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Implications of Decentralised Energy Planning for Rural India

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Abstract: The objective of this study is to develop a mathematical model for the effective utilization of renewable energy sources in a developing country like India. Decentralized energy planning (DEP) is in the interest of efficient utilization of resources. DEP is one of the options for meeting the rural and small scale energy needs in a reliable, affordable and environmentally sustainable way. The main aspect of the energy planning at a decentralised level would be to prepare an area-based DEP to meet energy needs and development of alternate energy sources at least-cost to the economy and environment. The geographical coverage and scale reflects the level at which the analysis takes place, which is an important factor in determining the structure of models. DEP planning involves multiple objectives and different kinds of constraints. The kinds of objective functions and constraints which have to be included in the DEP have been presented in the current work. The model developed here has been applied to a typical Indian block unit, Kunigal, which comprises several villages. Based on the analysis made in the present work, it is found that biomass-based energy systems have the potential to meet all the energy needs of Kunigal block.

Keywords: Decentralized Energy Planning; Energy planning; Goal Programming; Scenarios; Sustainable Energy Development Scenario.

1. Introduction

Energy is universally recognized as one of the most significant inputs for economic growth and human development. The growth of a nation, encompassing all sectors of the economy and all sections of society, is contingent on meeting its energy requirements adequately. Efficient use of energy and utilization of renewable energy sources are the orders of the day when it comes to mitigating greenhouse-gas emissions and, thus, the risks of possible global climate change with unpredictable consequences for our current way of life [1-2].

There is growing appreciation of the role that improvements in energy efficiency can play in bridging the gap between energy supply and demand. At the same time, there is increasing realization that these improvements are not penetrating society as rapidly as their potential would suggest. Attention is therefore being turned to the factors determining the implementation, acceptance and spread of these improvements [3].

The current pattern of commercial energy-oriented development, particularly focused on fossil fuels and centralized electricity generation, has resulted in inequities, external debt and environmental degradation. For example, large proportions of rural populations and urban poor continue to depend on low quality energy sources and inefficient [fuel-consuming] devices, leading to low a quality of life. The current status is largely a result of adoption of centralized energy planning, which ignores energy needs of the rural areas and poor, and has also led to environmental degradation due to fossil fuel consumption and forest degradation. As suggested by Reddy and Subramanian [4] and Ravindranath and Hall [5], decentralised energy planning (DEP) is one of the options available for meeting the rural and small scale energy needs in a reliable, affordable and environmentally sustainable way.

DEP is a concept of recent origin with limited applications. The central theme of energy planning at a decentralised level would be to prepare an area-based DEP to meet energy needs and development of alternate energy sources at least-cost to the economy and environment. Ecologically sound development of the region is possible when energy needs are integrated with the environmental concerns at the local and global levels [6]. Taking into account these features, the present work explains the methodology adopted for DEP by estimating the end-use energy requirement and energy resource in the region. Present work also tries to estimate the end-use energy requirement and energy resource in a typical block unit of India.

2. Experimental

2.1 Models for Decentralised Energy Planning

After presenting the resource available technologies, constraints and data availability for the region, this section deals with formulating a DEP model with multiple objectives and constraints to develop an optimal energy plan at different scales. Energy-planning involves finding a set of sources and conversion devices so as to meet the energy requirements of all the activities in an optimal manner. This optimality depends on the objective; such as to minimize the total annual costs of energy or minimization of non-local resources or maximization of a system's overall efficiency. Factors such as availability of resources in the region, costs and energy requirements of specific activities, impose constraints on regional energy planning. Thus, the DEP turns out to be a constrained optimization problem. 'Optimization' refers to the generation of the best result given certain constraints and circumstances as introduced by the programmer [7-8]. Two methods are normally used to solve the DEP problem:

2.1.1 Linear programming model (LP)

In order to meet energy planners' need for quantitative simulation a linear optimization model has been developed during the last several years [9-10]. Based on the standard method of linear programming, Groscurth et al. [11] has developed an optimization model called 'Deeco'. Bruckner et al. [1] used the 'Deeco' model to analyze competition and synergy between different technologies of the rational use of energy and for utilizing renewable energies [1]. It has been used by Lindenberger *et al.* for optimization of solar district heating systems [12] and for modernization of local energy systems [13]. Basically linear programming involves a single objective function to be maximized or minimized (subject to constraints). In some situations there may be more than one competing objective (or goal) and there may be a need to include trade-off objectives against each other. One way of handling problems with multiple objectives is to choose one of the goals as the supreme goal and to treat the others as constraints to ensure that some minimal 'satisfying' level of the other goals is achieved. A Linear Programming problem includes a single objective function and a set of absolutely binding constraints. The single objective optimization approach to the energy resource allocation at a regional level has received much research attention in the past. A number of optimization models have been developed for renewable energy allocation at both macro and micro levels. Ramakumar et al. [14] have developed a single objective linear programming model for the design of Integrated Renewable Energy Systems (IRES), where energy resource allocation for the minimization of cost was calculated on the basis of system efficiency. Henning [9] has developed an energy-system optimization model named 'MODEST' that uses linear programming to minimize the capital and operation costs of energy supply and demand-side management. Joshi *et al* [15] developed a linear programming model for DEP for three villages in Nepal. The optimization aimed at minimizing cost function by considering a mix of energy resources and conversion devices. Sinha and Kandpal [16] used a linear programming model for determining an optimal mix of technologies for domestic cooking, lighting, and irrigation sectors in the villages. A mathematical model involving conventional and renewable energy sources was formulated along with the detailed techno-economics of the different energy conversion technologies. Minimization of cost was chosen as the main objective in all their analyses. A single objective linear programming model for micro-level energy planning was developed for Bangalore North Taluka by Srinivasan and Balachandra [17], considering different energy sources and their end-use combinations.

