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ORIGINAL ARTICLE

Sustainable bioenergy production strategies for rural India

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Abstract The paper aims to assess the potential of decentralized bioenergy technologies in meeting rural energy needs and reducing carbon dioxide (CO_2) emissions. Decentralized energy planning is carried out for the year 2005 and 2020. Decentralized energy planning model using goal programming technique is applied for different decentralized scales (village to a district) for obtaining the optimal mix of energy resources and technologies. Results show that it is possible to meet the energy requirements of all the services that are necessary to promote development and improve the quality of life in rural areas from village to district scale, by utilizing the locally available energy resources such as cattle dung, leaf litter and woody biomass feedstock from bioenergy plantation on wastelands. The decentralized energy planning model shows that biomass feedstock required at village to district level can even be obtained from biomass conserved by shifting to biogas for cooking. Under sustainable development scenario, the decentralized energy planning model shows that there is negligible emission of CO_2, oxide of Sulphur (SOx) and oxide of nitrogen (NO_x), even while meeting all the energy needs.

Keywords Biomass · Decentralized energy planning · Energy security · Environmental protection

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1 Introduction

Biomass continues to be a dominant source of energy in developing countries contributing to around 12% of global primary energy supply (Sims 2003). Modern biomass however is more complex incorporating many biomass sources and many conversion technologies to provide useful forms of energy (Sims 2002). There is a link between growing biomass for energy purposes and forest carbon sinks (Intergovernmental Panel on Climate Change (IPCC) 2000). Plants remove carbon from the atmosphere and store it in biomass and in soils. Thus land-use and land management provide important opportunities for climate change mitigation. Further, plant biomass can be used as feedstock for modern bioenergy, substituting and offsetting the use of fossil fuels and reducing carbon emissions. An additional benefit of biomass-based decentralization of energy production, using energy crops to supply feedstock, is that it creates employment and energy self-reliance in rural areas (Grassi 1998; El Bassam et al. 1998; Moreira and Goldemberg 1999). Energy-planning involves finding a set of sources and conversion devices so as to meet the energy requirements or demands of all the activities in a least-cost and optimal manner. This could occur at a decentralized level. The focus of this analysis is to develop optimized bioenergy-based options and its suitability for rural India by applying decentralized energy planning model.

2 Methodology

Decentralized energy planning (DEP) involves scaling down energy planning to sub-national or regional scales. Energy planning at the village level is the lowest level of the application of decentralized planning principle. A village constitutes a cluster of households with distinct geographic boundary consisting of settlement, agricultural land, water bodies and any other land category. Each individual village forms a distinct rural identity, each of which is generally separated by agricultural or forest land. Further, the village level plans must be prepared within the limits set by a panchayat (local administrative unit), block or district level plan, for the sum total of various village plans must correspond to a panchayat, block (or taluka), or district level plans. The methodology adopted includes implementation of the different steps of DEP in an iterative way, i.e., at different stages of data collection and analysis. The initial stage led to the identification of data gaps, which was followed by another stage of data collection and analysis, and so forth. During the subsequent stages, issues related to the requirements, availability, collection and processing of data for area-based energy planning were identified.

2.1 Selection of location

Tumkur district in the state of Karnataka in India has been selected for the study. Location of the study area is presented in Fig. 1.

Tumkur district is located in the semiarid belt of the eastern half of the Karnataka state; the district has ten blocks (talukas) and has an area of 10,647 km^2. The district has a population of 2.57 million as per 2001 census (Government of India, Census Report 2001) as against 2.30 million during 1991(Government of India, Census Report 1991), showing a decadal growth rate of 11.87%. The population density is 213 persons per km^2 as per 2001 census. The district has 10 blocks, 321 Gram Panchayats (local councils), 2,537 inhabited villages and 181 uninhabited villages. The average annual rainfall in the

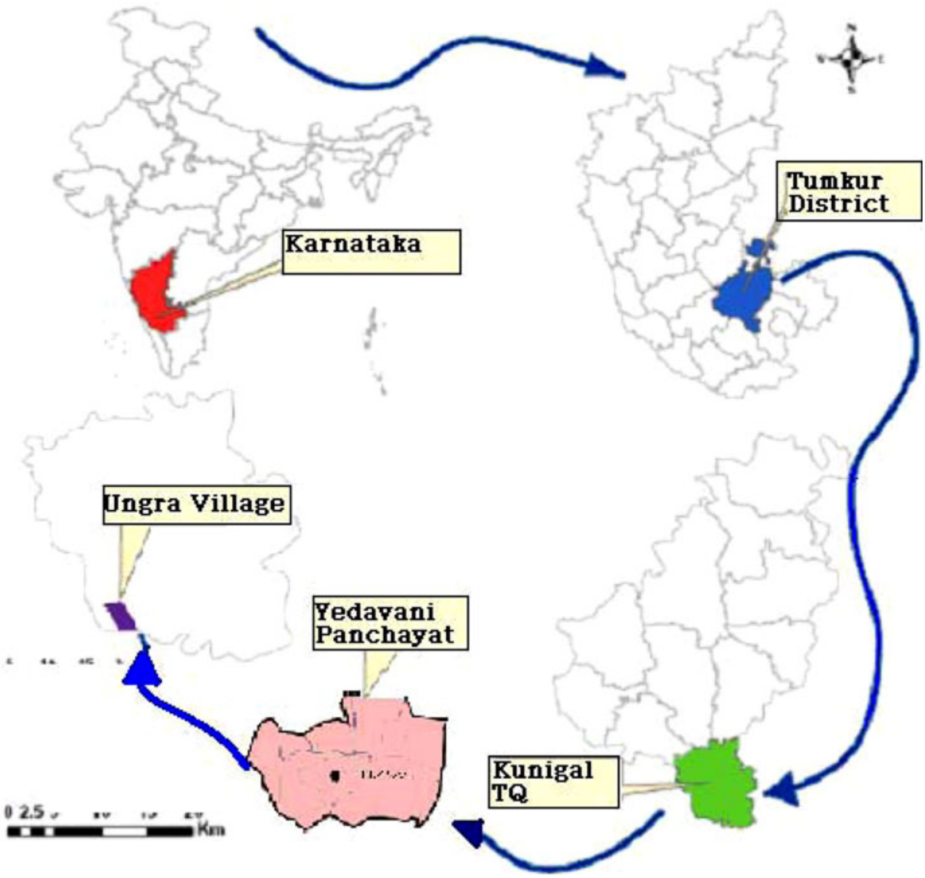

Fig. 1 Location of study area (Tumkur), which is part of Karnataka state of India. Map also shows chronological study area (village to district)

district is 687.9 mm. About 4% of the total area of the district is classified as forests. According to National Remote Sensing Agency (www.nrsa.gov.in) estimates, wasteland in Tumkur district is around 3084 km^2, which accounts for 26% of the total area of the district.

