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A HYDRO–WOOD NET-ENERGY APPROACH TO HYDRO PROJECT DESIGN

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Abstract—An integrated approach to energy planning, when applied to large hydroelectric projects, requires that the energy-opportunity cost of the land submerged under the reservoir be incorporated into the planning methodology. Biomass energy lost from the submerged land has to be compared to the electrical energy generated, for which we develop four alternative formulations of the net-energy function. The design problem is posed as an LP problem and is solved for two sites in India. Our results show that the proposed designs may not be viable in net-energy terms, whereas a marginal reduction in the generation capacity could lead to an optimal design that gives substantial savings in the submerged area. Allowing seasonal variations in the hydroelectric generation capacity also reduces the reservoir size. A mixed hydro–wood generation system is then examined and is found to be viable.

INTRODUCTION

Energy planning in developing countries has traditionally focussed on commercial energy sources (coal, oil, natural gas, and electricity) and neglected non-commercial sources (fuelwood, animal dung, and agricultural wastes). More recently, however, an integrated approach to energy planning has been proposed in which all of the sources of energy are considered. In this approach, optimal source and end-use matches that satisfy the criteria of catering to the basic needs of the population while being environmentally sound and sustainable are determined.[1] In light of these new criteria, a review of the planning of energy-generation facilities becomes necessary. We examine the methodology currently used for large hydroelectric projects and suggest modifications that include the cost of land submerged in energy terms. A linear programming (LP) model is proposed that optimizes the net-energy obtained from such a project. The manner in which electrical (hydro) and thermal (biomass) energies may be compared is discussed and alternative formulations are suggested for the net-energy function. Two project sites in India are then analyzed for different values of the productivity of submerged land and for the case when seasonal variations in generation capacity are allowed. Finally, the viability of a mixed generation system that balances seasonal variation in hydroelectric generation capacity with wood-based generation capacity is examined.

PLANNING OF HYDROELECTRIC PROJECTS

Hydroelectric energy (or "hydel" energy) is the only major renewable source of electrical energy today. It contributes about 22% of the global supply of electricity. But this amounts to only about 16% of the global potential for hydro-power generation.[2] Hydel energy generation is expected to increase from 1953 TWh in 1984 to about 7680 TWh by 2020 A.D. and a major portion of this growth is expected to take place in the developing countries.[3] The capital-intensive nature of hydel projects makes planning bodies opt for macro-hydel facilities in order to capture economies of scale.‡ Most of the future global energy-supply scenarios include very large hydro-power facilities.[4,2] Such facilities would inevitably flood large areas of land, which

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‡Macro-hydel facilities are defined as facilities having an installed capacity of more than 40 MW.

are often thickly forested. Consequently, the opportunity cost of such facilities could be substantial when measured in energy terms.

In order to construct a model that includes this cost, we present a brief review of the methodology that is currently used for determining project dimensions. Hydel facilities are traditionally designed for a constant year-round generation capacity, especially in regions deficient in thermal power. After the site is chosen from preliminary investigations, hydrologic data are obtained. The target for energy generation is fixed, using either some simplistic rules such as designing for a gross utilization of 90% of the average annual inflow or, preferably, on the basis of an economic analysis that maximizes net economic returns.[5] Given the desired generation capacity and knowing the generation head, the average seasonal power draft (i.e., volume of water drawn for power generation) is calculated. The active storage capacity required to ensure this release in every season with a specified level of dependability is then determined by using a standard procedure for storage-yield calculations.[6]

Large dams, whether used for hydro-power or for irrigation, have been severely criticized by environmentalists,[7] which suggests that they may not be environmentally sound. But the planning methodology for macro-hydel projects also violates the fundamental concept of integrated energy planning in three ways. First, the land submerged by the reservoir could be used to produce energy in other ways, e.g., energy from biomass. (Other possible alternatives such as solar or wind power do not appear to be economically viable at present.) The energy-opportunity cost of submerged land may be comparable to the benefit accruing from hydel energy, especially since the land submerged by such projects is often already thickly forested and has been a permanent source of fuelwood for the local population.[8,9] Second, an attempt to maximize electrical energy generation may not be commensurate with the criterion of satisfying the basic needs of society in a developing country. Third, in an integrated energy system, it may not be necessary to insist on the same hydel generation capacity in every seaaon.

We propose a revised planning methodology along the lines suggested by Subramanian[10] that maximizes the net energy from the project, takes into account the importance of fuelwood as a source of energy in developing countries, and allows for seasonal variations in generation capacity.

FORMULATION OF THE MODEL

We limit ourselves to a single-site, storage-type, hydro-only project, and assume that preliminary investigations have determined the dam and powerhouse sites, dam type, required dead-storage capacity, etc. The energy-opportunity cost of land submergence is taken to be the energy content of the biomass increment that would have been obtained from an energy plantation on that land. The input data consist of site-specific data (area–capacity relationship, inflow records, generation head, dead storage capacity, seasonal evaporation rates) and technical data (generator and turbine efficiencies, seasonal load factors, dependability norm, potential productivity of land submerged). We determine optimum values of the decision variables, consisting of seasonal power drafts, reservoir storage capacity, and installed generation capacity, to maximize the net-energy obtained. These are subject to hydrological continuity and minimum storage constraints, constraints on allowable inter-seasonal variation in generation capacity, and other constraints such as maximum submergible area or minimum installed capacity.