2.1.2 Goal programming model (GP)

All the linear programming models developed so far had a single over-riding objective, such as maximizing the revenue of the study area, maximizing the biomass energy production, minimizing the total cost of energy sources or maximizing the generation of surplus biomass, etc. However, in reality, achieving such a single objective though mathematically feasible, the outputs have little utility. Very often optimizing an energy system could involve multiple objectives, namely minimizing the cost, maximizing use of local energy sources, maximizing employment, reducing emission of pollutants, etc. Thus an approach or model to optimize multiple objectives for a given set of constraints is necessary. Goal programming (GP) is a powerful and flexible modeling tool to deal with the above types of multiple criteria decision-making problems in energy planning and management for sustainable development of rural areas. Goal programming provides a way of striving towards several such objectives simultaneously. The basic approach of goal programming is to establish a specific numeric goal for each of the objectives, formulate an objective function for each objective and then seek a solution that minimizes the weighted sum of deviation of objective functions from their respective goals. There are three possible types of goals:

1. A lower one-sided goal which sets a lower limit that we do not want to fall under (but exceeding the limit is fine).
2. An upper one-sided goal which sets an upper limit that we do not want to exceed (but falling under the limit is fine).
3. A two-sided goal which sets a specific target that we do not want to miss on either side.

GP is the most suitable technique for solving multi-objective resource allocation problems. Thus GP has been chosen for the analysis here. DEP problems have been applied most frequently in practice relative to other multi-objective decision-making techniques.

2.2 The rationale for selecting GP for DEP in the present analysis is due to the following

1. Multi criteria objectives have been considered.
2. It is less subjective even among techniques based on linear programming (LP), such as multi-objective LP. It offers a rather straightforward procedure for assigning weightages to the different objectives.
3. It is best suited for DEP at micro levels.

There have been a few applications of multiple objective models to DEP. GP has been used by Bryson et al. [18] and Ramanathan and Ganesh [19] for providing DEP for urban locations. They have incorporated only quantitative criteria in their analysis. Utility theory has been employed for selecting appropriate energy resources by Ahmed et al [20], while Nezhad [21] and Saaty and Mariano [22] have used the Analytic Hierarchy Process (AHP) for providing DEP.

In the past, several techniques have been used to deal with such a problem. Ramanathan and Ganesh [23] used integrated goal programming to optimally match seven energy resources usable for lighting in households against 12 objectives representing the energy-economy-environmental system. Hoog and Hobbs [24] discussed an integrated resource planning model, which considered several objectives such as cost, emissions, regional economic impact and net value to customers. More recently, dynamic programming has been applied to the resource allocation problem, adding more features to the selection procedure used by decision makers [25]. It can be concluded that the energy sector is an essential part of the whole economic system and that modern energy planning must incorporate social and environmental objectives, leading to a multi-objective optimization problem. The economic objectives consider costs, efficiency, energy conservation, and employment generation. The environmental objectives account for environmental-friendliness factors. The objectives are first quantified, then transformed into mathematical language to obtain a multi-objective allocation model which can be solved using pre-emptive goal programming techniques. A multi-objective non pre-emptive goal programming model was developed by Ramanathan and Ganesh [26]. Ghosh *et al.* [27] have developed a Multi Criterion Decision Making (MCDM) model. MCDM is a priority-based goal programming model for optimal allocation of land under cultivation in different seasons. Parikh [28] 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*. [29] presented a priority-based goal programming model for village level energy planning with several goals. Kanniappan and Ramachandran [30] developed a goal programming model for Nilakkottai block in Dindigul District, Tamilnadu. The model aims to achieve the desired goals through optimum allocation of land area for different crops and allows the block to consume energy generated from locally available energy sources. Based on literature reviews, the next section presents the model description, with different objectives and constraints, and the possible outcomes of different scenarios.

2.3 Data needs for DEP

DEP model requires the following set of data.

- Socio-economic features- employment, gender issue etc.
- Land use: forests land, wasteland, fallow land, cropping pattern, etc.
- Energy; activities, end use devices, efficiency of devices

- Biomass production for energy; area under forests and plantations, biomass productivity, production and availability of crop residue for energy
- Energy efficiency, energy conversions, energy use
- Energy: RET (Renewable Energy Technologies) and FF (fossil fuel) technologies
- Cost of energy systems operation and maintenance, cost and financial value of energy and products.

