ECONOMIC LIMITATIONS OF WIDE SPREAD USE OF RENEWABLE ENERGY SOURCES

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ABSTRACT

This paper presents an optimization technique to formulate the problem of optimum hybrid combination of renewable and conventional power systems. The linear programming technique is used to solve this problem. This technique offers the possibility to analyze the sensitivity of the optimal solution to changes in the input data without resolving the problem for each new value. This property is utilized to perform a sensitivity analysis to the possible changes in the different cost coefficients on the participation of each system to meet the load demand.

The economical limitations of wide spread use of renewable energy sources are analyzed by evaluating the cost of unit energy produced against the following topics:-

* The pricing policy of energy selling to and purchasing from the utility.
* The energy use strategy with consideration of shiftable load schedule instead of fixed load schedule.
* The capacity of storage system.
* The rated power of the tie-line.

INTRODUCTION

Most of the developing countries are poor in conventional fossil-fuel resources and have to import fuel with their meager foreign exchange reserves. There appear to be only two technically feasible solutions to their energy problems. One is a commitment to large central nuclear power plants and a power transmission and distribution network. The other is a decentralized system of solar and wind equipments installed to supply the remote loads. The reluctance to use nuclear energy is based on a number of factors related to lack of public acceptance because of perceived risk of accidents, long-term wastes, and fuel-cycle relationships to weapons proliferation. Also, the costs of nuclear waste disposal and clean up costs of a nuclear accident have historically not been fully included in the economic evaluations.

Limits on the use of renewable energy sources during the remainder of this century will not likely be technical or operational but rather economic [1]. The importance of assessing the economic benefits obtained from renewable energy sources, when they are operated alongside conventional fossil and nuclear plants, is recognized in Reference [2]. Farghal et al. [3] have presented an efficient methodology to evaluate the economical limitations as well as the marginal impact of the solar thermal power system (STPS) as a renewable energy source on the utility system reliability and operating cost. The economic limitation was formulated by evaluating the annual expected fuel cost saving due to the operation of the STPS as a fuel saver. The use of STPS with storage has already been discussed in Ref.[4]. A combined wind, solar and conventional system for electric power generation with energy storage facilities has been introduced in Ref.[5].

The major issue which prevents the wide spread use of renewable energy sources (RES) is not the lack of adequate technology but the high cost of the generated electricity compared with that purchased from the utility. In Ref. [4], the optimum design of stand alone STPS with reliability constraint has been developed. The major cost effective parameter in that system is the cost of storage facility for achieving the required level of reliability to meet the isolated demand. In Ref.[3], it was found that the operating cost and reliability may be improved when these STPS are used as peak shaving units. Now, what if the utility system is marginally introduced into the renewable energy system and what are the economic limitations for this option?.

In this paper, the economics of connecting the utility system to a renewable energy system is treated as an optimization problem. The economical limitations of wide spread use of renewable energy sources are analyzed by evaluating the cost of unit energy produced against the pricing policy of energy to & purchasing from the utility, the energy use strategy with consideration of shiftable load schedule instead of fixed load schedule, the capacity of storage system, and the rated power of the tie-line. The paper presents an optimization technique to formulate the problem of the optimum hybrid combination of the STPS, wind and conventional system with storage. The linear programming technique is used to solve this problem. A sensitivity analysis is developed to determine the effects of the possible changes in the load demand as well as the cost coefficients on the participation of each system to meet the load demand.

OPTIMIZATION MODEL

An optimization model to the hybrid solar, and wind with associated storage and conventional power system (tie line) will be split into an objective cost function and imposed constraints. Fig. 1 shows the feasible energy system. The processes of charging and discharging of the storage system as well as energy buying or selling to the utility should be represented in the optimization model in order to obtain an optimum energy use strategy.

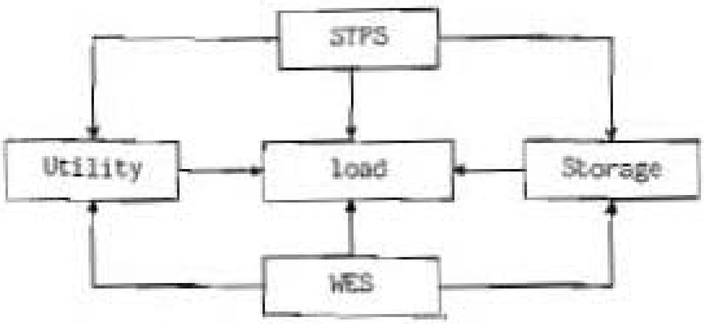

Fig. 1 Feasible energy system.

