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RELIABILITY AND PROFITABILITY STUDY OF CONVENTIONAL - PHOTOVOLTAIC - BATTERY STORAGE COMBINED SYSTEM

دراسة اعتمادية وربحية نظم القوى المرتبطة بالنظم الكهروضوئية وبطاريات التخزين

by

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خلاصة - طرق حساب مؤشرات اعتمادية نظم القوى التقليدية المرتبطة بالمصادر الغير تقليدية المقدمة والمنشوره لم تدرس كيفية ادخال بطاريات التخزين . والبحث المقدم قام بتطوير وتعديل هذه الطرق لحساب مؤشرات اعتمادية نظم القوى التقليدية المرتبطة بمصادر القوى الكهروضوئية وبطاريات التخزين . ويحتوى البحث المقدم على النقاط الاساسية الاتية :

١- استنباط استراتيجية تشغيل لمنظومة القوى المحتويه على نظم القوى التقليدية والكهروضوئية وبطاريات التخزين وكيفية استخدامها فى استيفاء حاجة الحمل ساعة بساعة على طول ساعات اليوم مع الحفاظ على القيود الفنية والاقتصادية المأخوذة فى الاعتبار .

٢- تعديل وتطوير طرق حساب مؤشرات اعتمادية نظم القوى التقليدية المرتبطة بالمصادر غيرالتقليدية لتتضمن تأثير ادخال بطاريات التخزين .

٣- تقديم طريقة حساب النفع الناتج عن عملية الربط والذى يعتمد اساسا على :

أ- الوفر فى وقود وحدات نظم القوى التقليدية نتيجة ربطها بالمصادر الكهروضوئية وبطاريات التخزين .

ب- تكلفة معرضة الوحدات التقليدية الاضافية اللازم اضافتها الى الوحدات الحاليه لتحقيق نفس قيم مؤشرات اعتمادية نظم القوى التقليدية بعد ربطها .

ويعرض البحث تطبيق رقمى شامل يوضح كيفية تطبيق استراتيجية التشغيل المقترحه وصلاحية تطبيق الطرق الرياضية المعدلة وحساب قيم النفع الناتج عن الربط وعرض اهم النتائج المستنبطة فى جداول عامة وتقديم الرسومات التوضيحية والتعبير عنها رياضيا وتلخيص لاهم النتائج والتوصيات المستنبطة منه .

ABSTRACT

The works published by different authors and intended for determining reliability indices of conventional generation systems integrated with unconventional ones do not deal with the impact of interconnecting storage batteries with them . The methods are developed in these works are modified here and modified to reflect the influence of interconnecting storage batteries with these systems .

This paper deals with the following important topics :

1. Derivation of an hourly operation strategy for the combined system selected for the study .

2. Modification of the previous methods used in providing the reliability indices of combined system to include the impact of storage batteries .

3. Determination of the profit resulting from the interconnection .

A numerical study is carried out to discuss the suggested operation strategy and, to verify the modified analysis, and also to determine the interconnection profit . The results are presented in the form of tables, figures and mathematical formulas.

Key-words

Reliability - Profitability - Photovoltaic - Battery Storage Loss-Of-Load Expectation - Expected Unserved Energy - Fuel saving - Load Carrying Capability - Levelized annual profit - Levelized reduction in energy cost .

1. INTRODUCTION

The suitable method for reliability and profitability evaluation of electric power system including fluctuating energy sources and/or storage systems should account for the fluctuating nature of energy supply and failure and repair characteristics of each unit [2] . The effect of the fluctuating nature of photovoltaic output on system economy and reliability are studied in [2, 3,12] . The fluctuating nature of the storage systempower (charging and discharging power) and its effect on the economic and reliability evaluation are considered in [11] .

This paper studies the effect of interconnecting photovoltaic and storage system with the conventional ones . The reliability and profitability of the combined system are investigated . Charging and discharging modes of the storage system are dealt with . The charging mode is dealt with as a load and the discharging mode is dealt with as a source .

An hourly operating strategy, , showing the units used in feeding the load,. is suggested for the generation units, conventional units, photovoltaic, and storage battery .

The reliability indices, "Loss-of-Load Expectation (LOLE)" and "Expected Unserved Energy (EUE)" are determined using the most accurate method (Singh and Gonzalez [2]) dealing with the battery as a load in the charging mode and as a source in the discharging one .

The profitability resulting from the interconnection of the photovoltaic panels and storage battery with a conventional system is estimated by computing its annual value by its energy and capacity components and subtracting the annual costof PV, BSC, and converters from this value ,

The schematic diagram of the suggested combined system is shown in Fig.1 . The conventional system consists of base, medium, and peak units . These units are connected to the grid and to the storage battery via a rectifier . PV panels are connected to the grid through an inverter . The storage battery is connected to the grid through a converter .