2.4 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 the environment. The historic trends and current priorities for the study area described earlier provide a starting point for the development of various scenarios, with and without the implementation of various technologies and policy measures. Seven scenarios are considered for analysis; 1) Present energy consumption scenario (consider present rate of growth), 2) Business As Usual scenario with no priority 3) Business As Usual scenario with equal priority (no specific policies to promote alternative energy technologies or to reduce emissions); 4) Economic Objective Scenario (government subsidy plays an important role in this scenario); 5) Renewable Energy Scenario (maximum use of locally available renewable energy resources); 6) Biomass Intensive Scenario (biogas and biomass power along with energy plantations such as sowing rapeseed, palm, sunflower etc. for meeting electricity needs); and 7) Sustainable Development Scenario (high quality fuels, efficiency improvements, low environmental impacts, equitable allocation of energy resources, etc). Based on the outputs of scenarios, energy demand, cost and number people employed and CO_2, NO_x and SO_2 emissions are estimated. Although the scenario approach is one of the forecasting techniques, it is especially attractive for development planning due to uncertainties arising from various factors such as availability of resources, changing demand scenarios, technological options and cost implications. The present case scenario is for the year 2005 and BAU, RES, EOS and SDS are for the year 2020.

2.4.1 Business as Usual (BAU)

This scenario is based on the direction in which the selected location is headed. 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, resulting in high energy-related emissions and falls short of achieving a transition towards sustainable development. This scenario is subdivided into 2 sub-scenarios.

(i) BAU NP (No priority): This scenario is developed without assigning any priority to the objective functions.

(ii) BAU EP (Equal priority): This scenario assumes all the objective functions are taken into account while arriving at energy resource allocation. The objective functions considered are economic, security acceptance and environmental, and equal priority is given to all the objective functions.

2.4.2 Economic Objectives Scenario (EOS)

Energy cost objective is given the highest priority. Employment, efficiency and reliability objectives are given low priority. Government subsidy for agricultural water pumping and grid electricity for rural households is assumed to continue into the year 2020.

2.4.3 Renewable Energy Scenarios (RES)

This scenario is characterized by sustainable development, with a shift towards environmentally benign energy technologies, with a significant role for renewables. Renewable system efficiency is assumed to increase by 25% by 2020; this scenario highlights the implication of renewable energy for future energy supply trends. However, this scenario does not consider the equity aspect aimed at meeting the energy needs of all the population.

- Environment objective (EMI): is ranked higher than the other objectives. EMI appears to be the costliest scenario as economic objective is ranked lower.
- Biomass Intensive Scenario (BIS): would include energy plantations raised on degraded lands. In BIS, cost, employment generation, use of local resources and environment emissions objective functions are assigned a higher priority compared to other objective functions. Active participation of the rural people in the bioenergy programmes is assumed for its successful implementation.

2.4.4 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. Increases 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.

2.5 Description of the model

The quality and quantity of energy dictates how the societies will evolve [31]. Thus they are like "dissipative" structures [32]. 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. Selection of the appropriate model is based on the requirement of data and suitability of the model at the Decentralised 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 study consists of 7 objective functions. This model cannot be solved by using ordinary linear optimization and hence goal programming has been employed to solve the optimization problem. These 7 goals may be either *over* (1) or *under* (2) achieved. Deviation variables are introduced to represent the over or under achievement of the goals:

d_1^+ represents the amount of over-achievement of goal (1)
d_1^- represents the amount of under-achievement of goal (1)
d_2^+ represents the amount of over-achievement of goal (2)
d_2^- represents the amount of under-achievement of goal (2).

Note that for any goal K:

If the goal is exactly achieved: $d_1^+ = 0$; $d_1^- = 0$
If the goal is over-achieved: $d_1^+ > 0$; $d_1^- = 0$
If the goal is under-achieved: $d_1^+ = 0$; $d_1^- > 0$
In all cases all deviation variables ≥ 0

The objective of the goal programmer is to minimize deviations from the goals given by:

$$\text{Minimize:} \quad \sum d_i^- + d_i^+ \qquad \text{where } (j = 1, 2\ldots 7) \qquad (1)$$

Adding pairs of deviation variables to the goals transforms them into a set of constraints:

Subjected to,

$$L_j + w_j d_j^- - w_j d_j^+ = b_j \qquad (2)$$

Where, d_j^- and d_j^+ represent the under-achievement and over-achievement of the goal respectively and w_j represents the weighing factors and b_j represents the goal values.