The LP model

For high-head sites, the generation head is approximately constant regardless of the actual water level in the reservoir. The annual hydel energy generation in kWh(e) is then given by

$$E_{\text{hydel}} = \sum_{i=1}^{S} D_i \times H \times g \times n_{gt} \times 1000/3.6 = \sum_{i=1}^{S} D_i \times k_1, \tag{1a}$$

i.e., by the sum of the energy generated from the power drafts in all the seasons. For a 2-season model, which we have found sufficient, Eq. (1a) becomes

$$E_{\text{hydel}} = (D_1 + D_2) \times k_1. \tag{1b}$$

On the other hand, the thermal energy [in kWh(th)] that would have been obtained from the annual biomass increment from the submerged land is

$$\begin{aligned} E_{\text{wlost}} &= A_{\text{sub}} \times f \times W \times c_{\text{w}}/3.6 \\ &= A_{\text{sub}} \times k_2. \end{aligned} \tag{2}$$

The area–capacity curve may be assumed to be linear for the range of values considered, i.e.,

$$\begin{aligned} A_{\text{sub}} &= a \times (\text{total storage capacity}) + b' = a \times (K_{\text{a}} + K_{\text{d}}) + b' \\ &= a \times K_{\text{a}} + b. \end{aligned} \tag{3}$$

Equation (2) can then be rewritten as

$$E_{\text{wlost}} = (a \times K_{\text{a}} + b) \times k_2. \tag{4}$$

Equation (3) can also be used to write the average seasonal evaporative loss in terms of the active storage volumes in the reservoir at the beginning and the end of any period, viz.,

$$EV_t = e_t(A_t + A_{t+1})/2 = e_t \times a(S_t + S_{t+1})/2 + e_t \times b. \tag{5}$$

We now pose the planning problem as an LP problem, which is to maximize

$$E_{\text{net}} = E_{\text{hydel}} - n \times E_{\text{wlost}}, \tag{6}$$

subject to the following constraints. First, the set of hydrological continuity constraints

$$S_t + Q_t - D_t - CU_t - EV_t >= S_{t+1} \quad \text{for } t = 1, \ldots, T. \tag{7}$$

If $t = T$ then $t + 1 = 1$ so as to take care of low-inflow years occurring at the end of the inflow sequence, and since the power drafts and consumptive usages are the same from year to year, $D_t = D_{t-S}$ and $CU_t = CU_{t-S}$ for all $t > S$. Second, the set of constraints on minimum storage

$$K_{\text{a}} >= S_t \quad \text{for } t = 1, \ldots, T. \tag{8}$$

Third, the constraint on inter-seasonal variation in generation capacity

$$P_1 = P_2, \qquad \text{if no variation is to be allowed,}$$

or

$$P_1 <= r \times P_2, \quad \text{if } P_1 \text{ is allowed to be up to } r \text{ times } P_2,$$

where season 1 is the wet season and season 2 is the dry season in the 2-season model. Using $P_i = k_1' \times D_i/LF_i$, where $k_1' = k_1/(4.380 \times 10^6)$,

$$D_1/LF_1 = D_2/LF_2, \tag{9a}$$

or

$$D_1/LF_1 <= r \times D_2/LF_2. \tag{9b}$$

Finally, we have the non-negativity bounds

$$D_i >= 0, \quad \text{for all } i = 1, \ldots, S; \tag{10}$$

$$S_t >= 0, \quad \text{for all } t = 1, \ldots, T; \tag{11}$$

and

$$K_{\text{a}} >= 0. \tag{12}$$

COMPARING TWO DIFFERENT ENERGY FORMS

The simplest approach to comparing electrical and thermal forms of energy would be to compare them in terms of their primary energy contents. This practice has been adopted by the U.N. Energy Resources Group and some others.[11] One ton of (dry) fuelwood with a calorific value of 4750 kcal/kg has a thermal energy content of 4.75×10^6 kcal or 5530 kWh(th). It should therefore be considered equivalent to the same amount of electrical energy, i.e., 5530 kWh(e). If this convention is followed, our net-energy function becomes

$$E_{\text{net}} = E_{\text{hydel}} - E_{\text{wlost}}, \tag{13}$$

i.e., the comparison factor n is assigned the value 1.0.

But most energy-planners prefer to consider only the final amount of electricity that any thermal source can produce, i.e., the thermal energy content of any source is discounted by the conversion efficiency of a thermal power plant based on that source.[12–14] According to this approach, our net-energy function becomes

$$E_{\text{net}} = E_{\text{hydel}} - n_1 \times E_{\text{wlost}}, \tag{14}$$

where n_1 is the average efficiency of a wood-based thermal power plant.