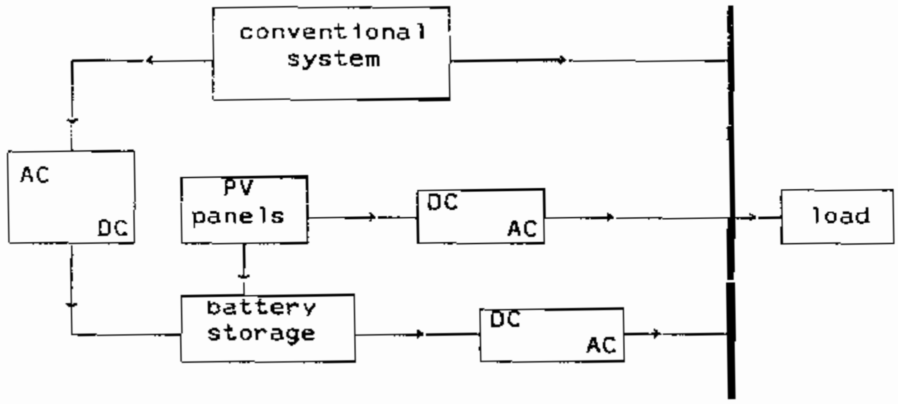


Fig.1 : Block diagram of the investigated system

Nomenclature

K	:	number of hours under study,
$C_L(n)$	:	load demand at hour n,
$C_s(n)$	:	storage battery output at hour n, (-ve during charging and +ve during discharging)
$C_{PV}(n)$	:	PV output at hour n,
$C_{LM}(n)$	:	modified load demand at hour n,
$C_M(n)$	:	output of medium units at hour n,
$C_P(n)$	:	output of peak units at hour n,
$C_{ch}(n)$	:	charging rate of the storage battery at hour n,
C_B	:	output of base units,
C_{PVR}	:	rated power of PV panels,
C_{dr}	:	maximum discharging rate of storage battery ,
C_{chr}	:	maximum charging rate of storage battery ,
E_{so}	:	initial stored energy in the storage battery,
E_{smin}	:	minimum allowable stored energy in the battery,
E_{smax}	:	maximum allowable stored energy in the battery,
$C_{PV}(j)$	:	capacity of PV panels at state j
$C_C(i)$	:	capacity of conventional units at state i,
$C_{s1}(m)$	:	maximum discharging rate of the battery at state m,
$C(L)$	:	capacity of overall generation model at state L,
$C(L1)$	:	capacity of overall generation model at state L1,
$P_{PV1}(j)$	:	probability of surviving state j of PV panels,
IM	:	total number of conventional units capacity states,
JM	:	total number of photovoltaic panels capacity states,
MM	:	total number of storage battery capacity states,

P_c (i) : probability of surviving state i of conventional units.
P_{b1} (m) : probability of surviving state m of storage battery.
P(L) : probability of surviving state L of overall model.
P(L1) : probability of surviving state L1 of overall model.

LOLE(n) : loss-of-load expectation at hour n.
EUE(n) : expected unserved energy at hour n.
LOLE : loss-of-load expectation.
EUE : expected unserved energy.
E_v : energy value in the first year.
V_c : capacity value in the first year.
LCC : load carrying capability.
C_f : fixed cost.
C_v : variable cost.
e_r : real fuel escalation rate.
e_a : actual fuel escalation rate.
e_i : inflation rate.
i : interest rate.
N : life-time.
P_{ve} : present value of energy value.
P_{vc} : present value of capacity value.
P_v : present value of variable cost.
L_1 : levelized annual energy value.
L_2 : levelized annual capacity value.
L_f : levelized annual fixed cost.
L_v : levelized annual variable cost.
L_p : levelized annual profit.
FOR : forced outage rate.
G : solar radiation intensity in mW/cm^2.
ω : solar angle in degree.
T : solar time.
PL : penetration level.
BSC : battery storage capacity,and
FS : first year fuel saving .

2.THE SUGGESTED OPERATION STRATEGY

The suggested operation strategy is presented in the flow chart shown in Fig.2 and summarized in the following statements :

1 - For a specific hour, n, throughout the day hours, the PV output is computed from the solar power density at that hour, I(n), PV panels area, A_{PV}, and their efficiency (is assumed to be constant) , η_{PV}, as follows :

$$C_{PV}(n) = A_{PV} * I(n) * \eta_{PV} \qquad (1)$$

2 - Estimation of load demand, $C_L(n)$ at the hour n from the daily load curve .

3 - Assessment of the power output from the base and medium units

of the conventional generation system, C_B and C_M respectively .

4 - Charging the storage battery firstly from the base and PV units . If the output of the base and PV units is insufficient to do this, the medium units are utilized in addition to them, for minimizing the operation period of the medium units and dump load

5 - Powering the load from the base units when :

$$C_B \geq C_L(n) \quad (2)$$

6 - The excess power resulting from the above statement $[C_B - C_L(n)]$ plus the PV output, $C_{PV}(n)$, is utilized in charging the storage battery , if it accepts . The storage battery accepts this power when the stored energy at the beginning of the considered hour, $E_s(n-1)$, is less than the maximum allowable value, E_{smax} . The rate of the battery charging must be considered . If the battery is fully charged, the rest of power is dumped .

7 - Supplying the load from the base units, C_B, and PV, $C_{PV}(n)$, when :

$$C_B < C_L(n) \quad (3)$$

and,

$$C_B + C_{PV}(n) \geq C_L(n) \quad (4)$$

Also, the excess power is used in charging the battery .

8 - Powering the load from base, PV, and medium units if :

$$C_B + C_{PV}(n) < C_L(n) \quad (5)$$

and,

$$C_B + C_{PV}(n) + C_M \geq C_L(n) \quad (6)$$

then, the output of the medium units at the hour n is :

$$C_M(n) = C_L(n) - C_B - C_{PV}(n) \quad (7)$$

9 - Feeding the load from the base , PV, medium, and storage battery if :

$$E_s(n-1) > E_{smin} \quad (8)$$

and

$$C_L(n) - \{C_B + C_M + C_{PV}(n)\} \leq (E_s(n-1) - E_{smin} \quad (9)$$

10 If:

$$C_L(n) > C_B + C_M + C_{PV}(n) + C_s(n) \quad (10)$$

and

$$E_s(n-1) > E_{smin} \quad (11)$$

then, the peak units are operated to feed the load as follows :

$$C_P(n) = C_L(n) - [C_B + C_M + C_{PV}(n) + C_s(n)] \quad (12)$$

11 - Feeding the load from the base, PV, medium, and peak units if :

$$C_L(n) > C_B + C_M + C_{PV}(n) \quad (13)$$

and,

$$E_s(n-1) = E_{smin} \quad (14)$$

12 - Repeating all the previous steps for every hour under study.