The system constraints:

The hybrid system is subjected to several constraints. The main imposed constraints can be developed as follows:

The power balance constraints:

At any hour, there is a power balance between the input power (STPS, WES, discharging of the storage system, and power purchased from the utility) and the output power (charging of the storage system, the power selling to the utility, and the load demand). This constraint is given by:

$$AP_{li} * \eta_{net} * A + WP_{li} * \eta_T * N + \eta_s (CH_{li} - DCH_{li}) + \eta_T (UB_{li} - US_{li}) = E_{li} \quad --- (1)$$

Where,

AP_{li} : the available insolation in the season l during the hour i, Kw/m .

η_{net} : the net efficiency of the STPS.

A : the decision variable representing the collector area, m^2.

WP_{li} : the output power of the wind generator (WG) in the season l at the hour i, Kw.

η_T : the efficiency of the of tie-line.

N : a decision variable representing the number of wind generators.

η_s : the efficiency of the storage system.

CH_{li} : a decision variable representing the power to the storage system (charging capacity) at the hour i in the season l, kw.

DCH_{li} : a decision variable representing the power from the storage system (discharging capacity) at the hour i in the season l, kw.

UB_{li} : a decision variable representing the utility power output at the hour i in the season l (purchased power), Kw.

US_{li} : a decision variable representing the power input to the utility at the hour i in the season l (selling power), kw.

E_{li} : the electric load demand at the hour i in the season l, Kw.

The rated power

The capital cost per unit capacity tends to go down as the capacity increases [6]. This phenomena restricts the designer or the planer. So the optimization model must include the maximum and the minimum permissible power rating. Also the cost vector of the objective function should be changed to include the new cost values. The rated power of the STPS (PST_r) should be greater than or equal to the maximum output of the STPS at any hour, this constraint is given by:

$$PST_r \geq AP_{max} * \eta_{net} * A \quad --- (2)$$

$$AP_{max} \geq AP_{li} \quad --- (3)$$

$$PST_r \leq PST_{max} \quad --- (4)$$

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$$AP_{max} \geq AP_{li} \quad \text{--- (3)}$$

$$PST_r \leq PST_{max} \quad \text{--- (4)}$$

Where,

AP_{max} : the maximum available insolation value during the year, Kw/m^2.

PST_{max} : the maximum permissible rated power of the STPS, Kw.

The rated power of the wind system (PWG_r) should be greater than or equal to the maximum output of the wind generators. This constraint is given by:

$$PWG_r \geq PW_{max} * N \qquad --- (5)$$

$$PW_{max} \geq PW_{li} \qquad --- (6)$$

$$PWG_r \leq PWG_{max} \qquad --- (7)$$

Where,

PWG_{max} : the maximum permissible rated power of the WES, Kw.

The rated capacity of the tie line (CTL) should be greater than or equal to the maximum power of buying or selling) energy at any hour. This constraint is given by:

$$CTL_{li} \geq UB_{li} \qquad --- (8)$$

$$CTL_{li} \geq US_{li} \qquad --- (9)$$

$$CTL_{li} \leq CTL_{max} \qquad --- (10)$$

Where CTL is the maximum permissible capacity of the tie line, Kw.

The energy constraints:

In designing a hybrid combination of renewable energy system with energy storage and energy interchange facilities with the utility through the tie-line, the energy balance constraints must be satisfied all over the year. The energy balance insures a continuity of feeding the load demand along the year. This balance is satisfied by determining a suitable size for the storage system. This size allows to displace the energy from the periods of excess energy to that of energy deficiency. The initial and final stored energy levels should be the same. This guarantees the repeatability of the optimum schedule. This constraint is given by:

$$\sum_{i=1}^{I} CH_{li} * t_{li} = \sum_{k=1}^{K} DCH_{lk} * t_{lk} \qquad --- (11)$$

Where t_{li}, t_{lk} are the charging and discharging periods, Hours.

The stored energy cannot exceed the capacity of the storage system (WB). This constraint is given by:

$$WB \geq \sum_{i=1}^{I} CH_{li} * t_{li} \qquad --- (12)$$

Charging (discharging) of energy to (from) the storage device is limited by the maximum storage charging (discharging) rate. This constraint is given by:

$$CH_{1i} * t_{1i} \leq R \qquad --- (13)$$

$$DCH_{1i} * t_{1i} \geq G \qquad --- (14)$$

Where,

R : the charging rate, kwh.

G : the discharging rate, kwh.