In insisting that thermal energy should be discounted by the conversion efficiency before comparing it with electrical energy, there is an implicit assumption that electricity is the ultimate form of energy and that, ideally, all energies should be converted into electricity and then transmitted and distributed. Simple system efficiency calculations suffice to show that this is not always desirable, and that one must consider the appropriateness of the energy form to the end-use. In particular, the use of electricity for medium and low-temperature thermal end-uses can be just as (in-)efficient as the use of fuelwood. The system efficiency of a hydro-power station–transmission line–cooking range system is the product of the generation efficiency (75–80%), transmission efficiency (80–90%) and end-use efficiency (60–75%), i.e., just 36–57%. For industrial boilers this figure is 42–68%. Since wood-fired boilers can also achieve efficiencies between 58 and 77%,[15] there is a clear case for replacing the thermal end-use of electricity with the direct use of wood. In general, if f_t is the fraction of electrical energy being consumed in thermal end-uses, that fraction can be directly substituted by the same amount of thermal (wood) energy. One unit of electrical energy may then be considered equivalent to $[f_t + (1 - f_t)/n_1]$ units of wood energy. For this scenario, the net-energy function becomes

$$E_{\text{net}} = E_{\text{hydel}} - n_2 \times E_{\text{wlost}}, \tag{15}$$

where $n_2 = 1/[f_t + (1 - f_t)/n_1] = n_1/[(n_1)(f_t) + (1 - f_t)]$.

The above approach, though more appropriate than the previous ones, is still limited in that it only looks at the generation and consumption of electrical energy. In developing countries like India more than 50% of the total consumed energy is provided by non-commercial sources.[16] Virtually all of this is consumed in rural or low-income urban households, and there is as acute a scarcity of fuelwood as of electricity.[17] Therefore, if one is to focus on the basic needs of society, fuelwood is as important as electricity. System efficiency considerations, peak power considerations and socio-economic considerations all rule out the possibility of electricity entirely substituting for fuelwood as a source of domestic energy. In such a situation, when comparing these two forms of energy, one should convert only the fraction of wood energy into electrical energy that is equal to the fraction of purely non-thermal consumption of electrical energy in a total of wood and electrical energy consumptions (measured in kilocalories). If w and e represent the relative fractions of fuelwood and electricity consumption respectively (such that $w + e = 1$), then 1 unit of wood energy is equivalent to $[w/(w + e)] + [e/(w + e)](n_2)$ units of electrical energy. The net-energy function should then be

$$E_{\text{net}} = E_{\text{hydel}} - n_3 \times E_{\text{wlost}}, \tag{16}$$

where $n_3 = [w/(w + e)] + [e/(w + e)](n_2)$.

These four alternative scenarios for the comparison factor n are summarized in Table 1 along with the range of values n could take in each scenario.

PROJECTS ANALYZED

Two project sites located in the range of mountains called the Western Ghats in India were analyzed using this model. One is located on the River Bedthi in Karnataka state, and the

Table 1. Alternative formulations of the net-energy function.

Scenario number	n	Description	Range of values for n
I	n_1	conversion efficiency of wood-based thermal power plant	0.20 to 0.30[†]
II	n_2	fraction of thermal end-use of electricity (f_t) is considered to be directly replaceable by wood	0.29 to 0.42[‡]
III	n_3	fraction of non-thermal enduse of electricity in total consumption of wood & electricity is taken into account	0.93 to 0.98[§]
IV	n_4	"kcal for kcal" comparison	1.00

[†] Conversion efficiencies of wood-based thermal power plants range from 0.20 (ref.18) to 0.30 (ref.19).

[‡] These figures are based on the given range of n_1 values and f_t=0.40 (ref.20).

[§] w/(w+e) = 0.963 for India as a whole.[21]

other is on the River Koyna in Maharashtra state. Details of the projects are given in the Appendix (Secs. A.1 and A.2). It should be noted that the Koyna site has a 2.6 times greater inflow, 20% higher head, and a valley profile that is 58% steeper than that for the Bedthi site. This makes the Koyna site much more favorable for hydel generation. It should also be mentioned that neither of the project proposals was actually implemented. The Koyna project had to be scaled down by about half because of protests by downstream users, and the Bedthi project was shelved following strong protests by the local populace as well as by members of the scientific community. Insufficient data on the potential productivity of the land necessitated the use of two values representing reasonable upper and lower bounds on the estimates (see Appendix, Sec. A.3).

RESULTS OF NET-ENERGY ANALYSIS

Before maximizing the net-energy function, we determine the viability limit for the sites, i.e., the point at which $E_{\text{net}} = 0$, and examine the effects of using different values for the comparison factor (n) and the potential biomass productivity of the submerged land (W) on this limit. We then calculate the optimum project dimensions (i.e., dimensions that maximize E_{net}) for different values of n and W, and for different constraints on inter-seasonal variation in generation capcity. Details of the values assigned to the various parameters are given in the Appendix (Sec. A.3).

Limits on maximizing hydel energy

For this part of the analysis, the LP problem can be rephrased as one of maximizing E_{hydel} subject to the constraint $E_{\text{hydel}} >= n \times E_{\text{wlost}}$, and constraints (7)–(12). The results for both the projects are given in Table 2. For low values of n ($= n_1 = 0.2$) and W ($= 15$), all the water can be utilized before the viability limit is reached. Intermediate values affect the Bedthi project significantly. The viable utilization drops to 90% for the $n = n_2$ scenario if the productivity is assumed to be 40 t/ha/yr. The Koyna project is not affected significantly; this is to be expected because the Koyna site is extremely favorable for hydel generation. In the extreme case when

Table 2. Designs for which the net-energy is zero.