13 - Determine the stored energy at the end of the last hour m, $E_s(k)$ and compare it with the initial stored energy, E_{si} .

a -If $E_s(k) < E_{si}$ (15)

then, modify the discharging rate of the battery of the last hour, m, achieving :

$$E_s(k) = E_{si} \quad (16)$$

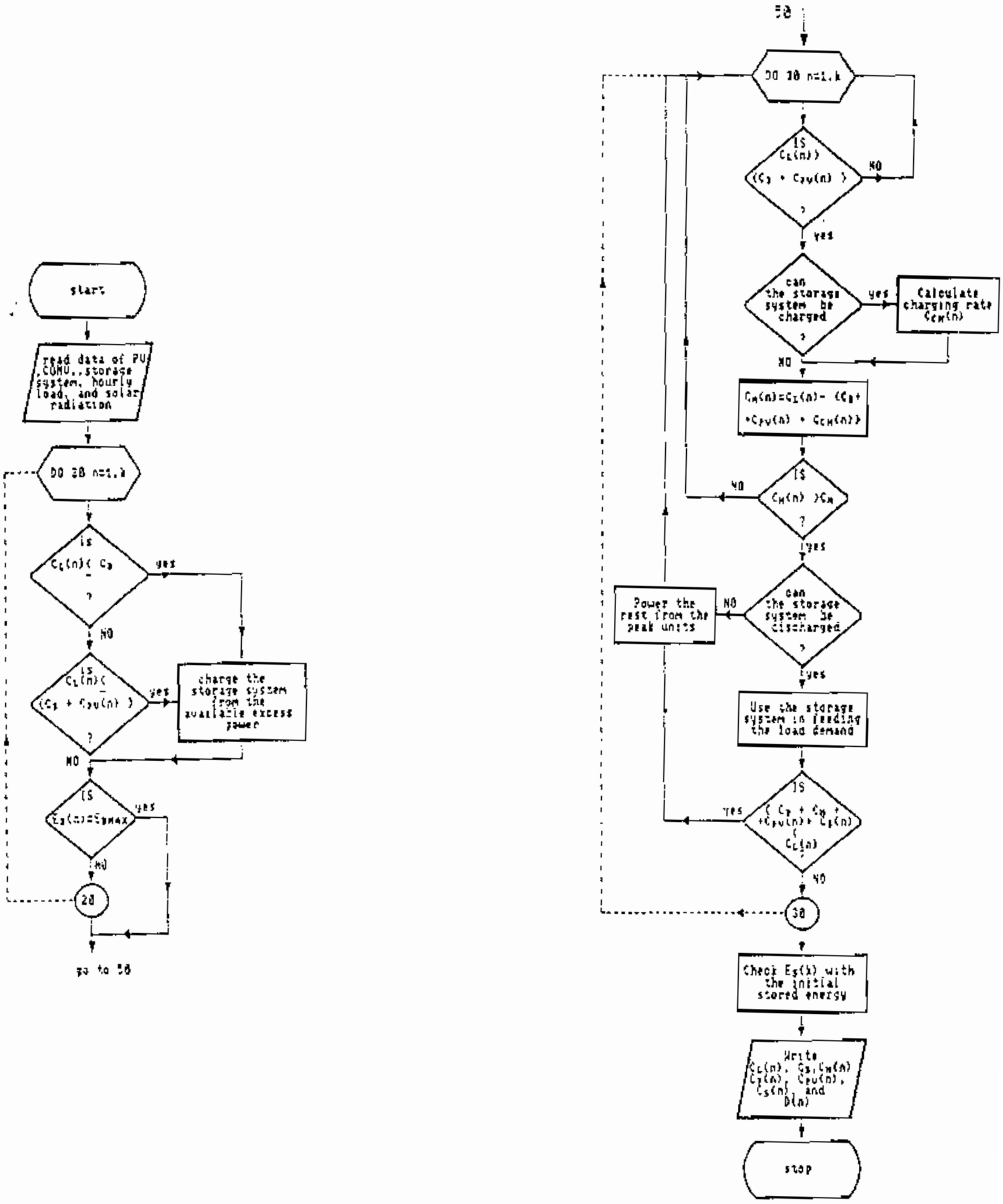


Fig.2 : Flow chart of suggested operation strategy

The operation strategy from the hour m to k is also modified .

b - If $E_s(k) > E_{si}$ (17)

then, decrease the charging rate of the battery of the last charging hour, n1, for achieving eq.16 .The operation strategy from the hour n1 to k is also modified according to the modified charging rate .

3.DEDUCTION OF THE RELIABILITY INDICES

The main contribution presented in this paper is the insertion of a storage system into the combined system (PV / conventional generation system) and deducing the reliability indices . The storage system has two operation modes :

a - Charging mode, during which the storage system is dealt with as a load . The charging rate of the storage system is added to the hourly load demand to determine the modified load demand .

b - Discharging mode, during which the storage battery is considered as a source . The discharging rate of the storage battery is modified hourly and the resulting rate is combined with the hourly conventional and PV generation models to get the hourly overall generation model . This model is combined with that of the load demand for deducing the most significant reliability indices, Loss-Of-Load Expectation (LOLE) and Expected Unserved Energy (EUE) .Fig.3 demonstrates the method proposed in deducing the reliability indices and the procedure is summarized as follows :

1 - Execution of the hourly operation strategy presented in section 2 .

2 - Preparation of the generation models (capacity and probability models) of the conventional generation, PV, and storage systems .

