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DECENTRALIZED ENERGY PLANNING MODEL FOR A TYPICAL VILLAGE IN INDIA

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Abstract—A simple linear model has been developed to minimize the cost function for an energy-supply system consisting of a mix of energy sources and conversion devices. The model has been applied to a typical village in India for both the domestic and irrigation sectors. The energy-demand assessment was made with an energy audit. The results of the study show that wood and agricultural residues are preferred energy sources for cooking in the domestic sector when stoves with 18 or 16% efficiencies are used. Biogas becomes economically feasible only for plants holding 8 m^3. Electricity is the best option for lighting. For irrigation, diesel-powered pumps are preferred to electric pumps. Biogas is economical for lighting only when the biogas-conversion efficiency in the mantle is taken to be twice the 2% that is presently available.

INTRODUCTION

Developing countries face dwindling supplies or growth rates for both commercial and traditional forms of energy. In rural areas, availability of almost cost-free sources has led to efforts for higher efficiency.[1] Locally available alternative energy sources must be examined together with traditional fuels to obtain an optimal mix.[2]

A large number of models based on cost factors have been developed for planning strategy. Some of these models refer to rural needs; thus, a model has been developed for integrated crop production, biogas production, rural forest, and agro-based industries but does not include the domestic sector.[3] A case study of Ref. 4 incorporates only cooking and involves income distribution for the villagers. In the integrated planning and implementation strategy of Ref. 5, the agricultural sector is included in the model but irrigation, which is a primary activity in this sector, is left out. A generalized model, based on a linear cost function, has been developed by the authors for optimizing the energy supply for the domestic sector of villages of Nepal with cooking, lighting, and space heating activities incorporated.[6] In the present paper, an attempt is made towards the development of a similar linear programming model for an Indian village in which the domestic and irrigation sectors are taken together. Constraints on certain activities are imposed so that demands are met within the available resources. A provision has also been made for various technological options, e.g., improved cookstoves, biogas for cooking and lighting, solar cookers, diesel pumps operating in the dual-fuel mode and using biogas or biomass, PV lighting, PV pumps for irrigation, etc.

In order to obtain an assessment of energy demand, an audit was conducted. In preparing the questionnaire, provisions were made for consideration of the structure of the society based on caste, creed, earnings, and occupation. These parameters influence the energy-consumption pattern for various activities. For the resource assessment, data were collected on number and types of animals, number of trees, land holding, and cropping pattern for calculations of the biogas and biomass resources and these were then converted into energy units by using appropriate expressions.

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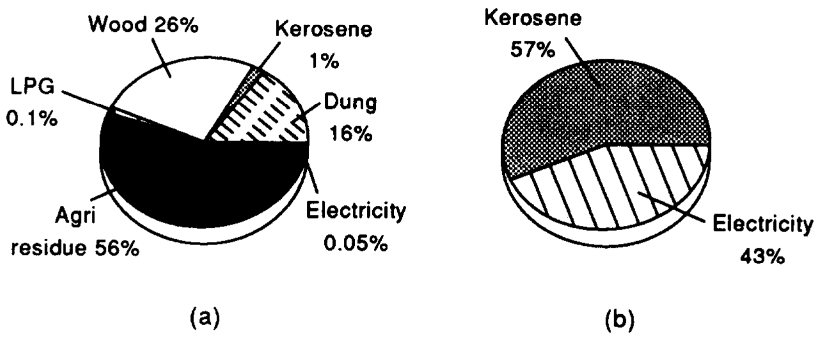

Fig. 1. Primary energy consumption patterns for the village Naunbasta for cooking (a) and lighting (b).

Description of the village

The study was undertaken close to Lucknow, a city about 500 km south-east of Delhi. The village chosen is typical for the central climatic zone which predominates in India.[7] Demographic and socioeconomic features of the Naunbasta village are given in Table 1.† The survey was carried out for 92 households (hhs). The shares of the various fuels used for the three end-use activities are shown in Figs. 1 and 2.

