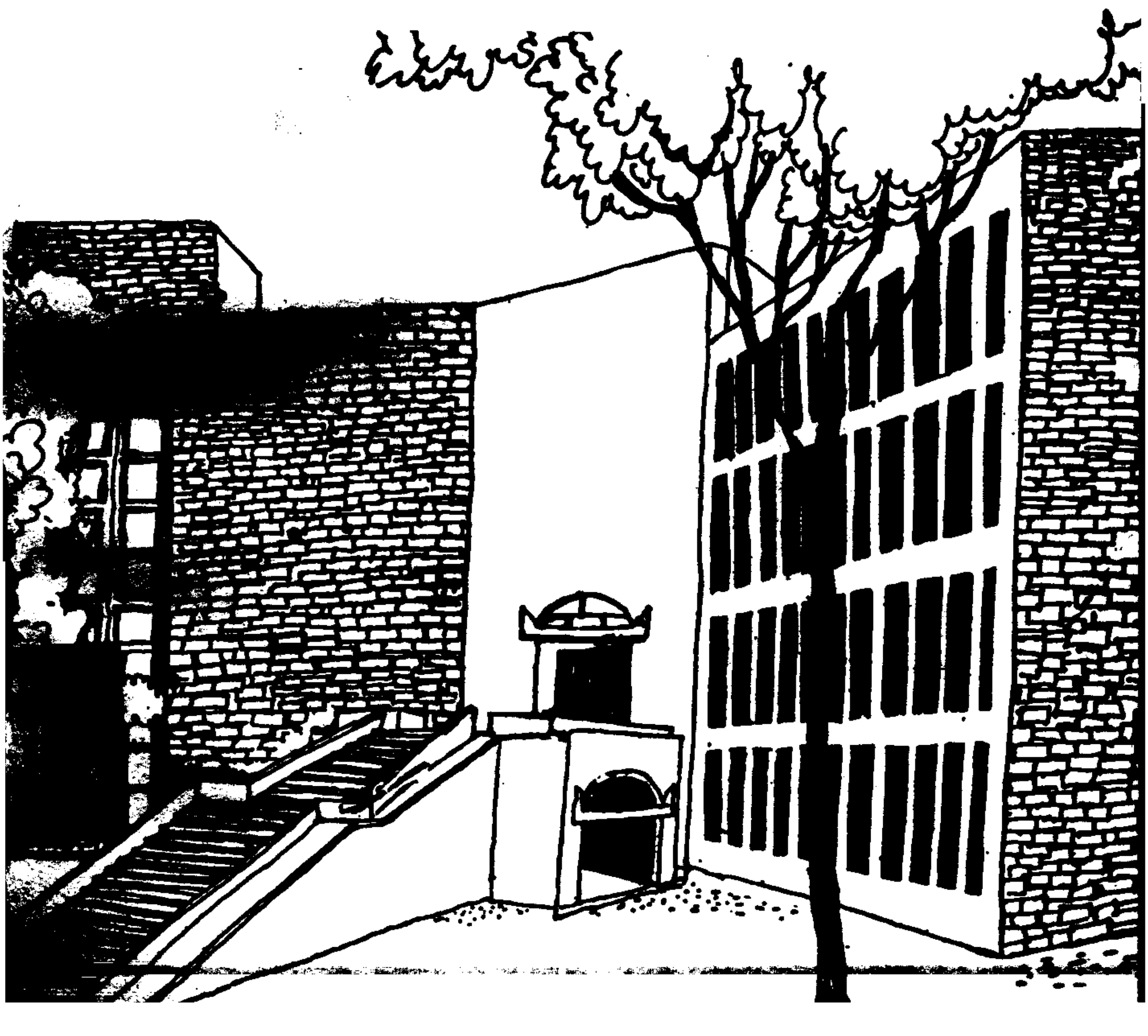
Working Paper



A GOAL PROGRAMMING MODEL FOR SELECTION OF INTEGRATED RURAL ENERGY SYSTEM

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Abstract

This paper presents a goal programming model for selection of Integrated Rural Energy System (IRES). The decisions involve (i) selection of a mix of energy generating systems and (ii) allocation of energy from these to different end-uses: These decisions are made considering several goals such as budget requirements, cost minimization, energy demand and supply, fuel-wood conservation etc. A pre-emptive priority structure for goal achievement is considered. The formulation thus results in a mixed integer linear goal programming (MILGP) model.