Site	Scenario	Half-yearly Power Draft (Mm^3)	Storage Capacity (Mm^3)	Submerged Area (km^2)	Installed Capacity (MW)	% Gross utili-tion
Bedthi	$n_1=0.2$; $W=15$	613.4	8109.0	467.4†	190.8	100.0‡
	$n_2=0.3$; $W=40$	576.9	2715.2	158.0	179.4	90.0
	$n_4=1.0$; $W=15$	569.7	2114.6	123.5	177.2	84.8
	$n_4=1.0$; $W=40$	393.0	559.9	34.3	122.2	61.3§
Koyna	$n_1=0.2$; $W=15$	1883.7	17808.0	651.0†	708.6	100.0‡
	$n_2=0.3$; $W=40$	1880.9	16992.0	622.6	707.2	99.8
	$n_4=1.0$; $W=15$	1870.8	12040.8	446.0	703.4	99.3
	$n_4=1.0$; $W=40$	1372.3	3358.5	136.3	516.0	72.9

† The submerged area values for utilizations close to 100% are not very accurate because the area-capacity curves have to be extrapolated to unrealistic values of reservoir volumes.

‡ All of the water had been utilized while E_{hydel} was greater than n x E_{wlost}.

§ Viable point was not found since E_{hydel} was less than n x E_{wlost} for all levels of utilization.

$n = 1$ and $W = 40$ t/ha/yr, there is no viable design possible for the Bedthi project. The project viability limit for Koyna is also reduced significantly to 73% utilization.

These results indicate that, if the energy loss is due to submergence is given some weight, there exists an upper bound on the maximum hydel energy that may be generated.

Maximization of net-energy

The optimization problem posed in Eqs. (6)–(12) is now solved for three different scenarios for n ($n = 0$, n_1, n_2 and n_4), two different productivity values ($W = 15$ and 40 t/ha/yr) and three kinds of constraints on inter-seasonal variation in generation capacity ($D_1 = D_2$, $D_1 <= 3D_2$, and no limits on the ratio $D_1 : D_2$). Not all the possible combinations of the above are considered; suitable combinations between extreme cases are chosen. In order to provide a basis for comparison, the dimensions of the designs proposed by the planners in the detailed project reports (DPRs) are also given. Results for the Bedthi and Koyna sites are given in Tables 3 and 4 respectively.

The $n = 0$ scenario, which essentially maximizes E_{hydel} [scenario (1) in Tables 3 and 4], is a hypothetical extreme. But it indicates how the storage capacity requirement can shoot up if 100% utilization is desired. This is a direct result of the stochastic variability in river runoff.

When, however, n is assigned a non-zero value, the optimum power draft, utilization and installed capacity values decrease [scenarios (3), (4)/(4-a) and (5-a)]. The decrease is substantial at even low values of n ($= n_1$) and W ($= 15$ t/ha/yr) for Bedthi; it is from 100 to 85% utilization and 191 to 176 MW. For Koyna, the decrease for these values of n and W is not very significant; optimum utilization is 97.8% and optimum installed capacity drops from 708 to 695 MW. Further increases in n or W affect both projects in the same manner, i.e., the Bedthi site is again more sensitive to such changes than the Koyna site.

The substantial reduction in submergence area that is obtained by a marginal reduction in

Table 3. Results of a net-energy analysis of the Bedthi hydel project.†

Scenario number	n value	D_1:D_2 limits‡	D_1 (Mm^3)	D_2 (Mm^3)	Volume V (Mm^3)	A_{sub} (km^2)	Installed Capacity (MW)	E_{hydel} (GWh(e))	E_{wlost} (GWh(th))	E_{net} (GWh)	% Gross utilization
(1)	n = 0	r = 1	613.4	613.4	8,109.0	467.4	190.8	1,002.6	3,525.7	10,002.6	100
(2) DPR design§		r = 1	550.0	550.0	1,608.8(?) (1,898.5)	99.6 (111.0)	210.0(?) (171.0)	1,060.0 (898.9)	--- (828.4)	--- (70.5)	90 (?) (84)
(3-a)		r = 1	564.8	564.8	1,951.1	114.1	175.6	923.1	860.4	751.1	85
(3-b)	n = n_1	r = 3	855.6	285.2	1,664.4	97.6	266.1	932.3	736.3	785.1	85
(3-c)		no limit	1049.0	102.3	1,476.9	86.9	326.2	940.8	655.2	809.8	85
(4)	n = n_2	r = 1	523.1	523.1	1,241.0	73.4	162.7	855.0	553.1	689.1	77
(5-a)		r = 1	488.0	488.0	860.9	51.5	151.8	797.7	388.6	409.1	72
(5-b)	n = n_4	r = 3	739.3	246.4	613.2	37.3	229.9	805.6	281.4	524.1	72
(5-c)		no limit	920.0	57.3	400.4	25.1	286.1	798.7	189.3	609.3	71

† Parameter values used : $n_1 = 0.2$; $f_t = 0.4$; W = 15 t/ha/yr.

‡ r=1 represents the $D_1=D_2$ case; r=3 represents the $D_1<=D_2$ case.