2.5.1 Nomenclature

The following notations will be used in this paper:

i = Type of end use device service
j = Type of energy resource available
k = Type of energy system used
C_{ijk} = unit cost of energy for i end-use, for j type of energy available by using k type of energy system in Rs/kWh based on life cycle costing
η_{ijk} = system efficiency coefficient for different end-uses
e_{ijk} = employment coefficient (i.e., number of persons employed per kWh of energy allocated for the combination of end use)
p_{ijk} = emission rate of carbon oxides of i type end-use of j type resource and k type of energy system used
q_{ijk} = emission rate of sulphur oxides of i type end-use of j type resource and k type of energy system used
r_{ijk} = emission rate of nitrogen oxides of i type end-use of j type resource and k type of energy system used
R_{ijk} = Reliability factor of renewable energy systems
r_c = yield to residue ratio/ha of crops c
y_c = yield of crop c/ha
$IRL_{(fuel)}$ = Irrigated area under crop c; the residue obtained for this area is used as fuel
$URL_{(fuel)}$ = Un-irrigated area under crop c; the residue obtained for this area is used as fuel
F_{Fuel} = Quantity of crop residue of fuel in tons/year
$D_{Cooking}$ = Total Cooking energy requirement
$D_{Lighting}$ = Total Lighting energy requirement
$D_{Water\ pumping}$ = Total water pumping energy requirement
$D_{Water\ heating}$ = Total Water Heating energy requirement
$D_{Rural\ industries}$ = Total Rural industries energy requirement
$D_{Home\ appliances}$ = Total Home Appliances energy requirement
Q_{Bg} = Volume of biogas used for purpose i (m^3)
Q_{BgT} = Total volume of biogas produced in (m^3)
Q_B = Total biomass available (tons)
Q_{Bu} = Quantity of biomass used for purpose i (tons)
Q_{BA} = Quantity of biomass available for purpose i (tons)
Q_{dc} = Quantity of dung cake used for purpose i (in tons)
d_b = Quantity of dung output from animal type b in tons /year
N_b = Number of animals type b
F_U = Fuelwood used as fuel for purpose i (tons)
F_T = Fuelwood available as fuel for purpose i (tons)
T_{DA} = Total quantity of dung available from animal type b in tons /year
N_A = Total number of adult humans available for employment
P_A = Total population of village or panchayat or block
IL = Amount of residue used as fuel obtained from irrigated land area (tons)
UL = Amount of residue used as fuel obtained from unirrigated land area (tons)
TL = Total fuel requirement (tons)
X_{ijk} = Quantity of final energy for i^th^ end-use, using j^th^ resource by k^th^ end devices
P_j = Potential limit of available resources
m= resource for specific end use
Cooking……………..m=12……. (j =1 to 12)
Lighting……………..m=21……. (j =12 to 21)
Water pumping ……..m=28……. (j =21 to 28)
Water heating………..m=42……. (j =28 to 42)
Rural industries………m=49……. (j =43 to 49)
Home appliances……..m=56……. (j =49 to 56)
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)

2.5.2 Objective Functions

Seven objective functions are considered in this work. What follows is a description of these objectives, together with the corresponding mathematical formulation.

2.5.2.1 Minimization of Cost

This cost minimization objective function is represented as:

$$\text{Min} \sum_{i=1}^{6} \left[\sum_{j=1}^{m} \left[\sum_{k=1}^{n} C_{ijk} X_{ijk} \right] \right] \qquad (3)$$

where C_{ijk} is the cost coefficient, which is the unit LCC value for combination j given in table 1.

Table 1. Cost of energy resource associated with different end-use combinations($/kWh).

	Cooking	Home Lighting	Water Pumping	Water Heating	Rural industries	Home appliances
Dung cake [(a,b)]	0.0067871	-	-	0.0067871	-	-
Firewood [(a,b)]	0.0157637	-	-	0.0157637	-	-
Agricultural waste [(a,b)]	0.0126898	-	-	0.0126898	-	-
Kerosene [(b)]	0.0179531	0.0179531	-	0.0179531	-	-
LPG [(b)]	0.0374387		-	0.0374387	-	-
Biogas [(a,b)]	0.0059114	0.0059114	-	0.0059114	-	-
Solar thermal [(a,b)]	0.0081008	-	-	0.0059114	-	-
Diesel electricity [(d)]	-	0.32841	0.32841	0.32841	0.32841	0.32841
Bio-diesel electricity [(b)]	-	0.0346801	0.0346801	0.0346801	0.0346801	0.0346801
Electricity (Grid) [(c)]	0.0867002	0.0867002	0.021894	0.0867002	0.0867002	0.0867002
Biomass electricity [(a,b)]	0.0912717	0.0912717	0.0912717	0.0912717	0.0912717	0.0912717
PV electricity [b]	0.32841	0.32841	0.32841	0.32841	0.32841	0.32841
Biogas electricity[(a,b)]	0.0851239	0.0851239	0.0851239	0.0851239	0.0851239	0.0851239
Biomass + diesel electricity (Dual fuel) [(a,b)]	0.1105034	0.1105034	0.1105034	0.1105034	0.1105034	0.1105034

[a] Planning Commission http://planningcommission.nic.in/reports/genrep/ar0405.pdf (accessed on 29th March, 2009)
[b] MNRES http://mnres.nic.in (accessed on 29th March, 2009)
[c] Based on 2007 State Electricity Board charges for rural households and irrigation end-uses
[d] Estimated on the basis of cost of diesel in 2007.