1. Introduction

The present authors have reported elsewhere [1] [2] [3] the use of a Mixed Integer Linear Programming (MILP) model for optimal selection of Integrated Rural Energy System (IRES). That model considered selecting for a village a mix of energy systems and allocation of energy from them to various end-uses that minimizes the total annual costs i.e. sum of fixed and variable costs for the village. Only objective considered thus was cost minimization and other important requirements such as annual budget finances, resources availability, demand, capacity of energy systems etc. were treated as constraints. Building of the same MILP framework, this paper presents a goal programming model for IRES selection which allows a more flexible framework for selection of IRES and considers various requirements as goals to be achieved with certain priorities instead of inviolable constraints.

1.1. Problem Statement

There are several energy sources for supplying energy to different end-uses. Some of these operate at different efficiencies during different time periods of a year. Energy demand at a village is for certain end-use which require different quantum of energy during different time periods in a year. Similarly there are several energy resources which have different level of availability during an year. Some of the energy systems can supply energy to several end-uses via some secondary energy systems and both types of systems are available in different sizes. At a given location, the problem then is to: (i) select the primary and secondary energy systems and (ii) decide allocation of energy from them to different end-uses in different time periods. These decisions must consider several goals with different priority levels such as (a) meet energy need of each end-use (b) use energy resources within certain limits (c) keep capital costs within budget limits (d) minimize annual total cost of energy system, i.e. sum of annual fixed and variable costs etc. The basic problem formulation approach is similar to the location-allocation problem [4] [5] and since both fixed and variable costs and several goals are considered to be met at different priority levels, the formulation results in Mixed Integer Linear Goal Programming (MILGP) model.

2. Goals and Priorities

Goals and their priorities are as given below. Pre-emptive priority structure [6] with lexicographic ordering (i.e. $P_1 >>> P_2 >>> \dots P_n$) is assumed.

Priority Level 1 (P_1)

Goal : Capacities of primary and secondary energy systems can not be exceeded. This is essentially a strict constraint for most energy systems. However in case of some other energy systems, capacity can be altered within absolute upper limits, (e.g.) capacity computation of some energy systems assume system availability generally only during sometime of a day, however if needed, energy system may be run longer at certain times.

Goal : Fixed (capital) costs should not exceed the maximum specified budget limits.

Priority Level-2 (P_2)

Goal: As cooking and hot water are considered most important end-uses, meeting demands for these end-uses is considered with second priority.

Priority Level-3 (P_3)

Goal : Meet irrigation demand.

Priority Level-4 (P_4)

Goal : Meet electricity demand.

Priority level 5 (P_5)

Goal: Fuel wood availability not to be exceeded. Available fuel-wood quantum is not considered as inviodable but is treated as lower priority goal, since if needed, additional fuel wood may be obtained from market.

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Priority Level 6 (P_6)

Goal : Minimize total annual costs, i.e. sum of annual fixed and variable costs.

Priority Level 7 (P_7)

Goal : Although using wood within normal availability limits is considered with fifth priority (P_5), conservation of fuel wood is considered desirable at this level of priority.

Priority Level 8 (P_8)

Goal : Although the strict upper limit of budget amount (B) for capital costs is considered with first priority (P_1), it is considered desirable at this level of priority to keep budget amount within a still lower limit ($B^1 : B^1 \leq B$)

Priority Level 9 (P_9)

Goal : Use all available gobar.

3. Model Assumptions

Following assumptions are made.

1. A year is divided into several time periods to account for different efficiencies of some energy systems and different energy demands for each end-use in different time period of a year.

2. For each energy system, the amount of raw materials used and variable costs are proportional to the amount of energy supplied.
3. Given the energy supplied by each energy system, the total cost and energy supplied are sums of costs and energy supplied by each source.
4. Fixed cost of a primary energy system is charged if and only if the system supplies positive amount of energy.
5. Fixed cost of a secondary energy system is charged if and only if any primary energy system supplies positive energy to an end-use that secondary energy system.

4. MODEL FORMULATION

Formulation of constraints and objective function is given below:

4.1 Legend and Variable and Co-efficient Definitions

P = Number of primary energy systems.

i = Index number for primary energy system - $i = 1,2,..p$

n_i = Number of sizes of i^{th} primary energy system.

j = Index number for sizes of each primary system. For i^{th} primary system $j = 1,2,..n_i$.

d = Number of End-uses requiring energy.

k = Index number for end-uses - $k = 1,2,..d$.

e = Number of time periods in a year.

t = Index Number for the time period - $t = 1,2,..e$

q = Number of secondary energy systems.

l = Index number for secondary energy system - $l = 1,2..q$

m_l = Number of sizes of l^{th} secondary energy system.

s = Index number for sizes of each secondary system. For the l^{th} secondary system - $s = 1,2,..m_l$.

h = Number of raw materials used by energy systems.

r = Index number of raw materials - $r = 1,2,..h$

Y_{ij} = Number of units of primary energy systems i of size j.