3 - The battery power at the n^{th} hour is $C_s(n)$, has two states :

a - $C_s(n) \leq 0.0$ (18)

The modified load demand, $C_{LM}(n)$,in this case is :

$$C_{LM}(n) = C_L(n) - C_s(n) \quad (19)$$

The capacity and probability models are :

$$C(L) = C_c(i) + \frac{C_{PV}(n)}{C_{PVR}} \cdot C_{PVi}(j) \quad (20)$$

$$P(L) = P_c(i) \cdot P_{PVi}(j) \quad (21)$$

Where i = 1,2, . IM and j = 1,2, . JM

Then, the hourly Loss-Of-Load Expectation and the Expected Unserved Energy are [2] :

$$LOLE(n) = \sum_{L=1}^{LM} P(L) \quad (22)$$

and

$$EUE(n) = \sum_{L=1}^{LM} [\ C_{LM}(n) - C(L)\ ] .P(L) \quad (23)$$

where LM = IM * JM

(except the states during which $C(L) \geq C_{LM}(n)$)

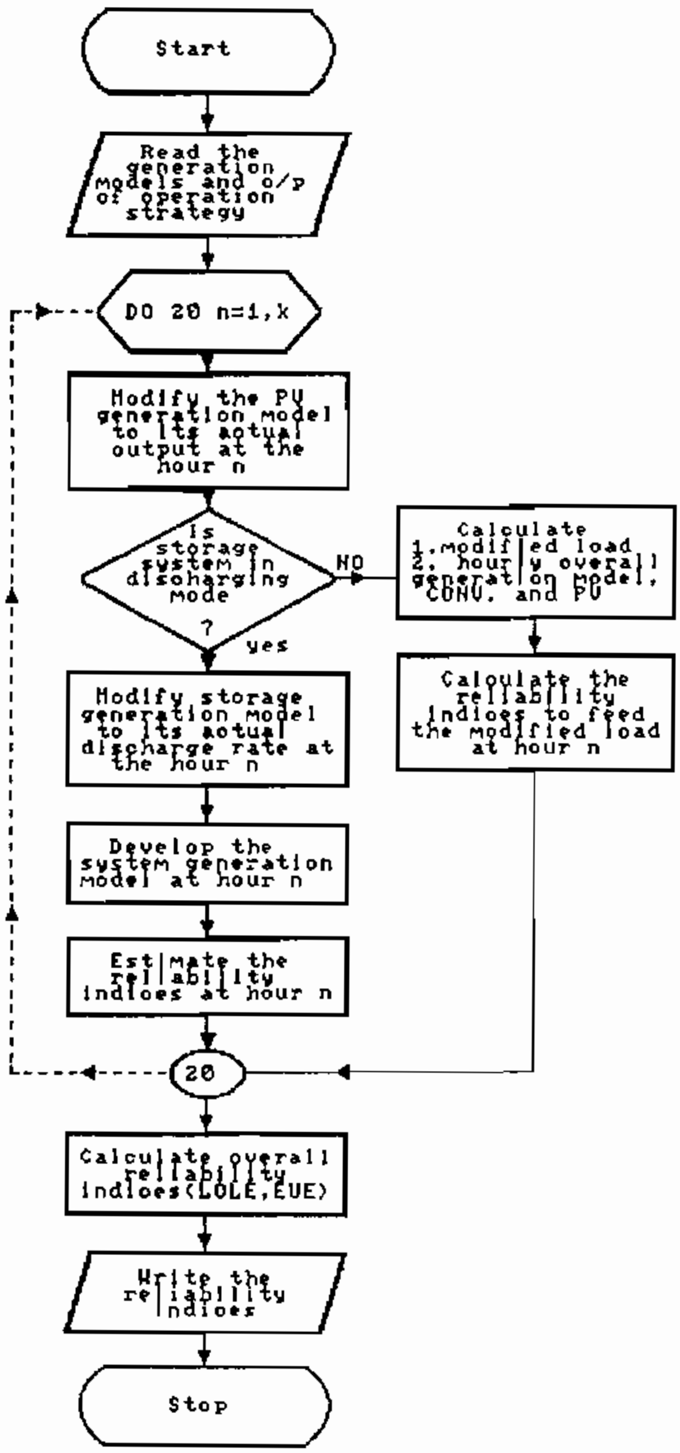


Fig.3 : Estimation of the reliability indices of the combined system

b - $C_s(n) > 0.0$ (24)

This means that the storage battery is in the discharging mode and is considered as a source . So, the capacity and probability models of the system are :

$$C(L1) = C_c(i) + \frac{C_{PV}(n)}{C_{PVR}} \cdot C_{PVi}(j) + \frac{C_s(n)}{C_{dr}} \cdot C_{si}(m) \quad (25)$$

and

$$P(L1) = P_c(i) \cdot P_{PVi}(j) \cdot P_{si}(m) \quad (26)$$

where i = 1,2, , IM , j = 1,2, ,JM and m = 1,2, , MM

The hourly Loss-Of-Load Expectation , LOLE(n) and Expected Unserved Energy, EUE(n) are :

$$LOLE(n) = \sum_{L1=1}^{LM1} P(L1) \quad (27)$$

and

$$EUE(n) = \sum_{L1=1}^{LM1} [\ C_{LM}(n) - C(L1)\ ] \cdot P(L1) \quad (28)$$

where LM1 = IM * JM * MM

(except the states during of which $C(L1) \geq C_L(n)$)

The overall reliability indices are given by :

$$LOLE = \sum_{n=1}^{k} LOLE(n) \quad (29)$$

and

$$EUE = \sum_{n=1}^{k} EUE(n) \quad (30)$$

The fluctuating nature of PV and storage systems, and the failure and repair characteristics of the PV panels are considered in the above analysis . The failure and repair characteristics of the battery are taken only during the discharging mode .

4. PROFIT OF THE COMBINED SYSTEM

Performance evaluation is important . However business decisions are made in terms of the profit which equals the value minus the cost . These two components must be calculated to determine a technology profit [3] .

4.1. Value of Resource

Utilities assess conventional generation technologies in terms of their energy and capacity values . Here, the unconventional units are dealt with like the conventional ones .

4.1.1. Energy Value

The energy value, E_v is the cost of providing the last kWh of energy by an alternative source . The energy value varies with the load . At peak load it is higher than that at low load. So, it is incrementally calculated .