2.5.2.2 Maximization of System Efficiency

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

This objective function is represented as:

$$\text{Max} \sum_{i=1}^{6} \left[\sum_{j=1}^{m} \left[\sum_{k=1}^{n} \eta_{ijk} X_{ijk} \right] \right] \tag{4}$$

where η_{ijk} represents the efficiency coefficient, given in the Table 2.

2.5.2.3 Minimization of use of petroleum products

This objective function is represented as:

$$\text{Min} \sum X_i \tag{5}$$

(i=4,5,8,13,15,17,22,24,32,33,36,38,43,45,50 and 52)

2.5.2.4 Maximization of use of locally available resources (LOCAL)

The relevant objective functions here can be represented as follows:

$$\text{Max} \sum X_j \tag{6}$$

(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)

2.5.2.5 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 [33]. The corresponding objective functions can be represented as follows:

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

(7)

where e_{ijk} denotes the number of persons employed per kWh of energy allocated for combination i. Job creation can be specified in three ways, namely:

i. 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.

ii. Indirect jobs - those jobs that arise in addition to the direct jobs referred to above, and includes services and inputs to the direct processes

iii. 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.

2.5.2.6 Minimization of CO_2, NO_X and SO_2 emissions

Three major pollutants are considered to describe the impact of human activities on the air quality. These are carbon oxides (CO and CO_2), sulfur oxides, and nitrogen oxides. The emissions due to the combustion of any energy resource depend on its composition. The corresponding objective functions can be written as follows:

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

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

$$\text{Min} \sum_{i=1}^{6} \left[\sum_{j=1}^{m} \left[\sum_{k=1}^{n} r_{ijk} X_{ijk} \right] \right] \tag{10}$$

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

2.5.2.7 Maximization of Reliability of Renewable Energy Systems

Reliability is the probability that a device will 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 rth component will have a reliability of exp $(-\lambda_{r\,t})$.

Table 2. End use energy efficiencies (%).

	Cooking	Home Lighting	Water Pumping	Water Heating	Rural industries	Home appliances
Dung cake [a]	9.5	0	0	9.5	0	0
Firewood [a]	14.25	0	0	14.25	0	0
Agricultural waste [a]	9.5	0	0	9.5	0	0
Kerosene [b]	21.6	0.72	0	21.6	0	0
LPG [b]	43.2	0	0	43.2	0	0
Biogas [a]	52.8	0.88	0	52.8	0	0
Solar thermal [d]	20	0	0	20	0	0
Diesel electricity [c]	0	11.52	23.04	21	21	21
Bio-diesel electricity [c]	0	10.72	21.44	16.08	16.08	16.08
Electricity (Grid) [c]	18.4	9.2	18.4	13.8	13.8	13.8
Biomass electricity [c]	21.888	10.944	21.888	16.416	16.416	16.416
PV electricity [e]	8	4	8	6	6	6
Biogas electricity [a]	28.16	14.08	28.16	21.12	21.12	21.12
Biomass + diesel electricity(Dual fuel) [c]	22.4	11.2	22.4	16.8	16.8	16.8
Wind electric power [f]	28	14	28	21	21	21

[a] Based on [5,34]

[b] Based on [35,36]

[c] Based on http://cgpl.iisc.ernet.in/ (accessed on 29th August, 2009), http://mop.nic.in (accessed on 29th August, 2009)

[d] Solar thermal does not have an external efficiency, since it comes from the Sun.

[e] Based on a 50 kW-5kW solar photovoltaic system [37].

[f] Based on [36].

Hence, the reliability for the system would be

$$\begin{aligned} R(t) &= \exp(-\lambda_1 t) \times \exp(-\lambda_2 t) \times \cdots \times \exp(-\lambda_s t) \\ &= \exp[-(\lambda_1 + \lambda_2 + \cdots + \lambda_s)t] \\ &= \exp\left(-\sum \lambda_{rt}\right) \end{aligned} \qquad (11)$$

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.

$$\text{Max} \sum_{i=1}^{6} \left[\sum_{j=1}^{m} \left[\sum_{k=1}^{n} R_{ijk} X_{ijk} \right] \right] \qquad (12)$$

The optimization model is generally subject to the following constraints:

2.5.2.8 Demand Constraints

1. Cooking energy requirement

$$\sum_{j=1}^{12} \left[\sum_{k=1}^{n} X_{jk} \right] \geq D_{\text{Cooking}} \qquad (13)$$

2. Lighting energy requirement

$$\sum_{j=13}^{21} \left[\sum_{k=1}^{n} X_{jk} \right] \geq D_{\text{Lighting}} \qquad (14)$$

3. Water pumping energy requirement

$$\sum_{j=22}^{28} \left[\sum_{k=1}^{n} X_{jk} \right] \geq D_{\text{Water pumping}} \qquad (15)$$