2.2 Description of the model

The quality and quantity of energy dictates how the societies will evolve (Rajvanshi 1993). Thus they are like "dissipative" structures (Prigogine 1980). For a self-organizing structure, a critical mass is required before it can sustain and grow. To achieve the goal of integrated and sustainable energy planning, energy models such as goal programming approach are used. Goal programming (GP) has been used by Bryson and Joseph (1999) and Ramanathan and Ganesh (1995a) for providing DEP for urban locations. They have incorporated only quantitative criteria in their analysis. Ramanathan and Ganesh (1995b) used integrated goal programming to optimally match seven energy resources usable for lighting in households against 12 objectives representing the energy-economy-environmental system. Parikh (1997) employed a goal programming framework to maximize net revenue, minimize emissions and minimize fertility loss of soil, subject to the energy supply and demand constraints. Deo et al. (1991) presented a priority-based goal programming model for village level energy planning with several goals. Selection of the appropriate model is based on the requirement of data and suitability of the model at the decentralized level to account for multiple energy needs. In a goal programming problem, there are multiple objectives (with trade-offs) and the deviations from constraints are penalized. The optimization model used in the present study consists of seven objective functions (Hiremath et al. 2009). The cost minimization, system efficiency maximization, maximization of employment generation and maximization of system reliability of renewable energy technologies are termed as economic objectives. The energy Security objectives include minimization of use of petroleum products and maximization of the use of local resources. The environmental protection objective includes minimization of emissions of carbon dioxide (CO_2), oxide of Sulphur (SOx) and oxide of nitrogen (NO_x). The first six objectives relate to economic and security considerations, while the last objective relates to policies on environmental protection. This model cannot be solved by using ordinary linear optimization and hence goal programming has been employed to solve the optimization problem. These seven goals may be either *over ($^+$)* or *under ($^-$) achieved*.

2.2.1 Objective functions

Seven objective functions are considered in this work. Details are given below:

A. Minimization of cost

This cost minimization objective function is represented as:

$$\text{Min} \sum_{i=1}^{6} \left[\sum_{j=1}^{m} \left[\sum_{k=1}^{n} C_{ijk} X_{ijk} \right] \right] \tag{1}$$

where C_{ijk} is the cost coefficient, which is the unit LCC (Life cycle cost) value for combination j and X_{ijk} is the quantity of final energy for i^{th} end-use, using j^{th} resource by k^{th} end devices.

B. Maximization of system efficiency

Analysis aims to maximize the system efficiency of a particular resource-end-use combination, which is the total efficiency of energy system including the efficiencies of production, distribution and end-use utilization.

This objective function is represented as:

$$\text{Max} \sum_{i=1}^{6} \left[\sum_{j=1}^{m} \left[\sum_{k=1}^{n} \eta_{ijk} X_{ijk} \right] \right] \tag{2}$$

where η_{ijk} represents the efficiency coefficient.

C. Minimization of use of petroleum products

This objective function is represented as:

$$\text{Min} \sum X_i \tag{3}$$

where X_i is the quantity of final energy for i^{th} end-use.

D. Maximization of use of locally available resources

The relevant objective functions here can be represented as follows:

$$\text{Max} \sum X_j \tag{4}$$

where X_i is the quantity of final energy for jth resources.

E. Maximization of employment generation

When energy is considered as a sub-system of the overall economic system, it should facilitate attainment of national goals such as employment generation. The corresponding objective functions can be represented as follows:

$$\text{Max} \sum_{i=1}^{6} \left[\sum_{j=1}^{m} \left[\sum_{k=1}^{n} e_{ijk} X_{ijk} \right] \right] \tag{5}$$

where e_{ijk} denotes the number of persons employed per kilowatt-hour (KWh) of energy allocated for combination i. Job creation can be specified in three types namely:

Direct jobs	those jobs resulting directly from the renewable energy project or installation, and includes the entire production cycle from fuel production and component manufacture to waste management.
Indirect jobs	those jobs that arise in addition to the direct jobs referred to above, and include services and inputs to the direct processes.
Induced jobs	those jobs generated through the increased cash flow in the broader society that arises from the wages of those employed in direct and indirect jobs.

F. Minimization of CO_2, NO_x and SO_x emissions

Three major pollutants are considered to describe the impact of human activities on the air quality. These are carbon dioxide, sulfur oxides, and nitrogen oxides. The emissions due to the combustion depend on the composition of the fuel used (or burnt). The corresponding objective functions can be written as follows:

$$\text{Min} \sum_{i=1}^{6} \left[\sum_{j=1}^{m} \left[\sum_{k=1}^{n} p_{ijk} X_{ijk} \right] \right] \tag{6}$$

$$\text{Min} \sum_{i=1}^{6} \left[\sum_{j=1}^{m} \left[\sum_{k=1}^{n} q_{ijk} X_{ijk} \right] \right] \tag{7}$$

$$\text{Min} \sum_{i=1}^{6} \left[\sum_{j=1}^{m} \left[\sum_{k=1}^{n} r_{ijk} X_{ijk} \right] \right] \tag{8}$$

Where, p_{ijk}, q_{ijk} and r_{ijk} are the emissions of carbon dioxides, sulphur oxides and nitrogen oxides respectively for combination j.

G. Maximization of reliability of renewable energy systems

Reliability is the probability that a device would operate without failure for a given period of time under given operating conditions. If the reliability factor of the system is to be determined, initially the individual reliability of the sub-systems or elements has to be estimated. If each component exhibited a constant failure rate, then the reliability factor for each component would be in the form of exponential $(-^{\lambda}t)$. The r[th] component will have a reliability of exp $(-^{\lambda}rt)$.

Hence, the reliability for the system would be

$$R(t) = \exp(-^{\lambda}1t) \times \exp(-^{\lambda}2t) \times \cdots \times \exp(-^{\lambda}st) = \exp[-(^{\lambda}1 + ^{\lambda}2 + \cdots + ^{\lambda}s)t] = \exp^{\left(-\sum \lambda_{rt}\right)}$$

where, t is time in hours.

The value of reliability R(t) is 1 at $t=0$, and it decreases continuously thereafter with time. When‘t’ becomes very large, all the components would fail, thus R(t) would reach a value of zero.

$$\text{Max} \sum_{i=1}^{6} \left[\sum_{j=1}^{m} \left[\sum_{k=1}^{n} R_{ijk} X_{ijk} \right] \right] \tag{9}$$

where, R_{ijk} is the reliability factor of renewable energy systems.

2.2.2 Demand constraints

Cooking energy requirement

$$\sum_{j=1}^{12} \left[\sum_{k=1}^{n} Xjk \right] \geq \mathrm{D}_{\mathrm{Cooking}} \tag{10}$$

where, $\mathrm{D}_{\mathrm{Cooking}}$ is the total cooking energy requirement.