The objective cost function

The objective of the optimum hybrid renewable and conventional energy system is to minimize the total cost of the hybrid system and fulfilling the imposed constraints. The cost of the hybrid system consists of the following items:-

1- The cost of the STPS,
2- The cost of the wind energy system,
3- The cost of the storage system,
4- The cost of the energy purchase from the utility and the income from selling energy to the utility.

The equivalent levelized end of year cost [6] is used for evaluating the present value of each alternative as:

$$L = PV \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right] \qquad --- (15)$$

$$PV = A_n (1+e_a) \frac{\left(\frac{1+e_a}{1+i} \right)^n - 1}{e_a - i} \qquad --- (16)$$

Where,

A_n : the annual cost,
i : the interest rate,
n : the life period,
e_a : the apparent escalation rate.

The cost of the STPS:

The cost of the STPS consists of the collector cost, the power conveyance cost and the energy conversion cost. The collector cost (C_c) is given by;

$$C_c = C * A \qquad --- (17)$$

Where,

C : the cost of the collector $/m^2

A : the collector area, m^2

The cost of the direct power conversion system C_d is given by:

$$C_d = (PCC + PTC + OM) * PSI_r = C_o * PSI_r \quad \text{--- (18)}$$

Where,

PCC : the cost of installing the power conversion system, \$/KW.

PTC : the cost of installing the power conveyance system (power lines and pipelines), \$/Kw.

OM : the operation and maintenance cost, \$/KW/year.

<u>The cost of the wind energy system</u>

A wind turbine used for electric production contains many components. At the top of the tower of a horizontal-axis turbine are the rotor, gear box, generator, bedplate, enclosure and various sensors, controls couplings, a brake, and lightning protection. At the foot of the tower are the transformers, switch gear, protective relays, necessary instrumentations, and controls. A distribution line connects the wind turbine to the utility grid. Land, an access road, and construction are also required to have a working system. The capital cost of all these items must be carefully examined in the study. The cost of wind generator is consisting of;

1- Wind generator capital cost (WGC), \$/KW,
2- Land and operation and maintenance cost (OM) \$/KW,
3- Cost of the access road and distribution line connects the wind turbine to the utility (TLC), \$/KW.

The wind plant cost (WPC) may be given by;

$$WPC = (WGC+OM+TLC*D)*PWG_r = WPC_o*PWG_r \quad \text{--- (19)}$$

Where D is the distance of the access road and/or the distribution line, Km.

<u>The cost of the energy storage system</u>

The cost of installing the energy storage system (C_s) is given by;

$$C_s = C_{wb} * WB \quad \text{--- (20)}$$

Where,

C_{wb} : the energy storage cost, \$/KWh,

WB : the capacity of the energy storage system, Kwh.

<u>The cost of the energy interchange with the utility</u>

The RES may take the advantages of the provisions requiring utilities to purchase back any available excess energy from their generation output at fair market prices by implementing rather rapidly varying energy purchase and selling prices to reflect their own varying production costs. Such time-varying rates have been refered to as spot prices and are rather commonly used [7].

The cost of the energy purchased from the utility may be given by:

$$UBC = \sum_{i=1}^{I} \alpha_i * UD_{ii} * t_{ii} \quad \text{--- (2[illegible])}$$

Where,

α_i : the cost of the energy purchased from the utility during the interval t_{1i}, $/MWh.

The cost of the energy selling to the tie line may be given by:

$$USC = \sum_{i=1}^{I} \gamma_i * US_{1i} * t_{1i} \quad \text{--- (22)}$$

Where;

γ_i : the cost of the energy selling to the utility during the interval t_{1i}, $/MWh.

The objective cost function of the total hybrid system (FH) is given by:

$$FH = C * A + C_o * PST + WFC * PWG + C_{wb} * WB + UBC - USC \quad \text{--- (23)}$$

Since both the system constraints and the objective cost function are linear, then, the linear programming technique can be used to solve the optimization model.

SENSITIVITY ANALYSIS

One particular important feature of the linear programming is the ease with which a sensitivity analysis can be carried out. This technique offers the possibility to analyze the sensitivity of the optimal solution to changes or uncertainty in the input data, without re-solving the problem for each new value. Such analysis provides insight into the structure of the problem which can not be gained by examining only the optimal solution. All the information needed for sensitivity analysis is contained in the final (optimal) tableau of the linear programming (LP) solution, and thus is generated automatically by the simplex method in the course of finding the optimal solution. The contribution of any source in the hybrid system depends on many factors such as;

* the fixed and/or the variable cost of the system (cost function),
* the load demand exchange (the right hand side of the constraints),
* the availability of the original source (solar insolation, wind power, ... etc.).