4.1.2. Capacity Value

The capacity value, V_c, is the value of the added reliability that the new source provides to the generation system . The capacity value is calculated by the following two steps : a - The utility generation system reliability is evaluated without the new source . This is used to determine the dollar value of an increment of perfectly reliable capacity, called the shortage value .

b - Calculation of the load carrying capability, LCC which is the amount of constant load increase that returns the system to the previous reliability level before the addition of the new source, so :

$$V_c = LCC \; . \; \text{shortage value} \qquad (31)$$

4.2. Cost

The total cost of any system consists of two parts :

a - Fixed cost, C_f, which is the cost of installation, instruments, and land .

b - Variable cost, C_v, which is the cost of fuel , maintenance , salaries, and all other variable cost items .

4.3. Profit [4, 12]

Economic comparison of different systems that can be used in powering a certain load is performed either by evaluating the present value or by determining the annual cost of them . The variation in the annual cost due to escalation makes the comparison more difficult ,especially when the starting dates and the expected life-times of these systems are different . The levelized annual cost overcomes this difficulty .When dealing with items dependent upon the fuel cost , the fuel escalation rate, e_r, should be taken into consideration . The present value of the energy, P_{ve}, can be determined as follows :

$$P_{ve} = E_v \; . \; (1+e_a) \; . \left[\frac{[(1+e_a) \;/\; (1+i)]^n - 1}{e_a - i} \right] \qquad (32)$$

The relation between the actual fuel escalation, real fuel escalation, and inflation rates is :

$$(1+e_a) = (1+e_r) \; . \; (1+e_i) \qquad (33)$$

So, the levelized annual energy value, L_1, is :

$$L_1 = P_{ve} \; . \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right] \qquad (34)$$

The present value of the capacity value, P_{vc}, is :

$$P_{vc} = V_c \, .(1+ e_i) \; . \left[\frac{[(1+e_i) \;/\; (1+i)]^n - 1}{e_i - i} \right] \qquad (35)$$

So, the levelized annual capacity and fixed cost values are given respectively as :

$$L_a = P_{vc} \cdot \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right] \quad (36)$$

and

$$L_f = C_f \cdot \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right] \quad (37)$$

Present value of the variable cost, P_v, and the levelized annual variable cost are given by :

$$P_v = C_v \cdot (1+ e_i) \cdot \left[\frac{[(1+e_i) / (1+i)]^n - 1}{e_i - 1} \right] \quad (38)$$

and

$$L_v = P_v \cdot \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right] \quad (39)$$

If there are many components having different expected life-times, both of the levelized annual fixed and variable costs are, individually, calculated for each component . The sum of these different levelized annual costs gives the overall levelized annual cost . The plant levelized annual profit, L_p, is [4] :

$$L_p = L_1 + L_2 - \Sigma (L_f + L_v) \quad (40)$$

5. NUMERICAL APPLICATION

For demonstrating the reliability and profitability obtained from combinding PV and battery with the conventional systems, the following system is studied . The data of the conventional units, PV panels, and battery are :

1 - Conventional units [5,6]

kind	Number of units	Capacity (Mw)	Type	FOR (%)	O&M cost ($/MWh)
Base	10	175	hydro	1.0	4.0
Medium	3	315	thermal(steam)	5.0	44.39
Peak	30	20	gas - fired	6.0	149.43
Stand-by	1	315	thermal(steam)	5.0	44.39

2 - PV panels [7]

Rating / panel	=	25	MW,
Installation cost	=	3.3	$\$/W_p$,
Operating and maintenance cost	=	0.5	$\$/W_p$,

3 - Storage Battery

Rating / oank	=	20	MWh,
Minimum discharge duration	=	2	hrs,
Maximum charge rate	=	10	MW,
Maximum discharge rate	=	10	MW,
Minimum stored energy	=	6	MWh,
Life-time	=	2000	cycles,
Efficiency	=	70	%, and
Forced outage rate	=	6	%

4 - Converter

Installation cost	=	282	$/kW,
Life-time	=	10	Years, and

5 - Load Demand [9]

The daily curve of the supplied loads is shown in Fig.5 .

Maximum load = 3120 MW,

Annual consumed energy = 21.243* 10^{6} MWh, and

Load factor = 0.777

6 - Solar Radiation Profile

The solar insolation is assumed for a clear as a half sine wave [10] with a maximum of 70 mW/cm^2, i.e. G = 70 sin ω mW/cm^2.

The daily solar radiation is shown in Fig.6

7 - Economic factors [7,11]

Interest rate, i = 18 %,

Inflation rate, e_i = 16 %,

Real fuel escalation rate, e_r = 6 %, and

Shortage value = 75 $/kW-Year

In this application, the operation strategies, loss-of-load expectation, expected unserved energy, fuel saving, load carrying capability, and levelized annual profit are investigated for different

a - Penetration levels of photovoltaic panels, rated power of the PV panels divided by the maximum load , and

b - Storage battery capacities .

5.1. Operation Strategies

The operation strategies of the combined system studied in this application are derived for :

a - PL of PV = 0.0 % and BSC = 0.0 (conventional units only, reference case)

b - PL of PV = 9.6 % and BSC = 0.0 (PV with the conventional units)

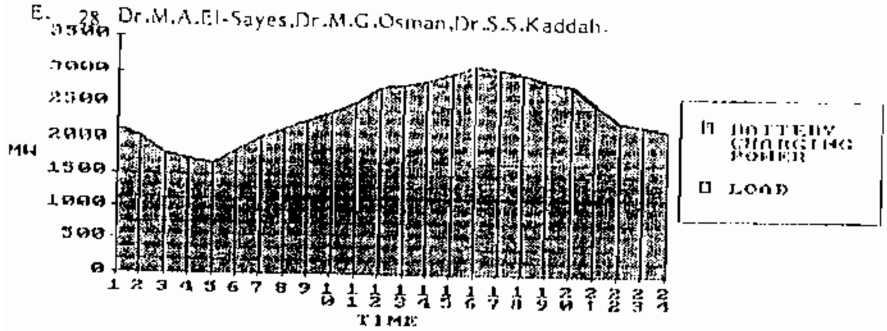
c - PL of PV = 0.0 % and BSC = 800 MWh (battery storage with conventional units)

d - PL of PV = 9.6 % and BSC = 800 MWh (conventional units with PV and battery storage)