Lighting energy requirement

$$\sum_{j=13}^{21} \left[\sum_{k=1}^{n} Xjk \right] \geq \mathrm{D}_{\mathrm{Lighting}} \tag{11}$$

where, $\mathrm{D}_{\mathrm{Lighting}}$ is the total lighting energy requirement.

Water pumping energy requirement

$$\sum_{j=22}^{28} \left[\sum_{k=1}^{n} Xjk \right] \geq \mathrm{D}_{\mathrm{Water\ pumping}} \tag{12}$$

where, $\mathrm{D}_{\mathrm{Water\ pumping}}$ is the total water pumping energy requirement.

Water heating energy requirement

$$\sum_{j=29}^{42} \left[\sum_{k=1}^{n} Xjk \right] \geq \mathrm{D}_{\mathrm{Water\ heating}} \tag{13}$$

where, $\mathrm{D}_{\mathrm{Water\ heating}}$ is the total water heating energy requirement.

Rural industries requirement

$$\sum_{j=43}^{49} \left[\sum_{k=1}^{n} Xjk \right] \geq \mathrm{D}_{\mathrm{Rural\ industries}} \tag{14}$$

where, $\mathrm{D}_{\mathrm{Rural\ industries}}$ is the total rural industries energy requirement.

Home Appliances energy requirement

$$\sum_{j=49}^{56}\left[\sum_{k=1}^{n} Xjk\right] \geq \mathrm{D}_{\text{Home appliances}} \tag{15}$$

where, $\mathrm{D}_{\text{Home appliances}}$ is the total home appliances energy requirement.

Fuel constraints:

Amount of residue used as fuel obtained from irrigated and un-irrigated land area≥total fuel requirement

$$\sum_{i=1}^{6}\sum_{k=1}^{6}(r_c \times y_c)I_{L_{ik}} + \sum_{i=1}^{6}\sum_{k=1}^{6}(r_c \times y_c)U_{L_{ik}} \leq \mathrm{T_L} \tag{16}$$

where, r_c is the yield to residue ratio/ha of crops c, $\mathrm{y_c}$ is the yield of crop c/ha, $\mathrm{I_L}$ is the amount of residue used as fuel obtained from irrigated land area (tonnes), $\mathrm{U_L}$ is the amount of residue used as fuel obtained from unirrigated land area (tonnes) and $\mathrm{T_L}$ is the total fuel requirement (tonnes).

2.2.3 Supply constraints

Limit for solar thermal usage for cooking: The solar thermal cookers cannot cook all varieties of food and therefore they are not meeting the total cooking requirement. Solar thermal cookers can be used for low-temperature cooking purposes only, which form approximately 20% of the total cooking requirement (Srinivasan and Balachandra 1993). Therefore, the potential limit for the use of solar thermal cookers is considered to be 20% of the total cooking energy requirement. The constraint function is:

$$X_7 \leq 20\% \text{ of total cooking requirement} \tag{17}$$

Biomass constraints: Quantity of biomass used for different end uses≤biomass available

$$\sum_{i=1}^{6}\sum_{k=1}^{6} Q_{BU_{ik}} \leq \mathrm{Q_{BA}} \tag{18}$$

where, Q_{Bu} is the quantity of biomass used for purpose i (tonnes) and Q_{BA} is the quantity of biomass available for purpose i (tonnes).

Dung balance: Quantity of dung used for dung cake and biogas production≤quantity of total dung available

$$\left[\sum_{i=1,4}\sum_{k=1}^{2} Qdc\,ik + \sum_{i=1}^{6}\sum_{k=1}^{3} QBg\,ik\right] \leq d_b N_b \tag{19}$$

where, $\mathrm{Q_{dc}}$ is the quantity of dung cake used for purpose i (in tonnes), $\mathrm{Q_{Bg}}$ is volume of biogas used for purpose i (thousands m^3), $\mathrm{d_b}$ is the quantity of dung output from animal type b in tonnes /year and $\mathrm{N_b}$ is the number of animal type b.

Fuel wood constraints: Quantity of fuel wood used for cooking and heating≤total quantity of fuel wood available

$$\sum_{i=1,4}\sum_{k=1}^{2} F_u ik \leq F_T \tag{20}$$

where, F_U is the fuel wood used as fuel for purpose i (tonnes) and F_T is the fuel wood available as fuel for purpose i (tonnes).

Biogas balance: Volume of biogas used for different purposes≤total volume of biogas generated

$$\sum_{i=1}^{6}\sum_{k=1}^{6} Q_{Bg_{ik}} \leq \mathrm{Q_{BgT}} \tag{21}$$

where, $\mathrm{Q_{BgT}}$ is total volume of biogas produced in (thousands m^3).

Biogas constraints: Dung required for biogas generation≤50% of total dung available

$$\sum_{i=1}^{6}\sum_{k=1}^{6} Q_{Bg_{ik}} \leq 50\%\,\mathrm{T_{DA}} \tag{22}$$

where, $\mathrm{T_{DA}}$ is the total quantity of dung available from animal type b in tonnes /year.

Dung cake constraint: The cooking pattern in Tumkur district indicates that the use of dung cakes for cooking and heating applications is very limited. During the survey, it is observed that a maximum of 50% dung available could potentially be used for making dung cakes. Therefore, it is assumed that 50% of the dung cakes produced could be used for cooking and heating applications. Therefore, dung required for making dung cake≤50% of total dung available.

$$\sum_{i=1,4}^{4}\sum_{k=1}^{2} Q_{dc_{ik}} \leq 50\%\,\mathrm{T_{DA}} \tag{23}$$

Employment constraints: Total number of adult humans available for employment≤60% available population of the village or block selected.

$$\sum_{i=1}^{6}\left[\sum_{j=1}^{m}\left[\sum_{k=1}^{n} N_{A_{ijk}}\right]\right] \leq 60\%\,\mathrm{P_A} \tag{24}$$

where, $\mathrm{N_A}$ is the total number of adult human population available for employment and $\mathrm{P_A}$ is the total population of village or block.

Reliability constraints: Reliability of different renewable energy resources≤Potential limit of available resources.

$$\left[\sum_{j=1}^{3}\left[\sum_{k=1}^{n}(1/R_j)\sum X_{ijk}\right]\right] \leq \mathrm{P_j} \tag{25}$$

where, $\mathrm{P_j}$ is the potential limit of available resources.