These quantities are uncertain and change with time, technology, site, and performance. So sensitivity analysis in the R.H.S. constraints and in the objective cost function is a useful tool to determine to what extent the changes in the R.H.S. and the objective cost function will affect the contribution of the hybrid system to the load demand.

The mathematical formulation can be rewritten in a concise form with a system of linear equations:

$$\text{Minimize } F = \sum_{i=1}^{N} C_i * NG_i = b_i \quad \text{--- (24)}$$

Subject to

$$\sum_{i=1}^{N} a_{ij}\, HG_i + S_j = b_j, \qquad j=2, \ldots, M$$

Where,

c_i : the cost coefficient.

a_{ij} : the linear coefficient.

HG_i : a decision variable representing the hybrid generation i.

S_j : a slack variable.

b_j : the binding coefficient.

N : the number of decision variables.

M : the number of equations.

The linear programming problem may be represented in matrix notation as follows:

$$[A][HG] + [U][S] = [b] \qquad \text{--- (25)}$$

Where,

[A] : an M*N matrix of coefficients of the initial tableau.
[HG] : an N*1 matrix of hybrid power generation.
[U] : an M*M unity matrix.
[S] : an M*1 matrix of slack variables.
[b] : an M*1 matrix of bonding coefficients.

Any matrix A can be subdivided or partitioned into a number of smaller submatrices. If conformable matrices are partitioned in a compatible fashion, the submatrices can be treated just as if they were scaler elements when performing the operations of addition and multiplication. Of course, the order of the products is not arbitrary, as it would be with scalars;

$$[A][HG] + [U][S] = [b]$$

$$[A_1 \,\vdots\, A_2]\begin{bmatrix} HG_1 \\ \hline HG_2 \end{bmatrix} + [U][S] = [b]$$

$$[A_1][HG_1] + [A_2][HG_2] + [U][S] = [b]$$

The simplex method moves from one basic feasible solution to another for improving the value of the objective function at each iteration until the optimal solution (final tableau of linear programming) is reached. The final tableau has the following form:

$$[A_1]^{-1}[A_1][HG_1]+[A_1]^{-1}[A_2][HG_2]+[A_1]^{-1}[U][S]=[A_1]^{-1}[b]$$

$$[U][HG_1] + [A_3][HG_2] + [B][S] = [B][b]$$

The knowledge of the [B] matrix will be useful in finding the sensitivity of the solution to changes in the b vector (the changes in the right hand side constraints) and the changes in the C vector (the objective cost function).

Using the simplex method for the solution of a linear programming problem step by step, is actually searching for and finding the right bases and gradually inverting the matrix which includes the optimal bases. After reaching the final solution in the linear programming problem, we can define the optimal decision variables and form a square matrix [B] which includes the decision vectors. Consequently, from the final solution the matrix [A_1^{-1}] can be described.

By looking at the final optimal solution, the final bases are recognized. (All the column vectors which have one unity element and others are zero). The original form of these vectors in the initial unsolved state forms the [B] matrix. The vectors in the final solution which related to the bases vectors in the original problem form the matrix of [A_1^{-1}]. In LP literature [8] this inverse is frequently given the symbol B.

Sensitivity of the solution to changes in the b vector

To know how the final solution might change if modest changes are made in the b vector, we simply form the product of the inverse B and the proposed new b vector. Thus, if instead of b the bounds on our constraints function are given by the new vector b+Δb, then to assess the effect of this change we form the product [B] [b + Δb] from which the new solution obtained. We must notice, however, that there are limits to the changes that we can make in the b vector and still be able to assess the impact of these changes simply by the product with the inverse of B. To identify the deviation in the original b vector that could be tolerated without changing the identity of the optimal basis, and hence without invalidating the product of the inverse B as a means for finding the new solution, we can write;

$$[\,B\,]\,[\,b+\Delta b\,] \geq 0.0$$

from which for example,

$$\begin{vmatrix} B_{11} & B_{12} & B_{13} \\ B_{21} & B_{22} & B_{23} \\ B_{31} & B_{32} & B_{33} \end{vmatrix} \begin{vmatrix} b_1+\Delta b_1 \\ b_2+\Delta b_2 \\ b_3+\Delta b_3 \end{vmatrix} \geq 0.0$$

$$B_{11}\,b_1+B_{12}\,b_2+B_{13}\,b_3+B_{11}\,\Delta b_1+B_{12}\,\Delta b_2+B_{13}\,\Delta b_3 \geq 0.0$$