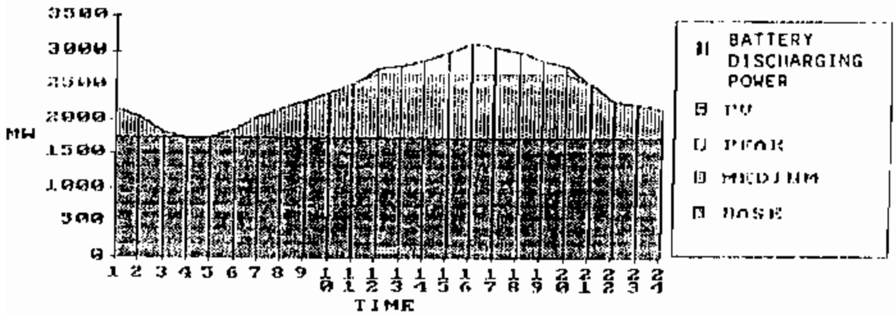
For these cases the hourly output of the : base, medium, and peak units of the conventional system, and the photovoltaic panels are derived . Also, the output or input power of the battery , and the power dumped are developed . The power of the battery is positive in the discharging mode but negative in the charging mode .The power required for the battery during the charging mode is added to the daily load curve resulting in the modified one . Table 1 presents the hourly output of the base, medium, and peak units of the conventional system, PV panels, battery storage, and dump load . The hourly output of each unit of the combined system is shown in Fig.4 for the four cases .

5.2.Loss-Of-Load Expectation and Expected Unserved Energy

Loss-of-load expectation and expected unserved energy of the combined system studied in this application due to different penetration levels of PV and battery storage capacities are shown in Fig.7 . The resulted LOLE and EUE can be represented as functions of battery storage capacity as follows :

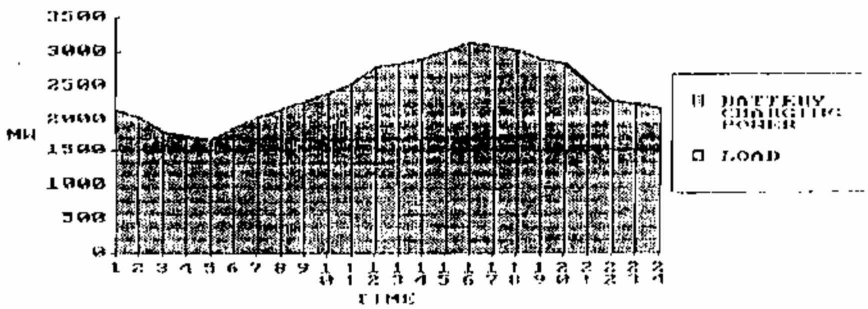


Daily load curve

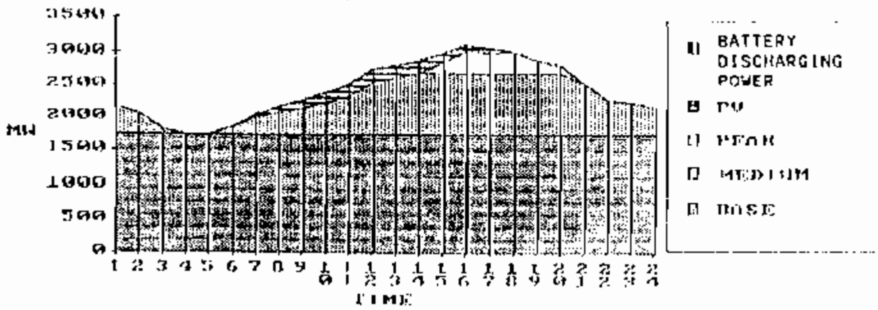


Daily generation curve

Fig.4.a : The daily operation strategy at:
PL = 0.0 % and BSC = 0.0 MWh



Daily load curve



Daily generation curve

Fig.4.b : The daily operation strategy at :
PL = 9.6 % and BSC = 0.0 MWh

$$LOLE(n) = A_1 + B_1 .(BSC) + C_1 . (BSC) \quad (41)$$

$$EUE(n) = A_2 + B_2 .(BSC) + C_2 . (BSC) \quad (42)$$

with correlation factors CF_1 and CF_2, respectively . The parameters of equations 40 and 41 are listed in Table 2 for different penetration levels . Also, LOLE and EUE can be represented as functions of PL as follows :

$$LOLE(n) = A_3 . EXP(-A_{33} .PL) \quad (43)$$

$$EUE(n) = A_4 . EXP(-A_{44} .PL) \quad (44)$$

with correlation factors CF_3 and CF_4 ,respectively .These parameters are tabulated in Table 3 for different battery storage capacities .

The improvement achieved in the LOLE and EUE due to different penetration levels of PV and battery storage capacities are revealed in Fig.8 .