End-use notations:

i=1–6 (Cooking)
i=1–6 (Lighting)
i=1–6 (Water pumping)
i=1–6 (Water heating)
i=1–6 (Rural industries)
i=1–6 (Home appliances)
Cooking................m=12.......(j=1–12)
Lighting................m=21.......(j=12–21)
Water pumping........m=28.......(j=21–28)
Water heating...........m=42.......(j=28–42)

Rural industries.........m=49.......(j=43–49)
Home appliances........m=56.......(j=49–56)
m=resource for specific end use
n=number of systems used for specific end use
Cooking.........................(*n*=8)
Lighting.........................(*n*=6)
Water pumping................(*n*=5)
Water heating.................(*n*=9)
Rural industries................(*n*=4)
Home appliances.............(*n*=4)

2.2.4 Mathematical programming

The goal programming model is described as follows:
Minimize:

$$\sum \mathrm{d_{j-}} + \mathrm{d_{j+}}, \text{where } \mathrm{j} = 1, 2......8$$

Subject to:

$$\left(\sum \mathrm{C_{ijk}} \times \mathrm{X_i}\right) + \mathrm{w_1 d_{1-}} - \mathrm{w_1 d_{1+}} = \mathrm{b_1}, \text{ where } \mathrm{j} = 1, 2..........56$$

$$\left(\sum \eta_{\mathrm{ijk}} \times \mathrm{X_{ijk}}\right) + \mathrm{w_2 d_{2-}} - \mathrm{w_2 d_{2+}} = \mathrm{b_2}, \text{ where } \mathrm{j} = 1, 2..........56$$

$$\sum \mathrm{X_j} + \mathrm{w_3 d_{3-}} - \mathrm{w_3 d_{3+}} = \mathrm{b_3},$$

where j=4, 5, 8, 13, 15, 17, 22, 24, 32, 33, 36, 38, 43, 45, 50 and 52.

$$\sum \mathrm{X_j} + \mathrm{w_4 d_{4-}} - \mathrm{w_4 d_{4+}} = \mathrm{b_4}$$

where j=1, 2, 3, 6, 7, 9, 10, 11, 12, 14, 16, 18, 19, 20, 21, 23, 25, 26, 27, 28, 29, 30, 31, 34, 35, 37, 39, 40, 41, 42, 44, 46, 47, 48, 49, 51, 53, 54, 55 and 56.

$$\left(\sum e_{\mathrm{ijk}} \times \mathrm{X_{ijk}}\right) + \mathrm{w_5 d_{5-}} - \mathrm{w_5 d_{5+}} = \mathrm{b_5}, \text{ where } \mathrm{j} = 1, 2..........56$$

$$\left(\sum p_{\mathrm{ijk}} \times \mathrm{X_{ijk}}\right) + \mathrm{w_6 d_{6-}} - \mathrm{w_6 d_{6+}} = \mathrm{b_6}, \text{ where } \mathrm{j} = 1, 2..........56$$

$$\left(\sum q_{\mathrm{ijk}} \times \mathrm{X_{ijk}}\right) + \mathrm{w_7 d_{7-}} - \mathrm{w_7 d_{7+}} = \mathrm{b_7}, \text{ where } \mathrm{j} = 1, 2..........56$$

$$\left(\sum r_{\mathrm{ijk}} \times \mathrm{X_{ijk}}\right) + \mathrm{w_8 d_{8-}} - \mathrm{w_8 d_{8+}} = \mathrm{b_8}, \text{ where } \mathrm{j} = 1, 2..........56$$

$$\left(\sum R_{\mathrm{ijk}} \times \mathrm{X_{ijk}}\right) + \mathrm{w_9 d_{9-}} - \mathrm{w_9 d_{9+}} = \mathrm{b_9},$$

where j=9, 10, 11, 18, 19, 20, 25, 26, 27, 39, 40, 41, 46, 47, 48, 53, 54, 55.

$$\sum \mathrm{X_{jk}} \geq \quad \text{Total cooking energy requirement}$$

where j=1, 2.......12. (Cooking energy requirement)

$$\sum X_{jk} \geq \quad \text{Total lighting energy requirement}$$

where j=13............21. (Lighting energy requirement)

$$\sum X_{jk} \geq \quad \text{Total pumping energy requirement}$$

where j=22............28. (Water pumping requirement)

$$\sum X_{jk} \geq \quad \text{Total water heating energy requirement}$$

where j=29............42. (Water heating energy requirement)

$$\sum X_{jk} \geq \quad \text{Total rural industries energy requirement}$$

where j=43............49. (Rural industries energy requirement)

$$\sum X_{jk} \geq \quad \text{Total appliances energy requirement}$$

where j=50............56. (Home appliances energy requirement)

$$\sum X_4 \geq 20\% \text{ of the total cooking energy requirement}$$

where j=4. (Solar thermal constraint)

$$\sum X_{jk} \leq \text{dung availability}$$

where j=1 and 29. (Dung availability limit)

$$\sum X_{jk}/\eta_{jk} \ \leq \quad \text{Available biogas energy}$$

where j=6, 11, 14, 20, 27, 34, 41, 43, 48 and 55. (Potential limit of biogas energy)

$$\sum X_{jk}/\eta_{jk} \ \leq \quad \text{Available biomass energy}$$

where j=9, 12, 18, 21, 25, 28, 39, 42, 49, 53 and 56. (Potential limit of biomass energy)

Where, b_i is the goal for the objective j, d_{j+} and d_{j-}=over-achievement and under-achievement of goal bj respectively and w_i is the weighing factor.

2.3 Scenarios considered for modeling

Energy scenarios provide a framework for exploring future energy perspectives, including various combinations of technology options and their implications. Many scenarios used in the literature illustrate how energy system development will affect economic development and environment.

2.3.1 Business as usual (BAU)

Business as Usual scenario is a conceptual baseline which projects what would happen in the area if there were no changes. It assumes current land use and other policies that guide or shape development remains the same that current market-based trends continue and that anticipated development projects occur as planned. This scenario also assumes that current demographic trends will continue as expected and future trends in urbanization and land consumption follow past patterns. This scenario is based on the direction in which the selected location is headed (http://info.energyscenariosireland.com/Business_As_Usual). Assuming continued moderate economic growth, energy consumption pattern and modest technological improvement, this scenario leads to adverse environmental impacts, ranging from regional acidification to climate change. Thus, this scenario leads to a higher dependence on carbon-intensive fossil fuels; which results in high energy-related emissions and falls short of achieving a transition towards sustainable development. This scenario is subdivided into two scenarios.

(i) Business As Usual—No priority (BAU NP): This scenario is developed without assigning any priority to the objective functions.
(ii) Business As Usual—Equal priority (BAU EP): This scenario assumes all the objective functions are taken into account while arriving at energy resource allocation. This scenario gives equal priority to all the objective functions.

2.3.2 Sustainable energy development scenario (SDS)

This scenario includes services that promote equity and quality of life based on locally available, convenient, safe, environmentally sound and sustainable technologies. A considerable change is expected in total energy consumption compared to other scenarios, reflecting varying approaches for meeting the energy needs in the future. Increase in research, development and deployment efforts for new energy technologies are a prerequisite for realization of the scenario that has the characteristics of sustainable development. Some of the features of the different scenarios are presented in Table 1.