§ The values for V and installed capacity obtained by us for a half-yearly power draft of 550 Mm^3 are at variance with those given in the Detailed Project Report and are given in brackets below the DPR figures; (?) indicates what we think are miscalculations.

Table 4. Results of a net-energy analysis of the Koyna hydel project.†

Scenario number	n value	W (t/ha/yr)	$D_1:D_2$ limits ‡	D_1 (Mm^3)	D_2 (Mm^3)	Volume V (Mm^3)	A_{sub} (km^2)	Installed Capacity (MW)	E_{hydel} (GWh(e))	E_{wlost} (GWh(th))	E_{net} (GWh)	% Gross utilization
(1)	n = 0	--	r = 1	1883.7	1883.7	17,808.5	651.7	708.3	3,722.7	4,863.8	3,722.7	100.0
(2)DPR design§		--	r = 1	1692.7	1692.7	4,424.2 (4,518.5)	152.8 (177.7)	660.0 (636.5)	3,819.0 (3,345.3)	--- (1,140.4)	--- (2,204.9)	91.0 89.0
(3-a)	$n = n_1$	15	(r = 1	1848.1	1848.1	6,818.3	259.7	694.9	3,652.4	1,938.1	3,264.8	97.8
(3-b)			(r = 3	2777.7	925.9	6,267.6	240.0	1044.4	3,659.6	1,791.5	3,301.4	97.9
(3-c)		40	r = 1	1720.2	1720.2	4,650.0	182.3	646.8	3,399.5	3,628.9	2,673.7	90.4
(4-a)	$n = n_2$	15	r = 1	1848.1	1848.1	6,818.3	259.7	694.9	3,652.4	1,938.1	3,071.0	97.8
(4-b)		40	r = 3	1720.1	1720.1	4,649.6	182.3	646.8	3399.4	3,628.5	2,310.8	90.3
(5-a)	$n = n_4$	15	(r = 1	1715.7	1715.7	4,615.7	181.1	645.1	3,390.7	1,351.7	2,039.0	90.2
(5-b)			(r = 3	2585.3	861.8	4,137.6	164.1	972.1	3,406.2	1,224.4	2,181.8	90.3
(5-c)		40	r = 1	757.5	757.5	1,208.9	59.6	284.8	1,497.1	1,186.1	311.0	39.4

† Parameter values used are $n_1=0.20$ and $f_t=0.4$.

‡ r=1 represents the $D_1=D_2$ case; r=3 represents the $D_1<=D_2$ case.

§ Figures in brackets indicate values obtained by us for the half-yearly power draft of 1692.7 Mm^3 used in the DPR.

the power draft and hence in the installed capacity is the most important result of this analysis. In particular, a 7% reduction in installed capacity at Bedthi (from 176 to 163 MW) leads to reduction in A_{sub} of as much as 36% (from 114 to 73 km^2). A further sacrifice of 7% in hydroelectric power (from 163 to 152 MW) leads to an additional reduction in the submerged area of 30% (from 73 to 52 km^2). For Koyna, a 7% reduction in hydel power (from 695 to 645 MW) can lead to a 30% reduction in A_{sub} (from 260 to 181 km^2).

Relaxing the constraint on inter-seasonal variability in generation capacity invariably leads to a substantial reduction in the submerged area, and a marginal increase in the hydel energy generated [scenarios (3-b) and (3-c), (5-b) and (5-c); also (4-b) in Table 3]. By allowing D_1 to be greater than D_2, more of the wet season's inflow can be utilized immediately and does not have to be stored, which reduces the storage requirement and hence the area submerged. For Bedthi, this reduction is between 15 and 50% depending upon the extent of relaxation and the n value used. The marginal increase in E_{hydel} [e.g., from 923 to 932 GWh for scenario (3)] results from reduced evaporative losses due to a smaller water-spread area. With better planning and load-scheduling in the overall generation system, generation capacity could be maintained constant with a proper mix of hydro and thermal generation on a monthly basis.

Notwithstanding some of the discrepancies between our calculations and those in the DPRs, one can conclude that the proposed size of the Bedthi project is too large. On the other hand, the DPR design for the Koyna project is smaller than most of the energetically optimum designs. This is because the Koyna design was based on an economic optimization exercise—an exercise that was not carried out in the Bedthi DPR.

A MIXED HYDRO-WOOD GENERATION SCENARIO

As mentioned above, in an optimally-planned power generation system, dry-season hydel generation could be augmented by thermal generation. Since we have considered an energy plantation as the alternative land-use for energy generation, the idea of a wood-based thermal power plant suggests itself. Designing for higher hydel power in the wet season and thus reducing the storage capacity requirement, one could use a part of the area thus saved from submergence to provide the balancing generation capacity in the dry season. The problem can be formulated in two ways: one focusing on the need for maximum possible electrical power generation, and another focusing on the need to minimize the area submerged.