$\vdots$ scaler

or,
$$\left.\begin{array}{l} B_{11}\,\Delta b_1+B_{12}\,\Delta b_2+B_{13}\,\Delta b_3 \geq -\text{scaler}_1 \\ \vdots \\ B_{31}\,\Delta b_1+\;\dots\;+B_{33}\,\Delta b_3 \geq -\text{scaler}_2 \end{array}\right\} \qquad \text{--- (26)}$$

Conditions (26) must prevail if the identity of the basic variables in the final solution is not to be changed. And therefore the new optimal solution can be determined via the product of the inverse B. To determine the lower bounds on b we can repeat the development;

$$[B] [b - \Delta b] \geq 0.0$$

To asses the impact of changes in F associated with changes in b vector and changes in the C vector, without invoking the full simplex procedure we need to acquaint ourselves with the "Simplex Multipliers." Any objective function equation can be treated as a constraint. Normally we so structure the simplex tableau that each constraint equation contributes one variable to the basis.

Calculating the Simplex Multipliers Directly.

There will always be a simplex multiplier for each constraint. Therefore, the vector of simplex multi-pliers is best treated as a column vector (π). The transpose of π, row vector π^t, can be determined by the relationship;

$$\pi^t = - C_b \; B$$

Where C is the row vector of the objective function coefficients, from the original tableau, of the variables that are to be basic in the current tableau. For any set of values for b for which (26) is not violated to determine F we form the product;

$$F = -\pi^t [b + \Delta b] = [b + \Delta b]^t \pi$$

In general, to assess the change in F associated with changes in b that do not alter the identity of the variables in the optimal basis, we exploit the following relationship;

$$F = - [\; b_1 \quad b_2 \; \ldots \quad b_m \;] \begin{bmatrix} \pi_1 \\ \pi_2 \\ \vdots \\ \pi_m \end{bmatrix}$$

Sensitivity of the optimal solution to changes in C vector. We would like also to know what changes in the C vector (the objective function coefficients from the original tableau), could we tolerated without changing the identity of the optimal basis.

To determined the simplex criterion of non basic variable X_i in any tableau, by processing only data from the original tableau, we can write;

$$C'_{n\,bx_i} = C_{n\,bx_i} - C_b \; B \; a_{x_i} \qquad \text{--- (27)}$$

Where,

$C'_{n\,bx_i}$: the simplex criterion of non basic variable X_i in the current tableau (a scaler).

$C_{n\,bx_i}$: the coefficient of non basic variable X_i in the original objective (scaler).

C_b : the row vector of coefficients in the objective function, from the original tableau, of the variables which are in the current tableau.

a_{x_i} : X_i's contribution to the current tableau (a column vector).

But since;

$$\pi^t = - C_b \; B$$

Expression (27) becomes;

$$C'_{n\,bx_i} = C_{n\,bx_i} + \pi^t \; a_{x_i} \qquad \text{--- (28)}$$

In expression (28), we have the simplex criterion of non basic variable X for the current tableau as a function only of elements that form or can be produced from the original tableau, if the identity of the variables to be basic in the current tableau is known.

To know what changes could be tolerated in the original objective function coefficients of the variables that are currently non basic without altering the identity of the optimal basis it is evident that the change $\Delta C_{n\,bx_i}$ could take any value so long as the following expression is not violated:

$$C_{n\,bx_i} + \Delta C_{n\,bx_i} + \pi^t \; a_{x_i} \leq 0.0$$

APPLICATIONS

The purpose of the applications is to utilize the optimization and the sensitivity analysis to find an optimum solution for the following cases:-

1- Optimum stand alone renewable energy system (STPS + WES + storage).
2- Sensitivity of the optimum stand alone renewable energy system to changes in the load demand (different load factors).
3- Sensitivity of the optimum stand alone renewable energy system to changes in the availability of the energy source (solar insolation and/or wind speed).
4- Optimum hybrid combination of renewable energy system and conventional energy system (optimum energy use strategy).
5- Sensitivity of the optimum hybrid system to changes in the price of selling and purchasing of energy from the utility (pricing policy).

Test system

The optimization model outlined above is implemented in a linear program and tested on a hypothetical load demand, wind power, and solar insolation data. The following data of WES and STPS are taken from [9]:

* Large wind-energy conversion system assumptions are;

- 25 wind machines rated at 2.5 MW at 27.7 mph,
- total energy output at capacity factor of 38%; equal to 208 million kwh per year,
- wind-system life of 30 years,
- capital costs of \$829/kw (1980\$) in 1990,
- 50% financed from debt at 14% interest,
- general inflation rate of 7.5% per year,
- 10.5% nominal discount rate.