3 Results and discussion

The major sectors using energy in the rural areas of Tumkur district are domestic, agriculture and rural industries. The major activities requiring energy can be categorized as:

- Heating at low (heating bath water), medium (cooking) and high temperature (kilns)
- Lighting: domestic, street and community facilities
- Stationary power: water pumping, flour milling and agro processing.

Table 2 presents the energy consumption for 2005 and 2020 for different end-uses for different area zones of Tumkur district. DEP model projections for 2020 show that biomass will continue to be the dominant fuel source in the domestic sector. Assuming a 1.1% population growth rate per year, the demand for all the fuels are projected to increase at least by two folds in 2020.

Table 1 Comparative features of different scenarios

BAU	SDS
Human population growth rate 1.1 %	100% gas for cooking
Current energy mix to continue	100% home lighting for all household
Current cattle to human ratio to continue	Equitable supply of energy

Table 2 Energy consumption (in GJ/Year) in 2005 and 2020 for different end-uses for different area zones of Tumkur district has been estimated. Zones comprises of Ungra village, Yedavani panchayat, Kunigal block and Tumkur district

End-use	Ungra Village		Yedavani Panchayat		Kunigal Block		Tumkur District	
	2005	2020	2005	2020	2005	2020	2005	2020
Cooking	8,807	11,043	56,086	72,999	1,894,554	2,549,837	16,000,960	20,883,616
Lighting	287	360	2,772	3,181	126,536	181,200	1,269,917	1,325,944
Water pumping	173	242	1,975	2,586	26,836	43,683	558,298	1,657,430
Water heating	1,180	1,480	21,146	27,533	700,891	943,313	5,079,670	6,629,719
Rural industries	56	61	11,641	12,805	130,517	143,568	1,777,884	2,320,402
Home appliances	81	144	621	798	22,948	32,861	253,983	331,486
Total	10,584	13,330	94,241	119,902	2,902,282	3,894,462	24,940,713	33,148,596

The total woody biomass feedstock required for meeting all the projected electricity (1.109 TWh/year) needs through biomass gasification is 1.19 Mt /year. The potential for biomass conservation is 1.95 Mt, using the biogas and efficient stove options. Thus, the saving that could be potentially achieved is more than adequate to supply wood for decentralized power generation in Tumkur district. However, if all the 1.19 Mt of woody biomass feedstock required has to be grown, the land required is 277,426 ha at a low productivity of 4 t/ha/year and 138,713 ha at a productivity of 8 t /ha / year, as shown in Table 3 which is less than the total wasteland availability.

3.1 Biogas options

The two biogas end-use options considered for meeting the energy needs are cooking and power generation. Both these technologies have been developed indigenously and are available off the shelf. Biogas dual-fuel systems based on dung as the feedstock for power generation, as well as biogas plants for cooking have already been implemented in villages. Their acceptability and operational feasibility has been demonstrated in Pura and elsewhere (Rajabapaiah et al. 1993; Ravindranath and Hall 1995).

3.2 Cattle (*Bos taurus*) dung biogas electricity

Biogas is a clean fuel and can be used in internal combustion engines directly or can be used to generate electricity by coupling a dual-fuel engine to a generator. Over 90% diesel

Table 3 Under different scenarios, land required and wasteland availability in Tumkur district for biomass feedstock production have been estimated

Scenarios	Total geographical area (M ha)	Total wasteland available [a]	Land required for energy plantation at productivity		% of wasteland area used for biomass energy plantations	
			4 t/ha/yr	8 t/ha/yr	4 t/ha/yr	8 t/ha/yr
BAU	1.18	305356	391,338	195,669	–	64
SDS	1.18	305356	277,426	138,713	90	45

[a] Total wasteland includes fallow land, non-agricultural, barren land and cultivable wasteland

substitution is possible or even full operation on biogas is also feasible. Community biogas is the only technically feasible option for power generation in villages. Pura village in Tumkur district showed that, it is not feasible to have several biogas-based power generation systems attached to several small biogas plants (Rajabapaiah et al. 1993). However, the power generated using biogas is only adequate for meeting the minimal base load requirements of end uses such as lighting. Biogas available based on dung resource is not feasible at panchayat level, block level and district level due to limited dung resource and complexities involved in transporting dung and piping biogas across villages.

3.3 Installed capacity for biogas power

Firstly, biogas potential available from the quantity of dung and leaf litter feedstock (barring minor seasonal variations) is calculated. Secondly, the power generation capacity as well as the number of hours of power generation is determined by using the quantity of biogas production/day. Scheduling of the base load activities as shown below, may be necessary to minimize the installed capacity, by distributing the activities at different periods in a day.

- Lighting; 5 h
- Pumping drinking water; 2 h
- Flour milling; 2 h
- An extra hour for additional activity

Ungra village would require an electricity supply for a minimum period of 10 h/day for the critical base load activities. The potential for installed capacity assuming 10 h of electricity supply per day is 13–42 kilowatt (KW) (Table 4). Thus, the electricity requirement for appliances, irrigation water pumping and rural industries cannot be met from biogas electricity option. This option is not considered since the dung resource available is limited. Biogas option is considered largely for cooking which is the dominant energy consuming activity even if alternate feedstocks are available.

Biogas can be used as a convenient fuel for cooking and even for water heating. Since cooking is the dominant energy using activity in rural areas, there is a need to meet its energy requirements on a priority basis. Though the biogas generation potential from dung available is inadequate to meet all the cooking fuel needs of a village, a large potential exists for increasing biogas generation using alternative feedstock such as leaf litter or crop

Table 4 By assuming a community biogas system with cattle dung plus leaf litter, estimation of Biogas for power generation at Ungra village has been done under different scenarios

Scenarios	Electricity generation potential[a]		Installed capacity at 10 h/day of operation (KW) from biogas power option	Installed capacity to meet all energy needs (KW)[d]
	Biogas (cubic meter/day)	Biogas (kWh/day)		
BAU[b]	95	127	13	85
SDS[c]	316	421	42	60

[a] Electricity generation potential is estimated by using the biogas production /day and 0.75 m^3 of biogas / KWh

[b] Biogas production only from cattle dung

[c] This scenario considers biogas production from cattle dung plus leaf litter available from energy plantation, biogas production from fresh leaf biomass=60 l/kg fresh leaves (Ravindranath and Chanakya 1986)

[d] Based on calculations made for the year 2020

residue not used as cattle fodder and by increasing gas yields per kg of dung by technological developments such as increasing the temperature of the slurry in the digester. Table 5 presents the biogas potential available at village, panchayat, block and district level for the year 2020.