MODELING TECHNIQUE

The objective function in the model is minimization of the total annual cost of the energy output from various technologies, expressed as

$$C = \sum C_{\mathrm{stu}} x_{\mathrm{stu}}$$

and subject to demand constraints for various end-uses

$$\sum x_{\mathrm{stu}} = D_{\mathrm{u}}.$$

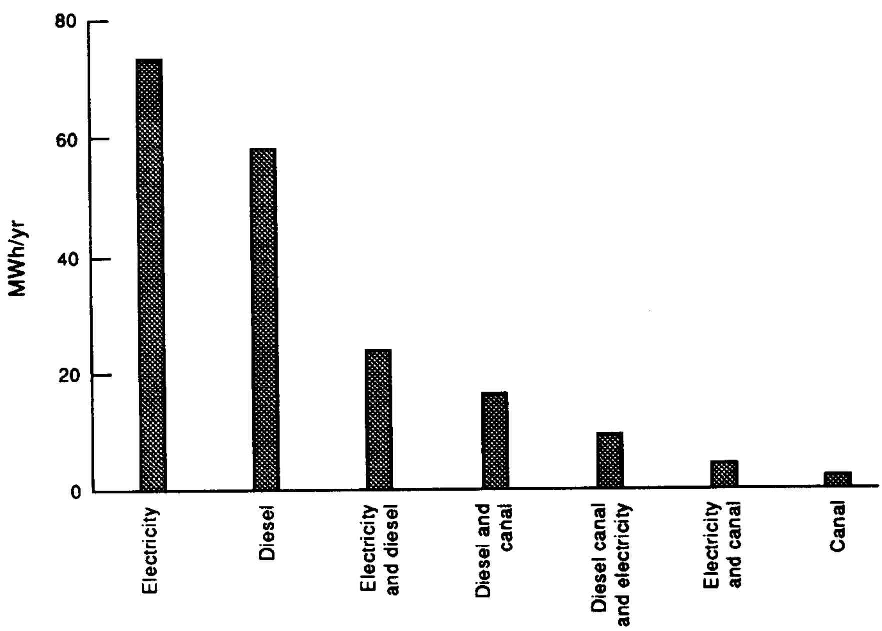

Fig. 2. Irrigation pattern for the village Naunbasta.

†The table may be obtained on request from the authors.

The supply constraints for various sources are

$$\sum (x_{stu}/n_{stu}) \leqslant S_s, \qquad x_{stu} \geqslant 0,$$

where the suffix s denotes the energy source (fuelwood, kerosene, etc.), t refers to the end-use device (cookstove, irrigation pumps) and u represents an end-use activity. C is the unit cost of useful energy conversion in Rs/KWh, which needs to be minimized; x is the energy source in kWh; n denotes the device efficiency; D is the useful energy demand and S the available energy source (both in kWh). A conceptual model for possible energy flows for cooking, lighting, and irrigation is given in Fig. 3.

Primary energy-resource assessment

The main forms of rural energy that are being quantified in the present studies are fuelwood, agricultural residue, animal dung or biogas, and solar energy.