4. Water heating energy requirement

$$\sum_{j=29}^{42} \left[\sum_{k=1}^{n} X_{jk} \right] \geq D_{\text{Water heating}} \qquad (16)$$

5. Rural industries requirement

$$\sum_{j=43}^{49} \left[\sum_{k=1}^{n} X_{jk} \right] \geq D_{\text{Rural industries}} \qquad (17)$$

6. Home appliances energy requirement

$$\sum_{j=49}^{56} \left[\sum_{k=1}^{n} X_{jk} \right] \geq D_{\text{Home appliances}} \qquad (18)$$

7. Fuel constraints:

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

$$\sum_{i=1}^{6}\sum_{k=1}^{6} (r_c \times y_c) I_{L_{ik}} + \sum_{i=1}^{6}\sum_{k=1}^{6} (r_c \times y_c) U_{L_{ik}} \leq T_L \qquad (19)$$

2.5.2.9 Supply Constraints

1. Limits for solar thermal usage for cooking: Solar thermal cookers cannot cook all varieties of food and therefore they do not meet the total cooking requirements. As such, solar thermal cookers can be used for low-temperature cooking purposes only, which form approximately 20% of the total cooking requirement [10]. 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% of total cooking requirement (20)

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

$$\sum_{i=1}^{6}\sum_{k=1}^{6} Q_{BU_{ik}} \leq Q_{BA} \qquad (21)$$

3. Dung balance: Quantity of dung used for purpose (dung cake + biogas production) ≤ quantity of dung available

$$\left[\sum_{i=1,4}\sum_{k=1}^{2} Qdc_{ik} + \sum_{i=1}^{6}\sum_{k=1}^{3} QBg_{ik} \right] \leq d_b N_b \qquad (22)$$

4. Fuel wood constraints: Quantity of fuel wood used for (cooking + heating) ≤ total quantity of fuel wood available

$$\sum_{i=1,4}\sum_{k=1}^{2} F_{u\,ik} \leq F_T \qquad (23)$$

5. Biogas balance: Volume of biogas used for different purpose ≤ total volume of biogas generated

$$\sum_{i=1}^{6}\sum_{k=1}^{6} Q_{Bg_{ik}} \leq Q_{BgT} \qquad (24)$$

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

$$\sum_{i=1}^{6}\sum_{k=1}^{6} Q_{Bg_{ik}} \leq 50\%\ T_{DA} \qquad (25)$$

7. Dung cake constraint: Limit for use of dung cake for cooking and heating: Cooking patterns of the region indicate that the dung cakes are not fully consumed for the cooking and heating applications. 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 are used for cooking and heating applications. Therefore, dung required for making dung cake ≤ 50% of total dung available

$$\sum_{i=1,4}^{4}\sum_{k=1}^{2} Q_{dc_{ik}} \leq 50\%\ T_{DA} \qquad (26)$$

8. Employment constraints: Total number of adult humans available for employment ≤ 60% of the available population of the area selected.

$$\sum_{i=1}^{6} \left[\sum_{j=1}^{m} \left[\sum_{k=1}^{n} NA_{ijk} \right] \right] \leq 60\%\ P_A \qquad (27)$$

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

$$\left[\sum_{j=1}^{3} \left[\sum_{k=1}^{n} (1/R_j) \sum X_{ijk} \right] \right] \leq P_j \qquad (28)$$

2.6 Mathematical Programming

The goal programming model is described as follows:

Minimize:

$\sum d_{j-} + d_{j+}$, where j=1,2,……8

Subject to:

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

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

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

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

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

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.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$\sum X_4 \leq$ 20% of the total cooking energy requirement

where j=4. (Solar thermal constraint)

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

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

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

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

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

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

3. Results and Discussion

This section presents the results of energy resource allocation at Kunigal Block level for the base year (2005). Different scenarios are developed for the year 2020 with an aim of identifying the optimal scenario for implementation. The selection of scenario is carried out on the basis of cost incurred in energy supply, associated emissions and use of local resources. The optimization model is solved using WINQSB package. Kunigal Block has 36 Panchayats (GPs) and 314 villages. The total area of the block is 99,110 ha and its total population is over 0.2 million. The block has 47,200 households out of which 8853 households are without electricity. Table 3 presents a summary of the DEP for results of different scenarios, which are explained in detail in the following sections.

3.1 Options for cooking energy needs

Energy resource allocation in Kunigal block shows that 68% of the households used solid biomass, 22% LPG and 13% kerosene as cooking fuel under the PECS scenario. BAU (EP) scenario with equal priority for all the objective functions shows that biogas produced from the available livestock dung in the block can meet 57% of cooking energy needs and the remaining through biomass, 22% and from LPG, 21%.

Biogas is produced from livestock dung and leaf litter collected from [vegetation] energy plantations grown on degraded lands. Liquefaction of biogas is not possible, so transportation of the gas is not an option. Thus, the optimal option for cooking is community biogas systems in the villages of Kunigal block under EOS, RES and SDS scenarios where 100% of energy needs can be met.