3.4 Biomass power

A biomass gasifier based power generation system is one of the feasible options. The technology is readily available and has already been tested in the field (Ravindranath et al. 2004; Mukunda et al. 1996). Biomass gasifier systems are available in India as biomass+ diesel dual-fuel systems and pure producer gas engines. The dominant power requiring service in villages is pumping of irrigation water. Electricity use for pumping irrigation water is characterized by (Amulya et al. 1990)

- Peaks and lean periods
- Dispersed water sources and pumping units, since farmers' land holdings are small, fragmented, and geographically dispersed
- The capacity of the majority of the pumps is in the range of 3.7–10 KW and limited by water availability
- The need for a large number of pumping units in a village

Table 5 Biogas potential from cattle dung and leaf litter (from energy plantation) for meeting the cooking energy requirements (land area under energy plantation estimated assuming a wood productivity of 8 t/ha/year) for the year 2020 has been calculated for different levels of administrative units

	Ungra village	Yedavani panchayat	Kunigal block	Tumkur district
Human Population (2020)	1353	9230	316,949	2,782,900
Biogas potential of cattle dung (m^3/day)	95	882	45,370	272,361
Land proposed for energy forest for producer gas electricity (@8 t/ha/year) ha	20	727	8261	138,713
Leaf harvest potential of land under energy forest [a] in t/year(fresh)	640	19,400	220,291	3,699,020
Biogas from leaf litter [a] (m^3/day)	220	1375	36,018	1,120,966
Total biogas from leaf biomass from energy forest+dung (m^3/day)[b]	315	2257	81,388	1,393,326
Saving in biomass (mainly wood) if all the biogas potential is used for cooking and water heating (t/yr)	457	6480	220,000	1,950,000
% population whose cooking energy needs can be met from biogas from dung+leaf biomass[c]	100	100	100	100

[a] Leaf litter productivity dry t/ha/year, leaf biomass harvest potential=mean yield of 8 dry t/ha/year or 30 fresh t/ha/year

Two-thirds of 8 dry t/ha/year (= 5.3 t/ha/year) is taken as available for biogasification (Ravindranath and Hall 1995). This scenario considers biogas production from cattle dung and leaf litter, 32 ha of wasteland is used for energy plantation, Biogas production from fresh leaf biomass=60 l/kg fresh leaves (Ravindranath and Chanakya 1986)

[b] Total biogas for SDS (example; Ungra village is 95 m^3 /day(from dung)+ 220 m^3 /day(from leaf and litter)= 315 m^3 /day)

[c] Biogas requirement=200 l/Capita/day for cooking

The producer gas electricity option could be considered at two levels:

1. Use of biogas electricity for meeting the base load requirement of services such as lighting, domestic water pumping and in some villages, flour milling, while the power requirement of the remaining services could be meet from producer gas.
2. Producer gas electricity alone could be considered for meeting all the electricity requirements of all the services, thereby keeping the biogas option for other services, particularly cooking.

3.5 Power generation capacity, size of units and number of units

The scale of power generation using a biomass gasifier should preferably be limited to one village, a cluster of a few villages (panchayat), or adjacent panchayats (within a block), since very large systems would require transportation of biomass over long distances, at high energy and financial costs. Very large megawatt (MW) level commercial systems might create pressure on the existing tree resources such as natural forests and may contribute to depletion of forests, plantations and village trees unless biomass resources are carefully managed. Thus, the government has regulations on large MW level biomass power systems in India (http://mnres.nic.in). The size, number of units and siting of biomass power systems can be assessed depending on the availability of degraded land for dedicated energy plantation, demand for power, locations of load, productivity of energy plantations and cost of transportation of woody biomass stock. Decision on size and siting of biomass power plants requires an optimization model. Further, the decision of DEP for power generation cannot be made at village scale, since all villages may not have adequate land area required for producing biomass feedstock and some villages may have surplus land. This may happen even at some panchayat scale in some locations. Thus, DEP for determining the size and location of biomass power generation systems will require an optimization model. The total decentralized power generation capacity at Kunigal block level would be about 13.5 MW and at Tumkur district level, 228 MW. This value is estimated assuming the use of efficient options with marginal or no transmission and distribution losses in SDS scenario for the year 2020 (Table 6). Installed capacity for power generation, wood and land required to meet all the electricity requirement of Ungra village, Yedavani panchayat, Kunigal block and Tumkur district through producer gas electricity is presented in Table 5. Power needs for all the villages in Tumkur district can be met by biomass power, though it may not be feasible at every village level, due to differing biomass supply potential. Land availability to meet biomass power needs varies from village to village, panchayat to panchayat and block to block. Surplus and deficit zones of wasteland area and biomass production should be analyzed at village, panchayat, block and district scales. Thus, there is a need for optimization of sizing and siting of biomass power plants, at not only village level but at multiple scales like panchayat, block and district level.

The analysis presented in Table 6 clearly shows that firstly, all the biomass feedstock required at all the four scales from village to district can be obtained from biomass conserved by shifting to biogas. Further, if all or part of the woody biomass has to be produced from dedicated energy forests, adequate wastelands are available at moderate biomass productivity (6–8 t /ha/ year). Thus, there is no need to convert crop land to energy forests and no competition between food and fuel.

Table 6 Wood required for energy forest at village, panchayat, block and district levels under BAU and SDS scenarios for biomass power generation has been calculated

Requirements	Ungra		Yedavani		Kunigal		Tumkur	
	BAU	SDS	BAU	SDS	BAU	SDS	BAU	SDS
Electricity power requirement in MWh	224	125	5380	4476	111,400	66,000	1,150,000	1,109,000
Capacity to be installed (KW) [a]	70	50	955	766	19,000	11,300	197,000	190,000
Installed Capacity required with power factor of 80% load (KW) [b]	85	60	1150	920	23,000	13,500	236,000	228,000
Wood and Land required (ha) at productivity								
Wood required at 1.3 kg/KWh at 18% efficiency (t/year)	291	162	6994	5819	111,476	66,087	1,565,350	1,109,706
Biomass conservation potential by adopting SDS scenarios for Ungra village , Yedavani panchayat, Kunigal block and Tumkur district are 457 t, 6480 t , 250,000 t and 1,950,000 t of fuelwood								
Total geographical area for Ungra village, Yedavani panchayat, Kunigal block and Tumkur district are 362 ha, 3674 ha, 91,266 ha and 1,180,000 ha								
Total wasteland area for Ungra village, Yedavani panchayat, Kunigal block and Tumkur district are 89 ha, 1354 ha, 30599 ha and 300,000 ha.								