F_{ij} = Fixed cost of installing a primary energy system i of size j.

$\bar{F}_{ij}$ = Annual fixed cost of installing a primary energy system i of size j.

Z_{ls} = Number of units of se condary power system of type l and size s.

G_{ls} = Fixed cost of installing a secondary energy system of type l and size s.

$\bar{G}_{ls}$ = Annual fixed cost of installing a secondary system of type l and size s.

X_{ikt} = Amount of energy supplied annually by a primary energy system i to end-use k in a period t.

C_{ikt} = Variable cost of using a unit of energy from energy system i for end-use k in time period t.

U_{ijt} = Capacity of primary energy system of type i of size j in time period t.

V_{lst} = Capacity of secondary energy system of type l of size s in time period t.

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a_{iktr} = Raw material of type r required to supply a unit of energy by primary energy system i to end-use k in period t.

A_{rt} = Availability of raw material of type r in time period t.

D_{kt} = Energy demand of end-use k in period t.

d_g^+ and d_g^- = Deviational variables for gth, constraint associated respectively with under achievement and over achievement of that goal.

In the present formulation, some indices have following interpretation.

Index value	1	2	3	4
k	Cooking	Hot Water	Irrigation	Electricity
t	Summer	Monsoon	Winter	
r	Wood	Gobar.		

4.2 Goal Constraints

1. Budget constraint

A. Fixed cost of IRES must not exceed maximum budget amount B.

$$\sum_i \sum_j F_{ij}Y_{ij} + \sum_l \sum_s G_{ls}Z_{ls} + \bar{d}_1 - d_1^+ = B$$

B. Fixed cost of IRES should be within amount B^1 ($B^1 < B$)

$$\bar{d}_1 + d_{11}^- - d_{11}^+ = B - B^1$$

II. Capacity Constraints

Energy supplied from a primary or secondary energy system can not exceed capacity of the system.

A. Primary Systems

$$\sum_k X_{ikt} - \sum_j U_{ijt} Y_{ij} + \bar{d}_{2it} - \overset{+}{d}_{2it} = 0, \forall i,t$$

B. Secondary systems

$$\sum_i \sum_{\substack{\epsilon i \\ k \epsilon k}} X_{ikt} - \sum_s U_{1st} Z_{1s} + \bar{d}_{31t} - \overset{+}{d}_{31t} = 0 , \forall 1,t$$

III. Energy Demand Constraints

These constraints require energy demand for different end-uses to be met.

A. Cooking Demand

$$\sum_i X_{i1t} + \bar{d}_{41t} - \overset{+}{d}_{41t} = D_{1t}, \quad \forall t$$

B. Hot water Demand

$$\sum_i X_{i3t} + \bar{d}_{43t} - \overset{+}{d}_{42t} = D_{2t}, \quad \forall t$$

C. Irrigation Demand

$$\sum_i X_{i3t} + \bar{d}_{43t} - \overset{+}{d}_{43t} = D_{3t}, \forall t$$

D. Electricity Demand

$$\sum_i X_{i4t} + \bar{d}_{44t} - \overset{+}{d}_{44t} = D_{4t}, \quad \forall t$$

IV. Resource Constraints

A. Use of Wood

This constraint considers that use of wood may not exceed quantity of wood locally available during the year.

$$\sum_i \sum_k \sum_t a_{iktl} \, x_{ikt} + \bar{d}_5 - \overset{+}{d}_5 = \sum_t A_{1t}$$

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B. Use of Gobar

This constraint is for the requirement that all gobar in the village shall be used.

$$\sum_i \sum_k a_{ikt2} X_{ikt} + \bar{d}_{6t} - \overset{+}{d}_{6t} = A_{2t}, \ \forall t$$

C. Fuel Wood Conservation

This constraint captures the requirement that fuel wood consumption be minimized.

$$\bar{d}_5 + \bar{d}_{51} - \overset{+}{d}_{51} = \sum_t A_{1t}$$

V. Total Annual Cost

This constraint requires that total annual cost of the IRES be minimized.

$$\sum_i \sum_j \bar{F}_{ij} Y_{ij} + \sum_l \sum_s \bar{G}_{ls} Z_{ls} + \sum_i \sum_k \sum_t C_{ikt} X_{ikt} + \bar{d}_7 - \overset{+}{d}_7 = 0$$