Maximization of electrical energy generation

In this approach the aim would be to maximize the total (hydel + wood-based) energy generation subject to two constraints, viz., (i) equal total generation capacity in both seasons, and (ii) some upper bound, A_{max}, on the total area that may be used for energy generation, i.e., the area submerged plus the area needed for the energy plantation that supplies the thermal power plant. For our 2-season formulation, the LP problem becomes one of maximizing

$$E_{net} = E_{hydel} + n_1 \times E_{wp} = k_1(D_1 + D_2) + n_1 k_2 A_w, \qquad (17)$$

subject to the following constraints. First,

$$P_{wet} = P_{dry} + P_{wood}, \qquad (18)$$

where P_{wet}, P_{dry} and P_{wood} are the wet-season, dry-season and wood-based generation capacities respectively. This relation may be rewritten as

$$k_1' \times D_1/LF_1 = (k_1' \times D_2)/LF_2 + (k_2' \times A_w)/LF_2,$$

where $k_2' = n_1 k_2/(4.38 \times 10^6)$ is the factor that converts km^2 of energy plantation to MW of wood-based generation. Second,

$$A_{sub} + A_w <= A_{max}. \qquad (19)$$

We also have constraints (7), and (10)–(12) as before, with an additional non-negativity constraint on the newly-added decision variable A_w.

Table 5. Results for maximization of power subject to $P_{wet} = P_{dry} + P_{wood}$ and $A_{sub} + A_w <= A_{max}$.

Project	n_1	W (t/ha/yr)	P_{wet} (MW)	P_{dry} (MW)	P_{wood} (MW)	D_1 (Mm^3)	D_2 (Mm^3)	V (Mm^3)	A_{sub} (km^2)	A_w (km^2)
Bedthi	0.2	15	175.6	175.6	0.0	564.8	564.8	1,951.1	114.1	0.0
		40	207.9	97.7	110.2	668.8	314.3	682.7	41.3	72.8
	0.3	15	182.1	144.0	38.1	585.6	463.0	1,179.3	69.8	44.3
		40	243.6	63.5	180.1	783.2	204.2	569.9	34.8	79.3
Compare with scenario (3-a) of table 2 wherein E_{net} is maximized subject to $P_{wet}=P_{dry}$:										
	0.2	15	175.6	175.6	--	564.9	564.9	1,951.1	114.1	--
Koyna	0.2	15	694.9	694.9	0.0	1848.1	1848.1	6,818.4	259.7	0.0
		40	708.2	585.8	122.4	1883.5	1558.1	4,553.3	178.9	80.8
	0.3	15	694.9	694.9	0.0	1848.1	1848.1	6,818.4	259.7	0.0
		40	741.0	553.2	187.8	1970.8	1471.4	4,501.3	177.0	82.7
Compare with scenario (3-a) of table 3 wherein E_{net} is maximised subject to $P_{wet}=P_{dry}$:										
	0.2	15	694.9	694.9	--	1848.1	1848.1	6,818.4	259.7	--

A_{max} is 114.1 km^2 for Bedthi and 259.7 km^2 for Koyna.

A_{max} should be chosen from the A_{sub} values obtained previously for the scenario in which n is equal to the conversion efficiency of a wood-based thermal power plant. We choose A_{max} to be 114.1 km^2 for Bedthi and 259.7 km^2 for Koyna. The results obtained for this formulation are given in Table 5 and are discussed below.

For the lowest values of n_1 and W, there is no shift towards a mixed generation pattern. This is because at these values the differential increase in P_{wood} resulting from a marginal decrease in A_{sub} area obtained by reducing D_2 is not enough to make up for the reduction in P_{dry}. At higher values of n_1 and/or W, however, the mixed hydro–wood generation pattern has the favorable features of a greater total generation capacity and smaller submerged area. In particular, for Bedthi an increase in n_1 from 0.2 to 0.3 leads to an increase in generation capacity by 4% and a decrease in A_{sub} by 39%. Similarly, a change in W from 15 to 40 t/ha/yr increases the generation capacity by 18% and decreases A_{sub} by 64% respectively. Together, these improvements in the parameter values result in a 39% increase in the generation capacity (from 176 to 244 MW) and a 70% reduction in A_{sub} (from 114 to 35 km^2). In the case of Koyna, the combined effect of increasing n_1 to 0.3 and W to 40 t/ha/yr increases the generation capacity by 7% and reduces the submerged area by 32%. These changes, though lesser than those observed for the Bedthi project, are not negligible.

Minimization of land-use for energy

In an alternative approach, one may wish to maximize the availability of fuelwood for domestic use, or the availability of the land for some other non-energy uses. One would therefore try to minimize the total area required by the mixed generation system, provided some minimum power requirements are met. The problem may be formulated as one of minimizing

$$A_e = A_{sub} + A_w, \tag{20}$$

subject to the constraint

$$P_{wet} = P_{dry} + P_{wood} >= P_{min}, \tag{21}$$

and the constraints (7), (8) and (10)–(12), along with a non-negativity bound on A_w. We set P_{min} equal to 175.6 MW for Bedthi and 694.9 MW for Koyna on the basis of the scenarios used earlier for assigning values to A_{max}.

The results obtained for the above formulation are given in Table 6. As before, no reduction is possible in the total land-use for energy in the worst-case scenario, i.e., when $n_1 = 0.2$ and $W = 15$. But for higher values of conversion efficiency and/or land productivity, it is possible to achieve a substantial reduction in A_e, which is between 12 and 37% in the case Bedthi and between 7 and 15% in the case of Koyna.