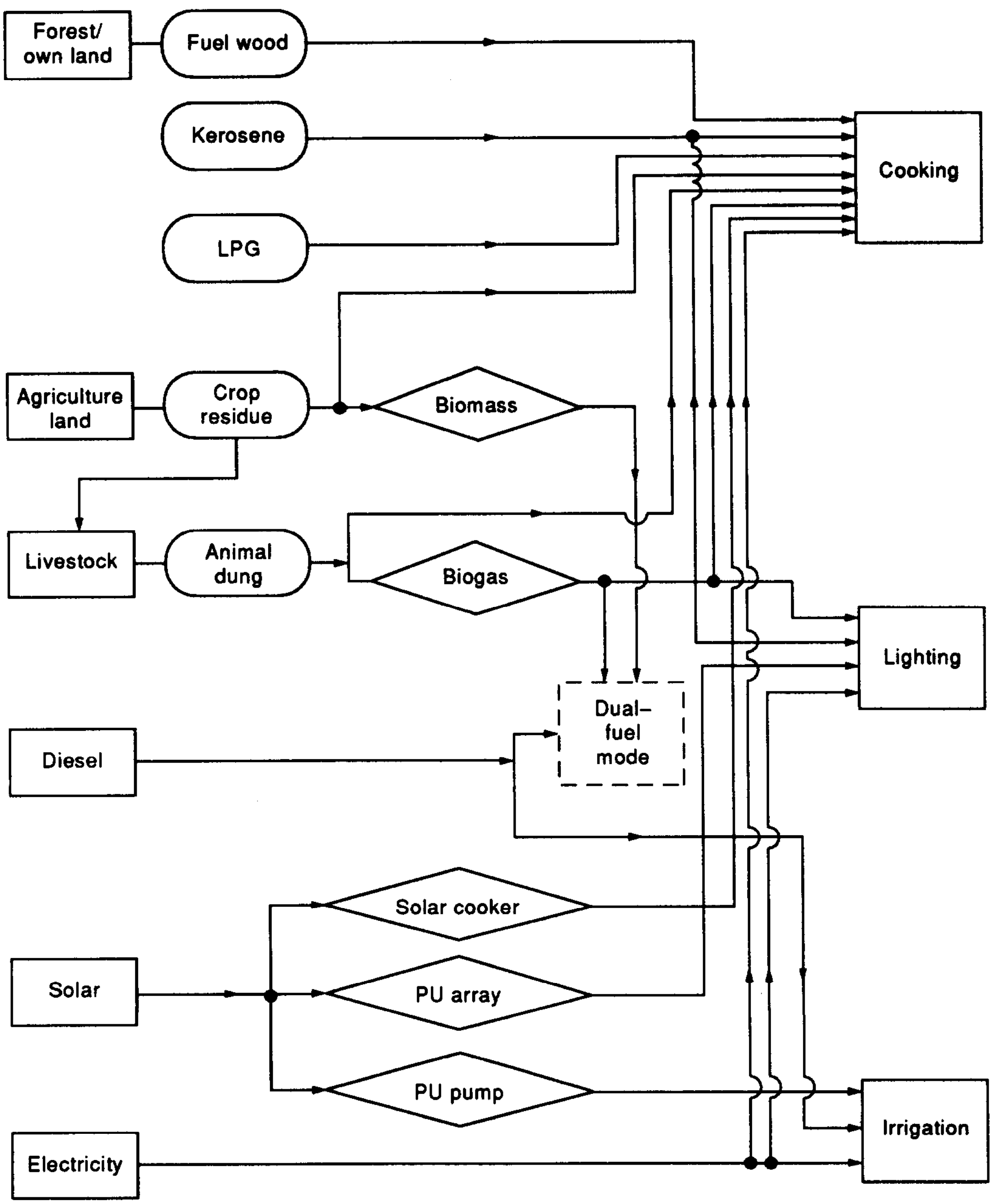

 Fig. 3. Energy flow diagram for cooking, lighting and irrigation for the village Naunbasta.

Fuelwood. Land-use and contour maps of the Lucknow district were collected from the Forest Department of Uttar Pradesh. These maps show that there is no forest area in the vicinity of the Naunbasta village. Some villagers have trees on self-owned land from which fuelwood is obtained at nominal cost. The maximum available wood is converted into suitable energy units using the known calorific value of wood.

Agricultural residue. Knowing the existing crop pattern and the agricultural residue-to-grain ratio for various crops, an estimation is made of the total agricultural residue as follows:

$$\text{total agricultural residue} = \sum (\text{total agriculture production}) \times (\text{agricultural residue-to-grain ratio}).$$

The residue-to-grain ratios for various crops are taken from the Agriculture Handbook.[8]

Animal dung and biogas. The total dung production is estimated from the relation

$$\text{total dung production} = \sum \text{livestock} \times (\text{dung production/livestock}).$$

The wet dung availability from animals is 15 kg per buffalo, 10 kg per head of cattle, 5 kg per head of young, and 15 kg per draught animal on the average. Assuming an 85% dung-collection efficiency, the total dung production is estimated. The availability of dry dung from a given quantity of fresh animal dung is represented in the model by a fixed ratio. A similar assumption is made for biogas production from a given quantity of fresh dung. According to the cattle holdings, households are categorized into biogas potentials of 1, 2, 3, 4, 6, 8, and 10 m^3/day.