4.3 Objective Function

Given the goal constraints, deviaticnal variables and the goal priority structure suggested earlier, the objective is to minimize the total deviations from goals in the lexiocographic order of given priority structure. The objective function thus would be:

$$P_1[\sum_i \sum_t \overset{+}{d}_{2it} + \sum_l \sum_t \overset{+}{d}_{31t} + \overset{+}{d}_1] + P_2[\Sigma \overset{+}{d}_{41t} + \Sigma \overset{+}{d}_{42t}] + P_3[\Sigma \overset{+}{d}_{43}t] + P_4[\Sigma \overset{+}{d}_{44t}] + P_5[\overset{+}{d}_5] + P_6[\overset{+}{d}_7] + P_7[\overset{+}{d}_{51}] + P_8[\overset{+}{d}_1] + P_9[\sum_t (\overset{+}{D}_{6t} + \bar{D}_{6t})]$$

4.4 Formulation Summary

From above, Goal Programming Formulation can be summarised as follows:.

$$\text{Minimize } Z = P_1[\sum_i \sum_t d^+_{2it} + \sum_l \sum_t d^+_{3lt} + d^+_1]$$
$$+ P_2[\sum_t (d^+_{41t} + d^+_{42t})] + P_3[\sum_t d^+_{43t}]$$
$$+ P_4[\sum_t d^+_{44t}] + P_5[d^+_5] + P_6[d^+_7]$$
$$+ P_7[d^-_{51}] + P_8[d^-_{11}] + P_9[\Sigma(D^+_{6t} + D^+_{6t})]$$

s.t:

$$\sum_i \sum_j F_{ij} Y_{ij} + \sum_l \sum_s G_{ls} Z_{ls} + d^-_1 - d^+_1 = B \quad \ldots(1)$$

$$d^-_1 + d^-_{11} - d^+_{11} = 0 \quad \ldots\ldots(2)$$

$$\sum_k X_{ikt} - \sum_j U_{ijt} Y_{ij} + d^-_{2it} - d^+_{2it} = 0, \ \forall i,t \ldots(3)$$

$$\sum_{i \in I} \sum_{k \in K} x_{ikt} - \sum_s U_{lst} Z_{ls} + d^-_{3lt} - d^+_{3lt} = 0 \ \forall l,t \quad (4)$$

$$\sum_i X_{i2t} + d^-_{42t} - d^+_{42t} = D_{2t}, \ \forall t \quad \ldots(5)$$

$$\sum_i X_{i1t} + d^-_{41t} - d^+_{41t} = D_{1t}, \ \forall t \quad \ldots(6)$$

$$\Sigma X_{i3t} + d^-_{43t} - d^+_{43t} = D_{3t}, \ \forall t \quad \ldots\ldots(7)$$

$$\Sigma X_{i4t} + d^-_{44t} - d^+_{44t} = D_{4t}, \ \forall t \quad \ldots\ldots(8)$$

$$\sum_i \sum_k \sum_t a_{iktl} x_{ikt} + d^-_5 - d^+_5 = \Sigma A_{1t} \quad \ldots\ldots(9)$$

$$\sum_i \sum_k a_{ikt2} X_{ikt} + d^-_{6t} - d^+_{6t} = A_{2t}, \ \forall t \quad (10)$$

$$\bar{d}_5 = \bar{d}_{51} - \overset{+}{d}_{51} = \Sigma A_{1t} \quad ..... (11)$$

$$\sum_i \sum_j \bar{F}_{ij} Y_{ij} + \sum_l \sum_s \bar{G}_{ls} Z_{ls} + \sum_i \sum_k \sum_t C_{ikt} X_{ikt} + \bar{d}_7 - \overset{+}{d}_7 = o \quad (12)$$

<u>Non-negativity Constraints</u>

$$X_{ikt} \geq 0, i = k,2,..m: k = 1,2,..d: t = 1,2... \quad (13)$$

$$Y_{ij} \geq 0, \text{ and free integer}, i = 1,2..n: j = 1,2..ni \quad (14)$$

$$X_{ls} \geq 0, \text{ and free integer}, l = 1,2..q: s = 1,2..ml \quad (15)$$

$$\overset{+}{d}_* \text{ and } \bar{d}_* \geq 0 \text{ , for all * values} \quad .... (16)$$

5. <u>Conclusions</u>

Compared to the MILP model [1] which minimizes total annual costs, the proposed goal programming model offers considerable advantages. Instead of treating constraints as inviolable, as in MILP model, the goal programming model treats them more flexibly as goals allowing deviations from constraint limits. Also, the pre-emptive priority structure allows achieving goals hierarchically rather than treating them equally as constraints as in MILP model Thus the goal programming model is more flexible and realistic. The sensitivity analysis with different pre-emptive priority structures can also provide insight to the decision maker in understanding the impact of changes in priority structure on decisions and goal achievements. The goal programming model for IRES selection compared to MILP model makes IRES planning superior and more realistic.

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