3.2 Option for water heating energy needs

Under PECS and BAU (NP), traditional stoves with low efficiency are the options for water heating using solid biomass. Solar water heater is the option for heating water under BAU (EP) and RES (ERS) as over 300 days of bright sun shine are available in the region. Improved stoves with an efficiency higher than 25% are the best option to heat water under EOS and BIS scenarios. Surplus biogas available from energy plantation appears to be the option for SDS scenario. Thus, the optimal options for water heating are surplus biogas and improved cooking stoves under SDS and BIS scenarios.

Table 3: Optimal energy resource allocation for Kunigal block under different scenarios

	PECS (2005)	BAU (2020)		Economic objectives scenario (2020)	RES (2020)		SDS (2020)
Activities		No priority	Equal priority	Cost (1)[b], Employment (2)[b], Efficiency and Reliability (3)[b]	ERS; Emission (1)[b], Economic (2)[b] and Security (3)[b]	BIS Cost, Employment, Local and Emissions (1)[b]	Economic, Security and Emission (1)[b]
Cooking	Biomass (65%) LPG (22%) Kerosene (13%)	Biomass (50%) LPG (50%)	Biomass (22%) LPG (21%) Biogas (57%)	Biogas (100%)	Biogas (100%)	Biogas (100%)	Biogas (100%)
Home Lighting	Kerosene (50%) Grid (50%)	Grid (100%)	PV Electricity (100%)	Biomass Electricity (100%)	PV electricity (100%)	Biomass Electricity (100%)	Biomass Electricity (100%)
Water Pumping	Diesel electricity (10%) Grid (90%)	Grid (100%)	Biomass electricity+ diesel electricity (100%)	Grid (100%)	PV electricity (100%)	Biomass electricity (100%)	Biomass Electricity (100%)
Water Heating	Biomass (100%)	Biomass (100%)	Solar thermal (100%)	Biomass using improved cook stoves (100%)	Solar thermal (100%)	Biomass using improved cook stoves (100%)	Biogas (100%)
Rural Industries	Diesel (10%) Grid (50%) Biomass (40%)	Grid (40%) Biomass (60%)	Biomass electricity+ diesel electricity (100%)	Biomass electricity (100%)	Biomass electricity (100%)	Biomass electricity (100%)	Biomass electricity (100%)
Home Appliances	Grid (100%)	Grid (100%)	Biomass electricity (100%)	Biomass electricity (100%)	PV electricity (100%)	Biomass electricity (100%)	Biomass electricity (100%)

[a] Using improved cook stoves.

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

3.3 Home lighting energy needs

PV electricity appears as the optimal source of electricity for lighting in BAU (EP) and RES (ERS) scenarios, where cost minimization is not the priority. Energy plantation grown on the available wasteland generates biomass, which is converted into electricity through biomass gasifiers. Biomass power is the optimal solution to meet the Home lighting needs of the block under EOS, BIS and SDS scenarios.

3.4 Options for water pumping energy needs

Water pumping energy needs under PECS are met by grid electricity (up to 90%) which is subsidized (at $0.022 kWh) and 10% by diesel electricity which is used when grid is unavailable (Figure 1). So, PECS is largely based on grid. Kunigal is projected to have 10112 irrigation pump sets by 2020 compared to 6212 in 2005. Biomass power is the optimal solution for meeting electricity demand for agricultural pumping activity under BIS and SDS scenarios.

3.5 Rural Industries

Rural industries like Jaggery manufacturing and pottery depend on solid biomass while others like milk processing units, rice mills and flour mills need electricity. Detailed Diesel (10%), biomass (40%) and grid electricity (50%) are used as sources of energy for industries (Figure 2). BAU (No priority): Results show that grid electricity and biomass meet 40% and 60% of energy needs of rural industry in Kunigal block, respectively, under BAU (NP). Biomass dual-fuel under BAU (EP), biomass power under EOS, RES and SDS scenarios are the optimal options for meeting the electricity needs of rural industry.

3.6 Employment generation, associated costs and emissions under different scenarios for Kunigal block

The associated costs, emissions and employment under different scenarios for Kunigal block are presented in Table 4. Results obtained from the analysis show that SDS is the least-cost, high employment and emission free scenario. The number of jobs created is also given in Table 4 and maximum employment is generated under RES (BIS) scenario due to dedicated biomass production and processing activities.