5.3 - Fuel Saving , Load Carrying Capability and Levelized Profit

The fuel saving , first year energy value , is the difference of the total system production cost after and before adding PV and storage battery to the conventional generation systems . Fig.9 shows the fuel saving due to different penetration levels of PV and different storage capacities . The fuel saving obtained can be modelled as functions of penetration level and storage capacity as revealed below :

$$FS(BSC) = A_5 + B_5 .(BSC) - C_5 . (BSC)^2 \quad (45)$$

$$FS(PL) = A_6 + B_6 .(PL) - C_6 . (PL)^2 \quad (46)$$

A_5 , B_5 , C_5 , A_6 , B_6 and C_6 for different penetration levels and battery capacities are listed in table 4 . Fig.10 shows the load carrying capability considering EUE as a reliability index and can be represented by the following relations :

$$LCC(BSC) = A_7 + B_7 . (BSC) - C_7 .(BSC)^2 \quad (47)$$

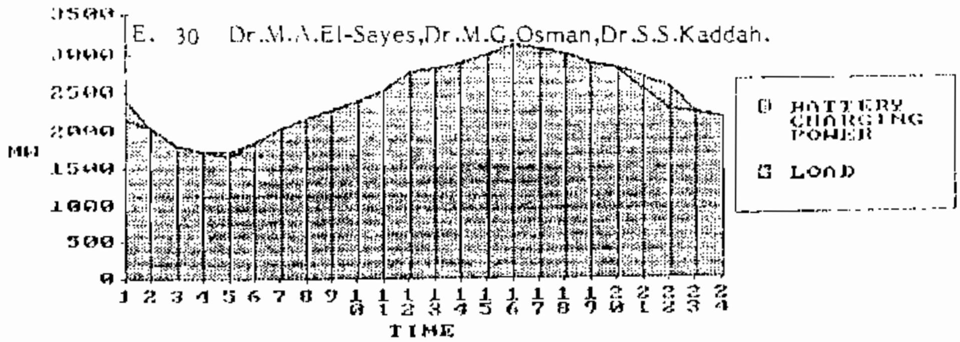
$$LCC(PL) = A_8 + B_8 . (PL) - C_8 .(PL)^2 \quad (48)$$

The parameters of the above two relations are listed in table 5 . Fig 11 shows the levelized annual profit and the resulted levelized reduction in energy unit (kWh) cost is revealed in Fig.12 . The levelized annual profit can be represented by the following models :

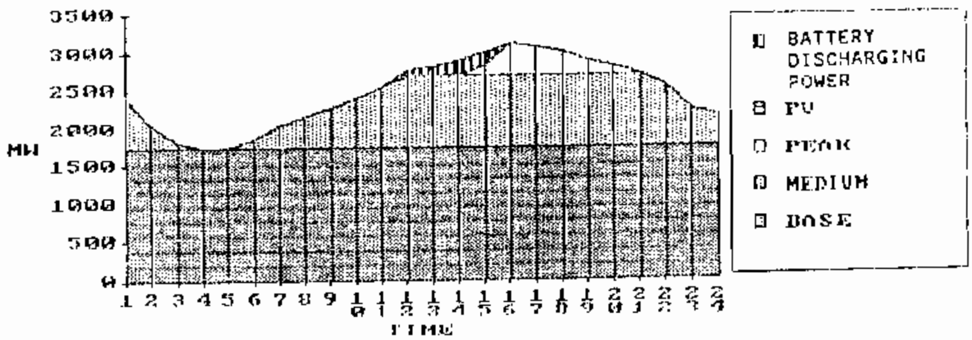
$$LP(BSC) = A_9 + B_9 . (BSC) - C_9 .(BSC)^2 \quad (49)$$

$$LP(PL) = A_{10} + B_{10} . (PL) - C_{10} .(PL)^2 \quad (50)$$

A_9 , B_9 , C_9 , A_{10} , B_{10} and C_{10} are listed in table 6 .