[a] Capacity (KW) depends on the number of irrigation pumps and capacity of the pumps (5 kW) and assuming only one fourth of the pumps have to be operational simultaneously. (Example: in Ungra, assuming the total requirements of 56 pumps in the year 2020 the installed power generation required would be 70 KW)

[b] Installed capacity consisting a power factor of (0.8), the actual capacity is 85 kW (assuming 80% of rated capacity). Ungra 85 KW (70 kW + 20% of 70 KW—rounded to 85 KW)

3.6 Reduction in CO_2, NO_x and SO_x emissions

If the decentralized biomass gasifier system substitutes for grid electricity which is derived mainly from coal-based thermal power plants, there would be a reduction in coal combustion leading to a reduction in CO_2, NO_X and SO_X emissions. Substitution of diesel systems with biomass power systems will also lead to offsetting CO_2 emissions. Thus, biomass power systems can play an important role in reducing emission of pollutants such as CO_2, NO_x and SO_x (http://www.ipcc.ch/pub/online.htm, Ravindranath and Hall 1995). When CO_2 emissions are considered, as shown in Table 7, SDS scenarios have no CO_2 emissions. Thus, SDS is characterized by least-cost, high employment generation and zero net CO_2 emissions.

4 Discussions and conclusions

According to Ravindranath and Balachandra (2009) bioenergy technologies have the potential to meet the heating, lighting, shaft power and motive power needs, particularly of the rural population. Further, bioenergy technologies are the prime candidates aimed at mitigation of climate change apart from land reclamation through growing energy plantations in degraded lands and reduction in domestic indoor pollution (Ravindranath and Balachandra 2009). The present study considers the potential strategies for sustainable bioenergy production for rural India through decentralized energy planning approach. The DEP model has been suitably scaled for obtaining the optimal mix of energy resources and

Table 7 Under different scenarios, Emissions have been estimated

Scenario	Priority for objective functions	Emissions associated in tons/year		
		CO_2,	SO_2,	NO_x,
BAU 2020	No Priority	6279544[a] (2.26)	115909[a]	125435[a]
	Equal priority	1347070[a] (0.48)	905[a]	3056[a]
SDS	Economic, Security and Emission (1)[c]	0[b]	2474[a]	530[a]

[a] Considering emissions from only unsustainable energy sources which account for be 40% of total emissions

[b] Carbon neutral energy sources

[c] (1) first priority, (2) second priority and (3) third priority

* Figures in parenthesis indicates the per Capita annual CO_2 emissions

technologies for Tumkur district by using a computer based goal programming technique. The objective of DEP is to allocate various types of energy carriers/sources optimally to a set of end-uses. The energy sources are selected based on either their present use or potential availability in Tumkur district. The effectiveness of using bioenergy has been analyzed in long term energy planning with short rotation plantations providing woody and leaf biomass feedstock.

Studies have shown that small biomass gasifier-based decentralized power generation systems can contribute to a considerable share of the electricity needs in rural India (Ravindranath et al. 2004). Heat energy for cooking and electricity for lighting and shaft power are the basic energy requirements for any village. Gaseous quality fuel such as biogas should be promoted for cooking. Cattle dung augmented with leaf litter is shown to be adequate to meet the cooking and water heating energy needs at village level under SDS scenario. Proper siting and sizing of biogas plant is very much essential at village scale depending on the dung and leaf litter feedstock availability. Community and family biogas systems are two options for meeting cooking needs of the village. Community biogas plants provide economies of scale—thus they are desirable. Cattle dung available in different

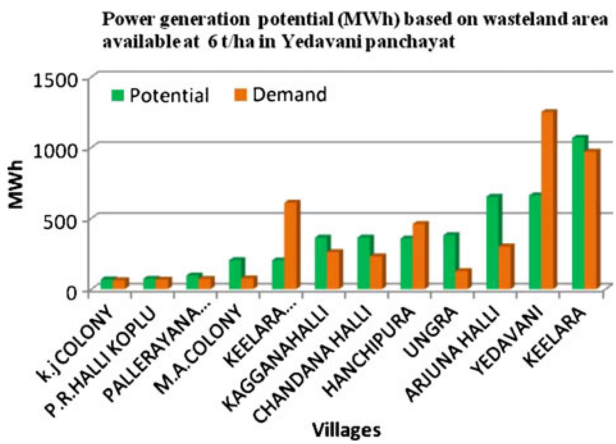

Fig. 2 Based on available wasteland area, power generation potential (MWh) at 6 t/ha in different villages under Yedavani panchayat has been estimated. As depicted, Ungra village has high biomass feedstock potential and low energy demand compared to Keelara village

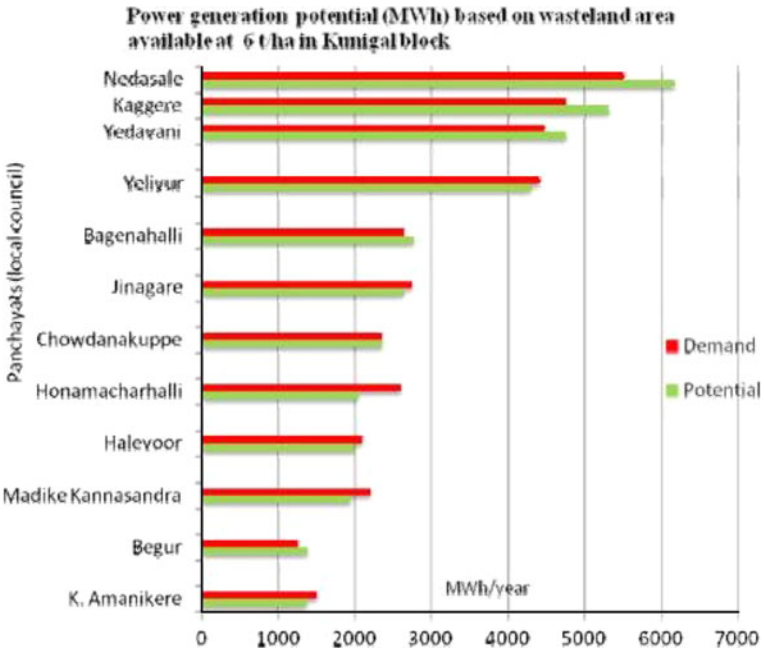

Fig. 3 Cluster of panchayat forms block, which is a higher administrative unit. Comparison of power generation potential (MWh) based on wasteland area available in different panchayats at 6 t/ha in Kunigal block has been shown and Honamacharhalli panchayat has high power demand and low power generation potential

villages of a panchayat is inadequate to meet the cooking energy needs. Biogas option is not feasible at panchayat level because condensed liquefaction of biogas is not possible for transportation from village to village. Further, transportation of dung and leaf litter is not feasible across villages. Thus, community biogas plants are feasible only at village scale. Biomass gasifier power sizing and siting depends on three factors; a) land availability and energy demand or load, b) cost of transportation of biomass to the biogasifier plant and c) transmission and distribution cost of power. In Yedavani panchayat, Ungra village has high biomass feedstock potential and low energy demand compared to Keelara village which has high demand and low generation potential for biomass power (Fig. 2). Thus, optimal