* Solar thermal-electric system-central receiver

- 100 MW rated capacity,
- total energy output at 35%; capacity factor equal to 303.5 million kwh per year,
- system life of 30 years,
- capital costs of \$1,665/kw (1980\$) in 1990.
- annual operation and maintenance costs = 2% of capital costs.

The load demand

The total energy demand per year is $1.96*10^5$ Mwh. The load factors of the load demands are 0.737, 0.658, and 0.564. The values of the load demand are listed in the last column in each table of the results. The yearly load demand is represented by one day average which is divided to 11 intervals.

Hypothetical solar and wind data

The available solar insolation data (AP_{1i}) is listed in column 2 of table 1. Two available wind data (WP_{1i}) are listed in columns 3&4 of table 1.

Prices of energy interchange with the utility

Two pricing policies for buying energy from the utility (α_i) are listed in columns 5&6 of table 1. Two selling prices of energy to the utility (δ_i) are listed in columns 7&8 of table 1.

Results

The results of the optimization model are tabulated in tables 2-9. Each table includes the schedule of the optimum generation of STPS, WES, the charging and discharging of the storage system, the selling and purchasing of energy from the utility. The decision variable of collector area (A), the rated power of the STPS system (PST_r), the rated power of WES (PWG_r), the capacity of the storage system (WB), the capacity of the tie-line (CTL) and the minimum cost of unit energy (MC) are written below each table.

The stand alone renewable energy system (STPS+WES+WB) is obtained when setting the tie-line capacity equals zero in the limiting capacity constraints of the optimization model. Table 2 shows the optimum stand alone renewable energy system. The minimum cost in this case is 49.0 $/MWh. The availability of the renewable energy source has an effect on the charging and discharging process of the stand alone system. Tables 2 and 3 show the difference between the charging and discharging of the storage system when the wave forms of the wind power are those in the column 2 and 3 of table 1.

Table 1 The input data

1	2	3	4	5	6	7	8
Period	XP_{11} (kw/m^2)	WP_{11} (kw)	WP_{11} (kw)	λ $/MWh	λ $/MWh	λ $/MWh	λ $/MWh
8-10	0.7	10	10	30	30	25	25
10-02	0.9	20	20	15	15	50	50
02-04	0.7	20	20	60	30	50	25
04-06	0.4	30	30	60	30	50	25
06-08	-	30	40	30	60	25	50
08-10	-	50	70	30	60	25	50
10-00	-	90	60	30	30	25	25
00-02	-	70	80	30	30	25	25
02-04	-	50	40	30	30	25	25
04-06	-	30	30	30	30	25	25
06-08	0.4	20	20	30	30	25	25

The hybrid combination of renewable energy and conventional system is obtained by setting the capacity of the storage system equals zero in the limiting capacity constraints of the optimization model. The results of the hybrid system are shown in table 4. The hybrid system is sensitive to the capacity of the tie line as shown in table 4, 5, and 6. The minimum cost of the energy system is decreased as the capacity of the tie line is increased. The energy costs(0.058, 0.044, and 0.043 $/KWh) correspond to the tie line capacities(10, 20, and 30 MW) respectively. The minimum energy cost of the stand alone renewable energy is sensitive to the load demand. Tables 2 and 7 show the optimum stand alone renewable energy system corresponding to two load demands. The load factors of the two loads are (0.7378 and 0.5647) respectively. The corresponding storage capacities are 48952 and 66658 KWh respectively. Also the corresponding minimum costs are (0.0493 and 0.0492 $/KWh) respectively. The minimum cost of the stand alone renewable system is proportional to the storage capacity. The price of the energy selling to and purchasing from the utility affects the cost of unit energy production as well as the energy interchange with the utility as shown in tables 8 and 9. The price data used for table 8 are given in columns 5&7 in table 1. The price data used for table 9 are given columns 5&8 in table 1.