Solar energy. The estimation of solar radiation is made from sunshine-duration data. The availability of global solar radiation is 1850 kWh/m^2 and the annual sunshine duration is 3000 h for this village. The maximum possible solar-collector area for various end-uses is determined on the following basis: (i) the maximum area for solar cookers is taken as 2 m^2/hh, whereas 4 m^2/hh is assigned for PV lighting; (ii) it is assumed that 0.1% of the total agricultural land can be utilized for the PV pump for irrigation.

Constraints

(i) It is assumed in the model that the value of the cost coefficient C_{stu} and the efficiency of the end-use device n_{stu} remain constant with respect to the level of x_{stu}. (ii) A few of the variables representing energy supplies are constrained to obtain realistic model results. The kerosene available from the government shops is only 5 l/hh/month, whereas kerosene available in the market at a higher cost is unconstrained. Keeping a maximum limit of 25 kWh/hh/month as the electricity supply and 10 l/hh/month of diesel availability, model results are calculated. Fuelwood purchased from the market at a higher rate and the LPG supply are kept unconstrained in the model. (iii) For diesel engines operating in a dual-fuel mode with biomass or biogas, it is assumed that 70% of the diesel is replaced by biomass or biogas.

Economics of various devices

Several economic indices can be used for comparisons of different end-use devices, e.g., cost per kW installed, cost per kW generated, etc.[10] The various factors that decide the economic viability of a given device are the capital cost, overall energy-conversion efficiency of the end-use device, operating and maintenance costs, fuel costs, life time of the device, etc. It is necessary to evolve a single index that incorporates all of these parameters. The energy cost in Rs/kWh is evidently the total annual cost in Rs divided by the total annual energy output in kWh.

The total annual cost includes the following costs: (i) the cost of the energy option used per year, which can be calculated from the specific fuel consumption (SFC) for that device, i.e.

$$\text{annual fuel cost (Rs)} = \text{maximum operating time (h/yr)} \times \text{SFC (kWh/yr)} \times \text{fuel cost (Rs/kWh)}.$$

(ii) The costs of primary-to-secondary energy conversion, as in the case of biogas production from animal dung or briquetting and pulverization of biomass. (iii) The costs of end-use devices, which include the costs of capital and of operation & maintenance (O&M). Transportation and distribution costs are included in the end-use costs as needed.

For end-use devices, the annual cost is the product of the capital recovery factor (CRF) and the capital cost, where

$$\mathrm{CRF} = i(1+i)^t/[(1+i)^t - 1], \tag{1}$$

i is the interest rate and t the lifetime of the end-use device. The annual energy output is calculated as follows:

$$\text{annual energy output (kWh)} = \text{maximum operating time (h/yr)} \times \text{SFC(kWh/yr)} \times \text{conversion efficiency.}$$

The energy costs (Rs/kWh) for various devices are summarized in tables.†

RESULTS AND DISCUSSION

Only those systems are acceptable which provide the maximum amount of energy per unit of investment and have typically minimal running or operating expenses. The optimal mix of technologies for cooking, lighting and irrigation, allowing for local resource availability and commercial sources, are shown in Table 10.† For existing consumption patterns, it is observed from the model results that the cooking demand is met by fuelwood from owned land using improved cookstoves. A 50% efficient kerosene pressure stove is the second choice for cooking. The remainder of the cooking demand is met by using biogas obtained from 8-m^3 plants and agricultural residue in improved stoves. Fluorescent tubes with 12% efficiency are the best option for lighting. A 10 HP diesel engine is preferred for irrigation.