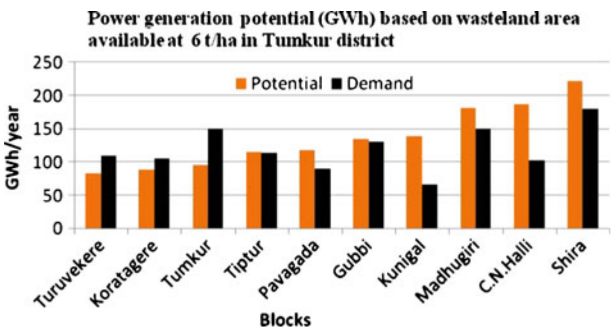

Fig. 4 District level estimation, which comprises of cluster of block unit, has been performed to find out the power generation potential (GWh) based on wasteland area available in different blocks at 6 t/ha

planning for capacity and siting biomass power is essential at multiple village scale in the panchayat. Hence, panchayat or cluster of village planning should be supported by village level energy planning. Nedasale panchayat has high level of power demand and also has large potential for biomass feedstock generation. On the other hand, Honamacharhalli panchayat has high power demand and low power generation potential. Every panchayat has different levels of power needs and power generation capacities (Fig. 3). Surplus and deficit zone for biomass feedstock availability has to be critically analyzed depending on the power demand of the panchayats and blocks. Village and panchayat level energy planning is very much essential for planning at block level to identify optimized capacity and siting of biomass power plants to account for spatial variation in biomass feedstock supply. As seen from Fig. 4, Shira block has high percentage of wasteland and high energy demand compared to other blocks in the district. This high demand can be met by wasteland available in the block. But, Tumkur block has high demand and low potential for power generation. There is a supply demand mismatch among different blocks within a district. Thus, it is necessary to carry out DEP analysis at district level based on analysis at village, panchayat and block level energy planning.

In the absence of biomass gasifier-based power supply, Tumkur district would have used liquid petroleum gas (LPG) for cooking, kerosene for lighting and diesel for pumping water for irrigation and would have been connected to the centralized grid, where nearly 70% of electricity at national level is generated from coal power plants. Diesel, kerosene, LPG and coal combustion leads to emission of CO_2 and other greenhouse gases. Thus, decentralized sustainable biomass energy systems could substitute kerosene and diesel as well as coal-based power used in a large percentage of villages and contribute to reduction in the emission of greenhouse gases. In Tumkur district, if all the energy services were to be provided by biomass based decentralized energy systems, 6.27 Mt CO_2/year of emissions could be avoided. Tumkur district shows the potential of sustainable biomass-based decentralized power generation system for mitigation of greenhouse gases in villages, panchayats and blocks, which dominate India.

The present study, based on optimization modeling, has shown the technical potential of biomass gasifier-based power generation and cattle dung plus leaf litter based-biogas systems in meeting all the power and cooking energy needs of villages in a sustainable way. Further, such a biomass-based decentralized system is carbon neutral. However, the financial policy and institutional barriers may exist in promoting bioenergy technologies, which need to be analyzed and addressed.

Reference

Amulya KNR, Sumithra GD, Balachandra P, D'sa A (1990) Operational research. Comparative costs of electricity conservation: centralized and decentralized electricity generation. Econ Polit Wkly 25:1201–1216

Bassam El, Graef N, Jakob K (1998) Sustainable energy supply for communities from biomass. Proceedings of Sustainable Agriculture for Food, Energy and Industry conference, Braunschweig, Germany, James & James, Ltd., London, pp. 837–843

Bryson N, Joseph A (1999) Generating consensus priority point vectors: a logarithmic goal programming approach. Comput Oper Res 26:637–643

Deo P, Modak S, Shulka PR (1991) Decentralized energy planning. Oxford and IBH Publishing Co. Pvt. Ltd, India

Government of India (1991) Census report for Tumkur district, Karnataka state

Government of India (2001) Census report for Tumkur district, Karnataka state

Grassi G (1998) Modern bioenergy in the European Union. Proceedings of the Sustainable Agriculture for Food, Energy and Industry conference, Braunschweig, Germany, James & James Ltd., pp. 829–836

Hiremath RB, Kumar B, Balachandra P, Ravindranath NH, Raghunandan BN (2009) Decentralised energy planning through a case study of typical village in India. J Renewable Sustain Energy 1:043103–1–043103–24

IPCC (2000) Special report on land use, land use change and forestry. United Nations Intergovernmental Panel on Climate Change, Cambridge Press, 377 pp

Moreira JR, Goldemberg J (1999) The alcohol program. Energy Policy 27:229–245

Mukunda HS, Shrinivasa U, Paul PJ, Dasappa S, Rajan NKS (1996) Stand alone small power level systems. Technical report, Combustion, Gasification and Propulsion Laboratory, Departments of Aerospace and Mechanical Engineering, ASTRA, Indian Institute of Science, Bangalore

Parikh J (1997) Energy models for 2000 and beyond. Tata McGraw Hill, New Delhi

Prigogine I (1980) From-being to becoming. W. H. Freeman and Co., San Francisco

Rajabapaiah P, Jayakumar S, Amulya KNR (1993) Biogas electricity; the Pura village case study. In: Johnansson TB, Kelly H, Reddy AKN, Williams RH (eds) Renewable energy. Island, Washington, pp 787–816

Ramanathan R, Ganesh LS (1995a) Energy alternatives for lighting in households: an evaluation using an integrated goal programming-AHP model. Energy 20:63–72

Ramanathan R, Ganesh LS (1995b) Using AHP for resource allocation problems. Eur J Oper Res 80:410–417

Rajvanshi AK (1993) Development of renewable energy technologies for third world—a need for international cooperation. American Chemical Society, Washington D.C

Ravindranath NH, Chanakya HN (1986) Biomass based energy system for a South Indian village. Biomass 9:215–233

Ravindranath NH, Hall DO (1995) Biomass, energy, and environment: a developing country perspective from India. Oxford University Press

Ravindranath NH, Dasappa S, Jayasheela Reddy CN, Somashekar HI (2004) Sustainable biomass power for rural India: case study of biomass gasifier for village electrification. Curr Sci 87:932–942

Ravindranath NH, Balachandra P (2009) Sustainable bioenergy for India: technical, economic and policy analysis. Energy 34:215–223

Sims REH (2002) The brilliance of bioenergy—In business and in practice, London. James and James, 320 pp., ISBN 1-902916-28-X

Sims REH (2003) Bioenergy to mitigate for climate change and meet the needs of society, the economy and the environment. Mitig Adapt Strateg Glob Change 8:349–370

Srinivasan R, Balachandra P (1993) Micro-level energy planning in India: a case study of Bangalore North Taluka. Int J Energy Res 17:621–632