4. Conclusion

This work formulates the different objectives functions which have to be considered for the DEP and states the constraints while formulating such problems. Although different approaches are available in the literature, Goal programming has been shown to be appropriate for DEP. Methodology for making objectives functions and constraints for DEP has been discussed in the manuscript. This study covers an assessment of the current energy demand and supply situations, the development of several forecasting scenarios (business-as-usual energy scenario, biomass energy intensive scenario, renewable energy scenario and sustainable development energy scenario), supply-demand balancing, the identification of intervention options, and an assessment of impacts of future trends and interventions in economic and environmental terms. Application of the present model has been shown in a typical block (Kunigal block) from India. A block constitutes a cluster of villages with distinct geographic boundary consisting of settlement, agricultural land, water bodies and any other land category, in most parts of India. Each individual village forms a distinct rural identity, each of which is generally separated by agricultural or forest land. The present model suggests that biomass-based energy systems have the potential to meet all rural energy needs. At the block level large expanses of wasteland are available (34% of geographic area). If these wastelands are used for raising energy plantation, all the electricity needs of the block could be met. High employment generation and carbon mitigation could also be achieved by adopting RES and SDS scenarios. Further, all cooking needs could be met from biogas options.

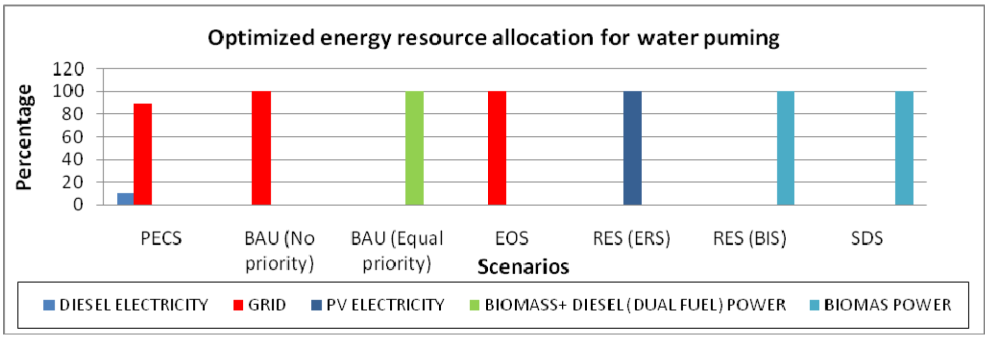

Figure 1. Optimized energy resource allocation and technology mix for meeting water pumping energy needs.

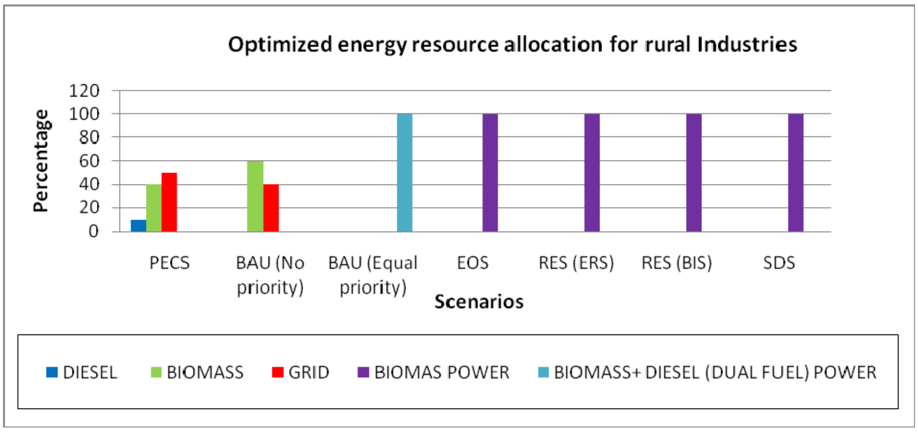

Figure 2. Optimized energy resource allocation and technology mix for rural industries in Kunigal block under different scenarios.

Table 4: Combined results of associated costs, emissions and employment under different scenarios for Kunigal Block.

Scenario	Priority to objective functions	Total life cycle cost associated million $/year	Emissions associated in Tons/year			No of jobs generated (persons employed)
			CO_2,	SO_2,	NO_x,	
PECS 2005		3.459252	255595.02[b] (1.09)	1476.46[b]	1853.32[b]	
BAU 2020	No Priority	29.77584	243169.52[b] (0.77)	2596.52[b]	2979.29[b]	
	Equal priority	24.91537	9842.24[b] (0.03)	2.63[b]	12.95[b]	
Economic	Cost(1)[d], Employment(2)[d], Efficiency and Reliability (3)[d]	12.4138[a]	1591.20 (0.01)	58.02[b]	94.22[b]	6688
RES	ERS : Emission (1)[d], Economic (2)[d] and Security (3)[d]	56.968 [a]	0[c]	18.77[b]	30.67[b]	8295
	BES: Cost, Employment, Local, Emission (1 [d]	12.566 [a]	0[c]	18.77[b]	64.94[b]	10059
SDS	Economic, Security and Emission (1)[d]	9.5019 [a]	0[c]	20.7 [b]	2.79[b]	6056

[a] Total cost includes cost incurred for energy plantation (Life cycle cost)

[b] Considering emissions from only unsustainable energy sources which accounts for 40% of total emissions. (Example; Total $CO_{2\ \text{emissions}}$ for PECS 2005 is 638987, thus 638987* 40% = 255595for CO_2 of PECS scenario)

[c] Carbon neutral energy sources

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

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