The results of a sensitivity analysis are indicated in Figs. 4 and 5. Case 1 refers to no available wood and the cooking demand is met by using kerosene, biogas, and agricultural residue. For lighting and irrigation, there is a negligible increase in the total annual cost. When the kerosene supply is stopped, as in case 2, cooking is strongly affected. A part of the cooking demand, which was met by kerosene in the base case, will now be met by using agricultural residue. When there is no electricity available from the grid, the total consumption pattern is changed. Kerosene and biogas are used for lighting, while wood and agricultural residue are used for cooking. In this case, there is a 5% increase in the total cost. Diesel is being used for irrigation only. Even when there is a 50% reduction in the diesel supply, diesel pumps remain most economical for irrigation (see Case 4 in Fig. 4). Case 5 refers to non-availability of fuelwood, kerosene, and electricity together with a 50% reduction in the diesel supply. Now the agricultural residue suffices for the cooking demand. Conversion of animal dung into biogas seems economically most feasible for lighting. Biogas, from various plants of sizes 1, 2, 3, 4, and 8 m^3, is used for lighting. The irrigation need is not affected by these supply constraints. The total annual cost increases by 10%. Assuming socioeconomic improvement of village life, with the total lighting demand increasing two to three fold as in cases 6 and 7 (Fig. 5), kerosene petromax with 2.5% lighting efficiency comes into the picture. The remaining lighting need is met by biogas. The consumption pattern in the cooking sector is also affected by this increase in lighting demand. Wood, kerosene, and agricultural residue are now used for this purpose. The irrigation demand again remains unaffected. A diesel pump is preferred for irrigation as in the previous case (Fig. 5). In case 8, all three demands are doubled. Wood, kerosene, and agricultural residue are now preferred for cooking. Electricity, kerosene, and biogas are used

†These tables may be obtained on request from the authors.

