methodologies are in the embryonic stage (Reddy 1979). But, these are matters which go beyond the scope of this paper.

Nevertheless, one conclusion is clear: for a ‘ technological solution ’ to be accepted into the matrix of society, it has to satisfy vital non-technical social criteria. Rural energy systems, therefore, must be society-specific and culture-specific. There cannot be standardised designs and packages for universal application. Rural energy centres cannot be mass-produced.

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References

Anon 1975 *Efficient use of energy: a physics perspective* (American Physical Society, USA)

Anon 1976 *An energy centre in Sri Lanka*, UN Environmental Programme, Report No. ER-76-R-8 of the Engg. Energy Laboratory, Oklahoma State University, USA

Anon 1979 *Rural energy project* (Messerschmitt-Bolkow-Blohm GMBH/BRD in co-operation with Bharat Heavy Electricals Limited, India)

Eckholm E 1976 *Losing ground: environmental stress and world food prospects* (New York: Norton)

Makhijani A 1976 *Energy for the rural third world* (London: Int. Inst. for Environment and Development)

Prasad C R, Bhat Kisan & Bhat A G 1979 *Prospect for ethanol as automobile fuel in India* (Bangalore: Int. Conf. on Energy and Environment for Developing Countries, Indian Institute of Management)

Prasad C R, Krishna Prasad K & Reddy A K N 1974 *Econ. Pol. Weekly* **9** 1347

Rajabapaiah, P Ramanayya K V, Mohan S R & Reddy A K N 1979 *Proc. Indian Acad. Sci.* **C 2** 357

Ravindranath N H, Somashekar H I, Ramesh R, Reddy A, Venkatram K & Reddy A K N 1979 (under preparation)

Reddy A K N 1976 *Ceres* **9** 43

Reddy A K N 1978 *Bull. At. Sci.* **34** 28

Reddy A K N 1979a in *Contributions of science and technology to national development* (Delhi: Indian National Science Academy)

Reddy A K N 1979b *Technology, development and the environment: a re-appraisal* (Nairobi: U.N. Environment Programme)

Reddy A K N & Krishna Prasad K 1977 *Econ. Pol. Weekly* **12** 465

Reddy A K N, Rajaraman Indira Subramanian D K & Rajabapaiah P 1979 *A community biogas plant system for Pura village—a feasibility study and proposal* (Bangalore: Karnataka State Council for Science and Technology)

Reddy A K N, Prasad C R, Rajabapaiah P & Sathyanarayan S R C 1979 *Proc. Indian Acad. Sci.* **C2** 387

Revelle R 1976 *Science* **192** 969

Rudolph L I & Lenth C S 1978 *Bull. At. Sci.* **34** 6

Seshadri C V, Venkataramani G & Vasanth V 1978 *Energy plantations—a case study for the Coromandel littoral* (Madras: A M M Murugappa Chettiar Res. Centre)

Shah N 1979 *Power, coal and oil: review of* 1978-79 *and prospects* (Bombay: Centre for Monitoring Indian Economy)

Shrinivasa U, Narasimha R & Govinda Raju S P 1978 *The prospects for exploiting wind energy in Karnataka State* (Report 78 FM 8) (Bangalore: Indian Institute of Science, Department of Aero. Engg.)

ERRATUM

Paper entitled "High resolution and high-voltage electron microscopy at the University of California, Berkeley" by G. Thomas and K. H. Westmacott, Vol. C2, Part 2, May 1979, pp. 263-285.

The running titles on pages 265, 267, 269, 271, 273, 275, 277, 279, 281, 283 and 285 should read

Electron microscopy work at University of California

and not

Electron microscopy work at Caltech