Table 2

Period	STES (Mw)	WES (Mw)	WB char. (Mw)	WB disch. (Mw)	Tie Line US (Mw)	Tie Line UB (Mw)	Load (Mw)
08-10	8.49	5.0	-	11.51	-	-	25.0
10-02	10.91	10.0	-	4.09	-	-	25.0
02-04	8.49	10.0	-	1.51	-	-	20.0
04-06	4.85	15.0	-	10.15	-	-	30.0
06-08	-	15.0	-	5.0	-	-	20.0
08-10	-	30.0	5.0	-	-	-	25.0
10-00	-	40.0	15.0	-	-	-	25.0
00-02	-	35.0	15.0	-	-	-	20.0
02-04	-	25.0	10.0	-	-	-	15.0
04-06	-	15.0	1.5	-	-	-	13.5
06-08	4.85	10.0	-	10.15	-	-	25.0

A = 40408 m^2, PST_r = 10.9 MW, N = 500, PWG_r = 50.0 MW
WB = 48952 KWh, CTL = 00.0 MW, MC = 49.397 $/MWh

Table 3

Period	STES (Mw)	WES (Mw)	WB char. (Mw)	WB disch. (Mw)	Tie Line US (Mw)	Tie Line UB (Mw)	Load (Mw)
08-10	8.49	5.0	-	11.51	-	-	25.0
10-02	10.91	10.0	-	4.09	-	-	25.0
02-04	8.48	10.0	-	1.52	-	-	20.0
04-06	4.85	15.0	-	10.15	-	-	30.0
06-08	-	20.0	-	-	-	-	20.0
08-10	-	35.0	10.0	-	-	-	25.0
10-00	-	30.0	5.0	-	-	-	25.0
00-02	-	40.0	20.0	-	-	-	20.0
02-04	-	20.0	5.0	-	-	-	15.0
04-06	-	15.0	1.5	-	-	-	13.5
06-08	4.85	10.0	-	10.15	-	-	25.0

A = 40408 m^2, PST_r = 10.9 MW, N = 500, PWG_r = 50.0 MW
WB = 48952 KWh, CTL = 00.0 MW, MC = 49.397 $/MWh

Table 4

Period	STES (Mw)	WES (Mw)	WB char. (Mw)	WB disch. (Mw)	Tie Line US (Mw)	Tie Line UB (Mw)	Load (Mw)
08-10	14.99	4.14	-	-	-	5.87	25.0
10-02	19.27	8.28	-	-	9.0	6.45	25.0
02-04	14.99	8.28	-	-	3.27	-	20.0
04-06	8.56	12.44	-	-	-	9.0	30.0
06-08	-	12.44	-	-	-	7.56	20.0
08-10	-	24.86	-	-	-	0.14	25.0
10-00	-	33.15	-	-	8.15	-	25.0
00-02	-	29.0	-	-	9.0	-	20.0
02-04	-	20.72	-	-	5.72	-	15.0
04-06	-	12.43	-	-	-	1.07	13.5
06-08	8.56	8.29	-	-	-	8.15	25.0

A = 71361 m^2, PST_r = 19.2 MW, N = 414, PWG_r = 41.4 MW
WB = 0.0 KWh, CTL = 10.00 MW, MC = 58.579 $/MWh

Table 5

Period	STES (Mw)	WES (Mw)	WB char. (Mw)	WB disch. (Mw)	Tie Line US (Mw)	Tie Line UB (Mw)	Load (Mw)
08-10	7.79	2.51	-	-	-	14.69	25.0
10-02	10.02	5.02	-	-	8.04	18.0	25.0
02-04	7.79	5.02	-	-	-	7.18	20.0
04-06	4.45	7.53	-	-	-	18.0	30.0
06-08	-	7.53	-	-	-	12.55	20.0
08-10	-	15.06	-	-	-	9.92	25.0
10-00	-	20.08	-	-	-	4.89	25.0
00-02	-	17.57	-	-	-	2.4	20.0
02-04	-	12.55	-	-	-	2.43	15.0
04-06	-	7.53	-	-	-	5.96	13.5
06-08	4.45	5.02	-	-	-	15.52	25.0

A = 37100 m^2, PST_r = 10.0 MW, N = 251, PWG_r = 25.14MW
WB = 0.00 KWh, CTL = 20.00 MW, MC = 44.507 $/MWh

Table 6

Period	STES (Mw)	WES (Mw)	WB char. (Mw)	WB disch. (Mw)	Tie Line US (Mw)	Tie Line UB (Mw)	Load (Mw)
08-10	7.79	1.0	-	-	-	16.21	25.0
10-02	10.02	2.0	-	-	14.02	27.00	25.0
02-04	7.79	2.0	-	-	-	10.21	20.0
04-06	4.45	3.0	-	-	-	22.35	30.0
06-08	-	3.0	-	-	-	16.99	20.0
08-10	-	6.0	-	-	-	18.99	25.0
10-00	-	8.0	-	-	-	16.99	25.0
00-02	-	7.0	-	-	-	12.99	20.0
02-04	-	5.0	-	-	-	9.99	15.0
04-06	-	3.0	-	-	-	10.49	13.5
06-08	4.45	2.0	-	-	-	18.55	25.0