Apart from the significant reductions in reservoir volumes and the consequent reductions in dam heights and sizes (and therefore in economic costs) that would be obtained from the mixed generation system, such a system has two other advantages. First, the overall reliability of a mixed system is much higher than that of a purely hydro-based system because hydel generation is more susceptible to the vagaries of the climate than the productivity of an energy plantation. Second, because an energy plantation is an intensive form of land use, it provides substantial opportunities for permanent employment as well as secondary benefits such as fodder, soil conservation, etc.

CONCLUSIONS

In order to promote economic growth and hence (supposedly) development, attempts are being made to exploit the known sources of commercial energy to the fullest extent. In the case of hydro-power, construction of larger dams on more remote sites and of cascades of dams and connected reservoirs seems the direction planners will take. It is thought that the only objections to such macro-hydel projects will come from environmentalists—objections that are perforce qualitative and hence likely to be less effective. On the other hand, the energy cost of land submergence can be quantified, and may be substantial. In trying to compare the electrical energy generated by the hydro-power station and the thermal energy in the potential biomass increment from the land to be submerged, two facts have to be taken into account. First, the direct use of fuelwood for many thermal end-uses is actually more efficient than the use of electricity. Second, the domestic demand for fuelwood for cooking and other heating applications in developing countries is very substantial. These facts force us to consider the two forms of energy to be nearly equivalent in kilocalorie terms.

Our results suggest that though the energy-cost of submergence varies from site to site, there will, in general, exist an upper bound on the area of the reservoir if the project is to yield a positive net-energy. Moreover, if the aim of the planning exercise is the maximization of net-energy rather than utilization of water, the optimum project dimensions would be distinctly smaller, so that the optimum gross utilization may be as low as 72%. At exceptionally favorable sites, i.e., sites with a steep valley, high inflow and high head, optimum utilization could be more than 90%. On the other hand, in tropical or semi-tropical conditions, the biomass productivity of land may be so high as to render projects at less favorable sites completely non-viable, while even at more favorable sites, the optimum utilization may be as low as 39%.

The use of an optimization model highlights a very important feature of macro-hydel projects: a marginal (in this case 7–13%) increase in the hydel generation capacity can lead to a very significant (33–54%) reduction in the area submerged. The model also demonstrates the

Table 6. Results for minimization of energy-landuse subject to $P_{wet} = P_{dry} + P_{wood} >= P_{min}$.

Project	n_1	W (t/ha/yr)	P_{wet} (MW)	P_{dry} (MW)	P_{wood} (MW)	D_1 (Mm^3)	D_2 (Mm^3)	V (Mm^3)	A_{sub} (km^2)	A_w (km^2)	A_e (km^2)
Bedthi	0.2	15	175.6	175.6	0.0	564.8	564.8	1,951.1	114.1	0.0	114.1
		40	175.6	128.8	46.8	564.8	414.3	785.3	47.2	30.9	78.1
	0.3	15	175.6	150.2	25.4	564.8	483.1	1,200.0	71.0	29.5	100.4
		40	175.6	128.8	46.8	564.8	414.3	785.3	47.2	20.6	67.8
Koyna	0.2	15	694.9	694.9	0.0	1848.1	1848.1	6,818.4	259.7	0.0	259.7
		40	694.9	599.1	95.8	1848.1	1593.2	4,574.3	179.6	63.3	242.9
	0.3	15	694.9	694.9	0.0	1848.1	1848.1	6,818.4	259.7	0.0	259.7
		40	694.9	599.0	95.9	1848.1	1593.2	4,574.2	179.6	42.2	221.8

P_{min} = 175.6 MW for Bedthi and = 694.9 MW for Koyna.

savings in land submergence that could be obtained if the hydel generation capacity is adjusted according to the seasonal variations in the river's runoff. As large dam projects in thickly populated developing countries face strong opposition from the people likely to be displaced, planners will have to focus their attention increasingly on the submergence impact of the projects. In such situations the above tradeoffs may become more attractive, if not inevitable.

We have also demonstrated the viability (in energy terms) of a mixed hydro–wood generation system. Such a system could lead to a significant reduction in the total area used for energy generation or, conversely, could provide a higher total generation capacity. Further work needs to be done on the economics and the environmental implications of wood-based power generation. We have only highlighted the energy-cost of hydroelectric power and have demonstrated the need to exercise caution while exploiting this supposedly cheap, renewable and clean source of energy. More work also needs to be done to develop a fully integrated, environmentally sound, and socially practicable model for energy planning.

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APPENDIX

Project Details and Parameter Values

A.1. Bedthi hydroelectric project[22]

Location: River Bedthi, Uttara Kannada district, Karnataka state, India; height above sea-level = approx. 400 m. Climate: average minimum temperature = 20°C, average maximum temperature = 42°C, average annual rainfall = 1340 mm, 90% of which occurs in the wet season (June–November). Catchment: area = 2230 km^2, vegetation type: mainly thick moist evergreen and semi-evergreen forest, some cultivation in valley bottom. Hydrology: average annual runoff at site = 1517.2 Mm^3 (data: 1925–1975), average evaporation rates = 0.51 m in the wet season and 0.85 m in the dry season. Local consumptive usage = 63.7 Mm^3 in the wet season only. Topography: area–capacity curve is approximately given by $A\,(km^2) = 0.05738 \times V\,(Mm^3) + 2.1$, average net generation head = 395.0 m ± 4%, dead storage requirement = 153.9 Mm^3.