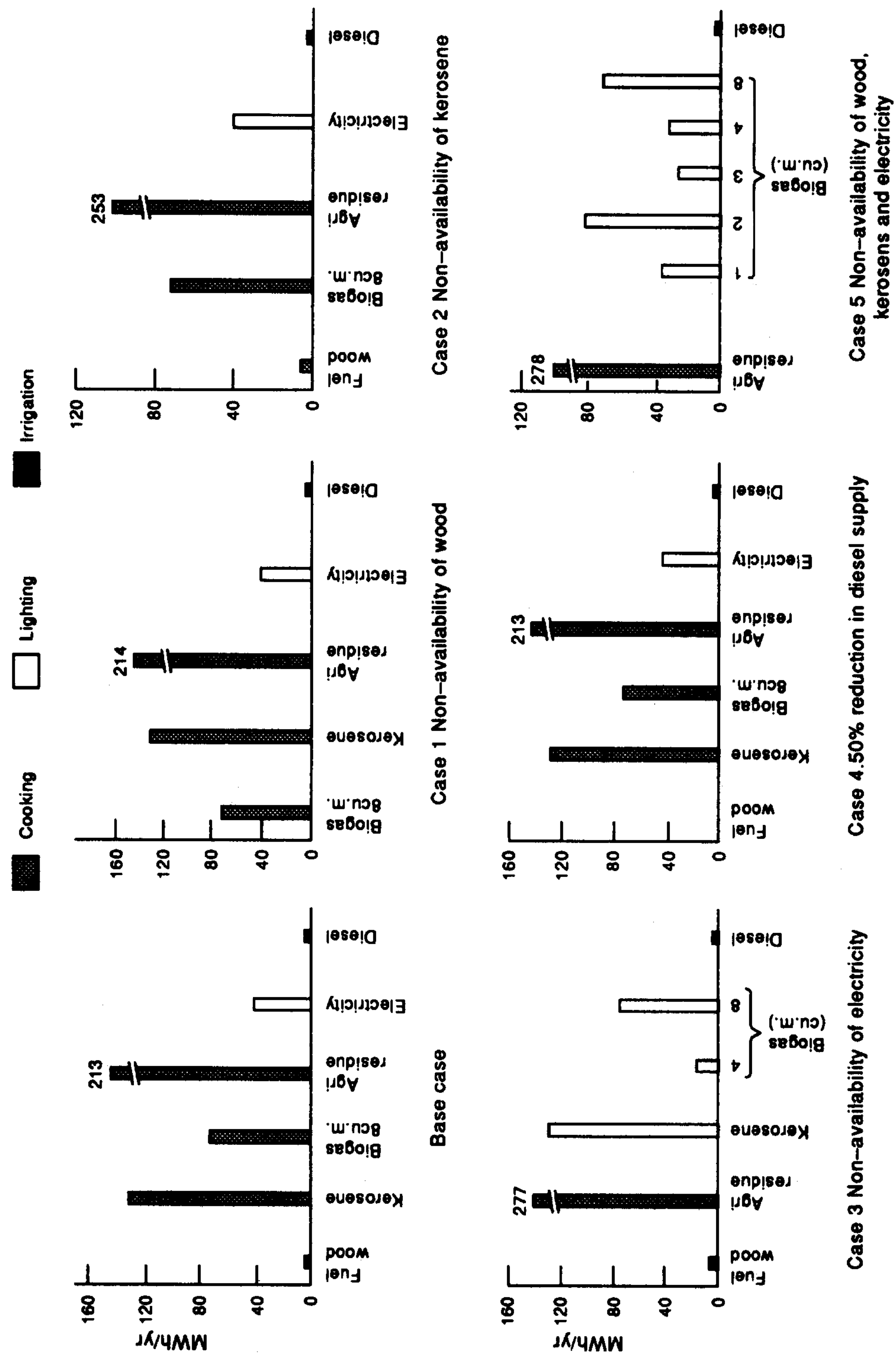

Fig. 4. Sensitivity analysis.