$A = 37100\ m^2$, $PST_r = 10.0$ MW, N = 100, $PWG_r = 10.0$ MW
WB = 0.00 KWh, CTL = 30.00 MW, MC = 43.398 $/MWh

Table 7

Period	STES (Mw)	WES (Mw)	WB char. (Mw)	WB disch. (Mw)	Tie Line US (Mw)	Tie Line UB (Mw)	Load (Mw)
08-10	8.49	5.0	-	1.51	-	-	15.0
10-02	10.91	10.0	0.91	-	-	-	20.0
02-04	8.49	10.0	-	11.51	-	-	30.0
04-06	4.85	15.0	-	20.15	-	-	40.0
06-08	-	15.00	-	15.00	-	-	30.0
08-10	-	30.00	10.00	-	-	-	20.0
10-00	-	40.00	20.00	-	-	-	20.0
00-02	-	35.0	20.0	-	-	-	15.0
02-04	-	25.0	10.0	-	-	-	15.0
04-06	-	15.0	1.5	-	-	-	13.5
06-08	4.85	10.0	-	15.15	-	-	30.0

$A = 40416\ m^2$, $PST_r = 10.9$ MW, N = 500, $PWG_r = 50.0$ MW
WB = 66658 KWh, CTL = 00.0 MW, MC = 50.005 $/MWh

Table 8

Period	STES (Mw)	WES (Mw)	WB char. (Mw)	WB disch. (Mw)	Tie Line US (Mw)	Tie Line UB (Mw)	Load (Mw)
08-10	7.79	4.64	-	3.56	-	9.0	25.0
10-02	10.04	9.28	3.32	-	-	9.0	25.0
02-04	7.79	9.30	-	11.91	9.0	-	20.0
04-06	4.46	13.95	-	20.59	9.0	-	30.0
06-08	-	18.60	-	-	-	1.4	20.0
08-10	-	32.50	7.50	-	-	-	25.0
10-00	-	27.89	2.89	-	-	-	25.0
00-02	-	37.20	17.20	-	-	-	20.0
02-04	-	18.59	3.59	-	-	-	15.0
04-06	-	13.95	0.45	-	-	-	13.5
06-08	4.45	9.3	-	2.25	-	9.0	25.0

$A = 37100\ m^2$, $PST_r = 10.0$ MW, N = 465, $PWG_r = 46.5$ MW
WB = 40334 KWh, CTL = 10.0 MW, MC = 54.6377$/MWh

Table 9

Period	STES (Mw)	WES (Mw)	WB char. (Mw)	WB disch. (Mw)	Tie Line US (Mw)	Tie Line UB (Mw)	Load (Mw)
08-10	7.79	4.39	-	3.82	-	9.0	25.0
10-02	10.02	8.78	2.8	-	-	9.0	25.0
02-04	7.79	8.78	-	-	-	3.43	20.0
04-06	4.46	13.17	-	3.37	-	9.0	30.0
06-08	-	13.18	-	15.82	9.0	-	20.0
08-10	-	26.35	-	7.65	9.0	-	25.0
10-00	-	35.13	10.13	-	-	-	25.0
00-02	-	30.74	10.74	-	-	-	20.0
02-04	-	21.95	6.95	-	-	-	15.0
04-06	-	13.17	-	-	-	0.33	13.5
06-08	4.45	8.78	-	2.77	-	9.0	25.0

$A = 37100\ m^2$, PST = 10.0 MW, N = 439, $PWG_r = 43.9$ MW
WB = 35191 KWh, CTL = 10.0 MW, MC = 45.148 $/MWh

CONCLUSIONS

This paper presents an optimization technique to formulate the problem of the optimum hybrid combination of renewable and conventional energy systems. This technique offers the possibility to analyze the sensitivity of the optimal solution (the participation of each system) to changes in the different cost coefficients, the changes in the load demand, and the changes in the availability of the renewable energy sources.

In order to encourage the wide spread use of the renewable energy systems, they should take the advantages of the provisions requiring utilities to purchase back any available excess energy from their generation output at fair market prices. An optimum pricing policy can direct the consumers having renewable energy sources to sell energy to the utility at its peak load hours and purchase energy from the utility at its off-peak hours. This interaction can improve the economy of the consumer energy sources and also can improve the reliability of the utility grid. Also, the economics of the energy produced from the renewable energy systems can be improved if the customer load can apply shiftable load schedule to offer optimum energy use strategy.

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