The Detailed Project Report was prepared in 1977 and revised in 1981, but the project was finally shelved.

A.2. Koyna hydrelectric project[23]

Location: River Koyna, Satara district, Maharashtra state, India; height above sea-level = approx. 600 m. Climate: average minimum temperature = 18°C, average maximum temperature = 36°C, average annual rainfall = 6630 mm, 95% of which occurs in the wet season (June–November). Catchment: area = 896 km^2, vegetation type: thick tropical mixed evergreen forest on the slopes, cultivation on the valley bottom. Hydrology: average annual runoff at site = 3966.2 Mm^3 (data: 1829–1949—only annual values; average within-year distribution was determined from 6 yrs' data), average evaporation rate is 0.75 m in the wet season and 1.32 m in the dry season. Topography: area–capacity curve is approximately given by $A\,(km^2) = 0.03567 \times V\,(Mm^3) + 16.5$, average net generation head = 477.6 m ± 5%, dead storage requirement = 148.3 Mm^3.

The Detailed Project Report was prepared in 1950, and was revised in 1952 and again in 1958; the project in its revised form was finally completed in 1966.

A.3. Parameter values

(1) Dependability = maximum, i.e., no shortfall in generation is allowed in any year. (2) $n_{gt} = 0.76$ (turbine efficiency = 0.80, generator efficiency = 0.95). (3) Average seasonal load factor $LF_i = 60\%$ for both seasons 1 and 2. (4) Fraction of submerged area available for biomass cultivation, $f = 90\%$. (5) Calorific value of wood $c_w = 4750$ kcal/kg. (6) Productivity of energy plantation: a survey of available data shows that the productivity is a function of a host of variables—soil quality, temperature, solar insolation, rainfall, irrigation, fertilizer use, tree species, planting density, rotation period, etc.[24] Both the project sites analyzed by us are located in a semi-tropical region with a high average temperature and heavy rainfall. Whitaker and Likens[25] report a net primary production of 16–22 t/ha/yr of dry matter in moist evergreen forests, so we have taken 15 t/ha/yr as a representative lower estimate. At the other extreme, eucalyptus plantations in climatically similar regions in southern India have been reported by Seshadri et al to yield 43.7 t/ha/yr,[18] and leucena is known to yield more than 50 t/ha/yr on a sustainable basis.[26] So we choose 40 t/ha/yr as the higher value.

NOMENCLATURE

a = Slope of the reservoir's linearized area–capacity curve (km^2/Mm^3); 1 $Mm^3 = 10^6\,m^3$

A_e = Total area used for electrical energy generation (km^2)

A_{sub} = area submerged at full reservoir level (km^2)

A_t = Reservoir water-spread at the beginning of time period t (km^2)

A_w = Area of energy plantation supplying wood-based power plant (km^2)

b = Reservoir water-spread at dead storage level (km^2)

c_w = Calorific value of firewood [MJ/t(dry)]

CU_t = Fixed loss from the reservoir during period t (such as local consumptive use) (Mm^3)

D_t = Power draft from reservoir during period t (Mm^3)

e_t = Average rate of evaporation from reservoir's surface during period t (m)

E_{hydel} = Annual hydel energy generation [kWh(electrical)]

E_{wlost} = Energy content of potential annual biomass increment from area submerged [kWh(thermal)]

E_{wp} = Energy generated in wood-based thermal power plant [kWh(th)]

EV_t = Volume of water lost due to evaporation during period t (Mm^3)

f_t = Fraction of electrical energy being consumed for thermal end-uses

f = Fraction of submerged area available for biomass cultivation

g = Gravitational acceleration (m/sec^2)

H = Average net generation head (m)

k_1 = Factor for converting power draft to electrical energy [$kWh(e)/Mm^3$]

k'_1 = Factor for converting power draft to continuous power (MW/Mm^3)

k_2 = Factor for converting area submerged to thermal energy lost [$kWh(th)/km^2$]

k'_2 = Factor for converting energy plantation area to units of continuous power from wood-based thermal power plant (MW/km^2)

K_a = Active storage capacity of reservoir (Mm^3)

K_d = Dead storage capacity of reservoir (Mm^3)

LF_i = Average load factor for the ith season

n_i = Factor converting 1 kWh(th) to 1 kWh(e) in the ith formulation

n_{gt} = Product of generator and turbine efficiencies

P_{dry} = Hydel generation capacity in dry season of 2-season model (MW)

P_{min} = Minimum all-year-round generation capacity requirement (MW)

P_{wet} = Hydel generation capacity in wet season of 2-season model (MW)

P_{wood} = Half-yearly wood-based generation capacity (MW)

Q_t = Inflow into reservoir during period t (Mm^3)

r = Allowable ratio between wet- and dry-season generation capacity

S = Number of within-year seasons

S_t = Active storage in reservoir at the beginning of period t (Mm^3)

T = Total number of periods in the inflow sequence ($Y \times S$)

W = (Potential) biomass productivity of land submerged [$t(dry)/km^2/yr$]; the more convenient unit of t/ha/yr is used in the discussion

Y = Number years in the inflow or runoff sequences used.