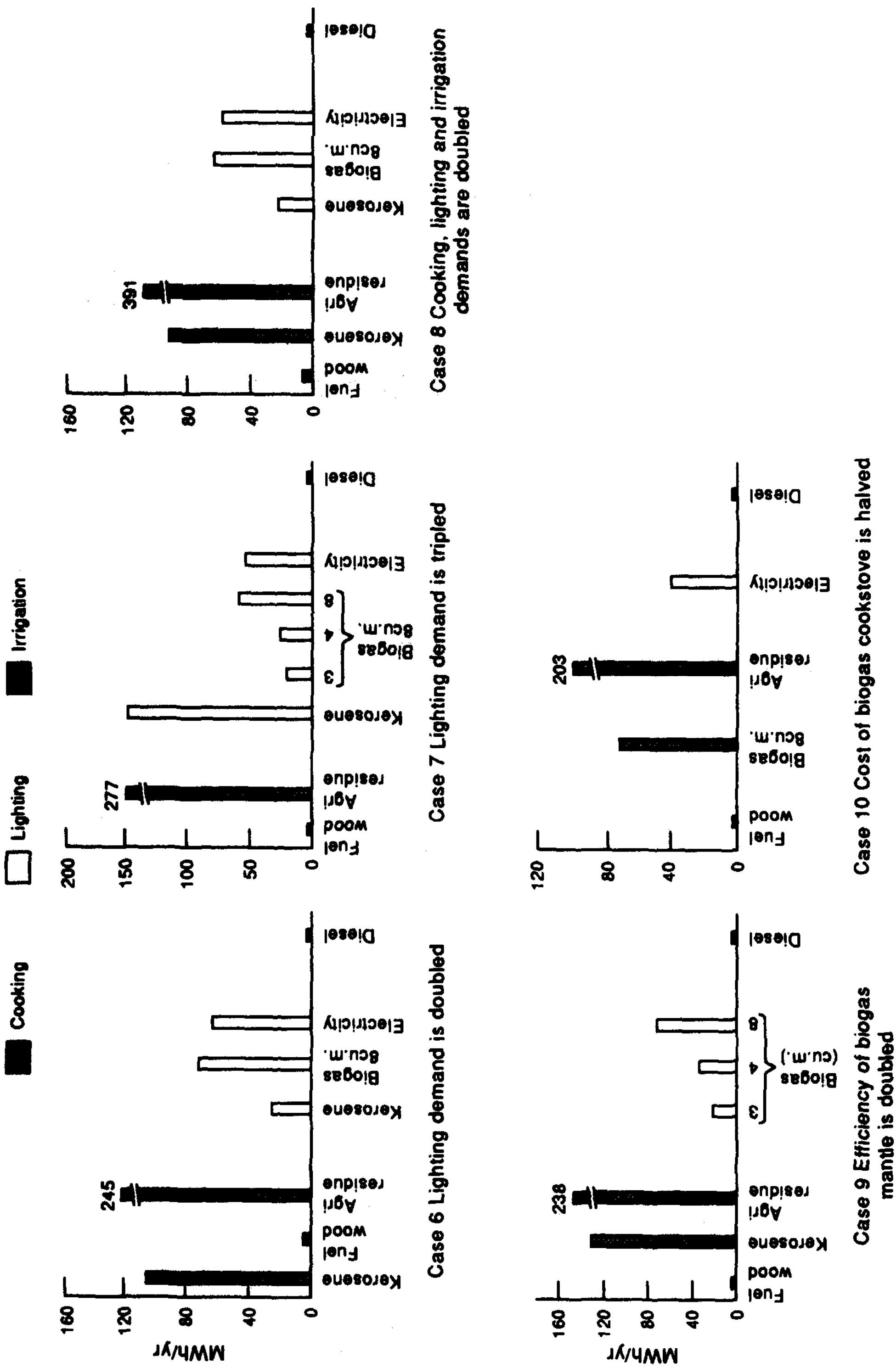

Fig. 5. Sensitivity analysis.

for lighting, whereas the irrigation demand is met by using diesel only. The biogas option enters when there is a scarcity of conventional fuels. However, if the efficiency of the biogas mantle is doubled to the maximum presently available effiiciency (i.e. 4%), then it can be used for lighting.

According to the model results, at the present cost and efficiency, none of the solar devices is a viable option for any of the thre end-uses. However, if a subsidy of Rs 550 per solar cooker provided by the government is used as "free", then the solar cooker becomes a viable option.

CONCLUSIONS

The major conclusions are: (i) Biomass continues to constitute the major source of energy for the subsistence economy. This source constitutes the cost-effective fuel for cooking, whether in the form of wood or as agricultural residue. (ii) If all of the lighting-energy requirements of a typical village have to be met, electricity from the grid appears to be the most cost-effective option. (iii) If the biogas mantles are made more efficient, their utilization for lighting appears attractive. (iv) The use of solar energy in rural areas does not appear to be feasible in the immediate future because of limitations of technologies and costs.

REFERENCES

1. United Nations, *Energy Issues and Options for Developing Countries,* 234 pp., Taylor & Francis, New York (1989).
2. R. P. Codoni, Hi-chun, and K. V. Ramani, *Integrated Energy Planning: a Manual,* Vol. I, pp. 170–192, Asian and Pacific Development Centre, Kuala Lumpur (1985).
3. M. S. Alam, A. M. Z. Huq, and B. K. Bala, *Energy The International Journal* **15,** 131 (1990).
4. T. Das, D. Chakraborty, and S. Seth, "Integrated Rural Energy Programme", Survey Report and Action Plan Frame, pp. 338–342, Jadavpur University, Calcutta (1986).
5. C. Subhash and P. S. Satsangi, *Energy—The International Journal* **15,** 913 (1990).
6. B. Joshi, T. S. Bhatti, N. K. Bansal, K. Rijal, and P. D. Grover, *Int. J. Energy Res.* **15,** 71 (1991).
7. N. K. Bansal, and G. Minke, "Climatic Zones and Rural Housing in India," Scientific Series of the International Office, pp. 17–22, KFA, Juelich, Germany (1988).
8. ICAR, *Handbook of Agriculture,* Indian Council of Agricultural Research (ICAR), New Delhi (1990).
9. A. Mani, *Handbook of Solar Radiation Data for India,* Allied Publishers, New Delhi (1080).
10. V. V. N. Kishore and K. Thukral, in *Technoeconomics of Renewable Energy Power Generating Systems,* pp. 170–175, K. S. Rao, V. V. N. Kishore, and N. K. Bansal eds., Sarita Prakashan, New Delhi, India (1989).