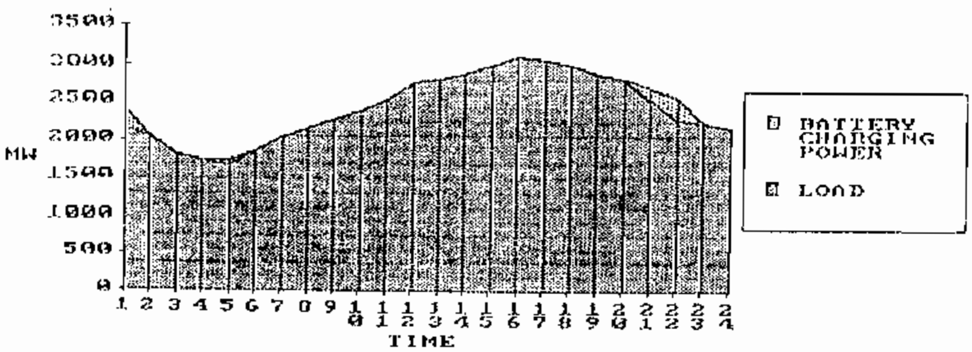


Daily modified load curve

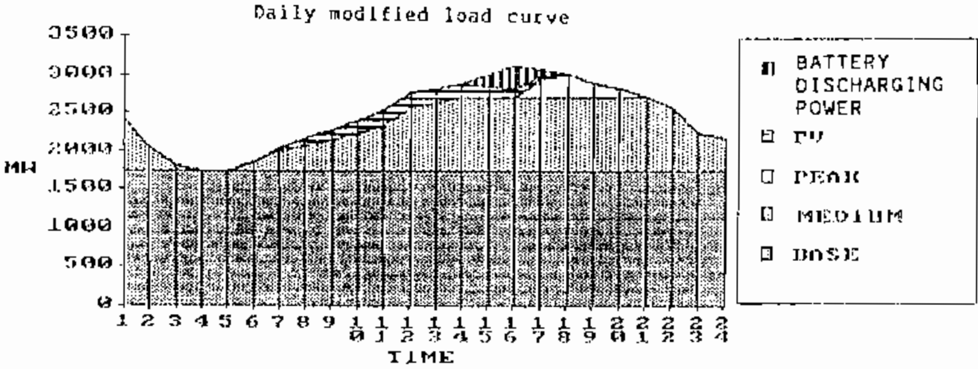


Daily generation curve

Fig.4.c : The daily operation strategy at :
PL = 0.0 % and BSC = 800 MWh



Daily modified load curve



Daily generation curve

Fig.4.d : The daily operation strategy at :
PL = 9.6 % and BSC = 800 MWh

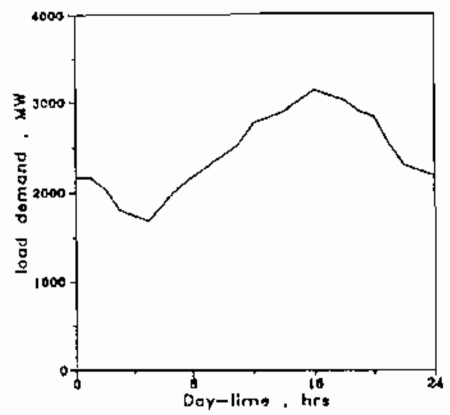


Fig.5 : Daily load curve

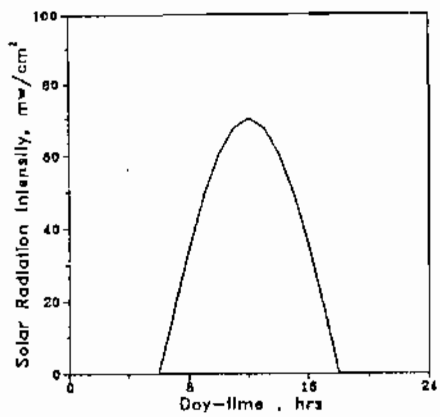


Fig.6 : Daily solar radiation intensity

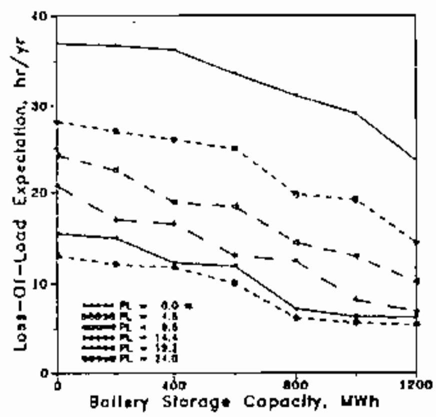


Fig 7.a : Loss of load Expectation vs. BSC and taking PL as a parameter

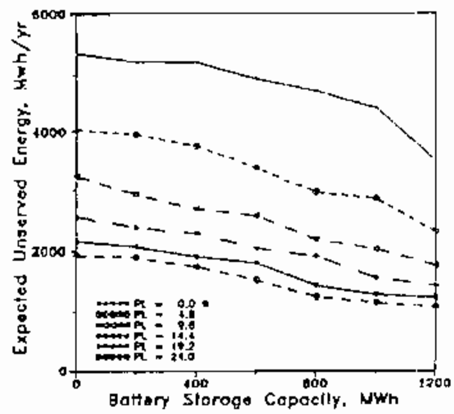


Fig 7.b : Expected Unserved Energy vs.BSC and taking PL as a parameter

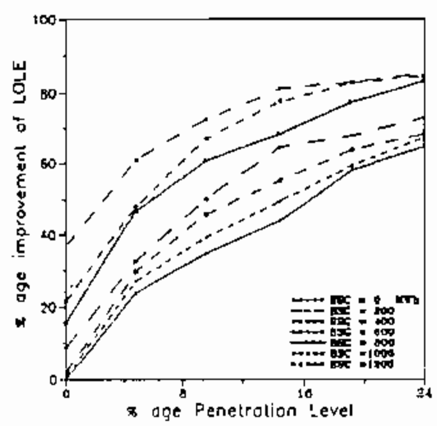


Fig 8.a : Improvement of LOLE vs. PL and taking BSC as a parameter

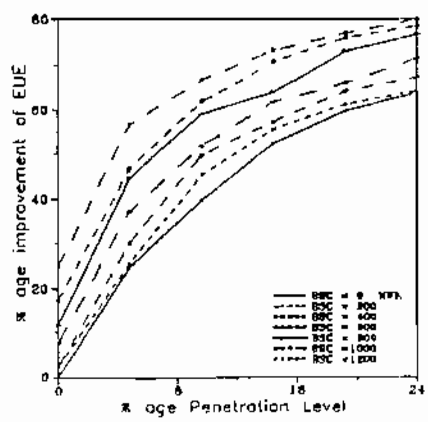


Fig 8.b : Improvement of EUE vs. PL and taking BSC as a parameter

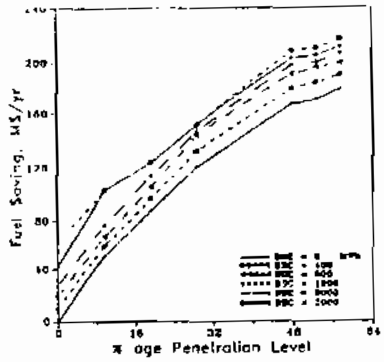


Fig 9.a : Fuel Saving vs. PL and BSC is taken as a parameter

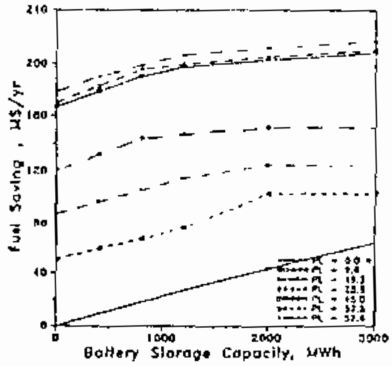


Fig 9.b : Fuel Saving vs. BSC and taking PL as a parameter

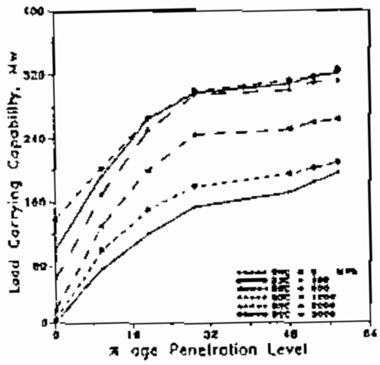


Fig.10.a : Load Carrying Capability vs. PL and BSC is taken as a parameter

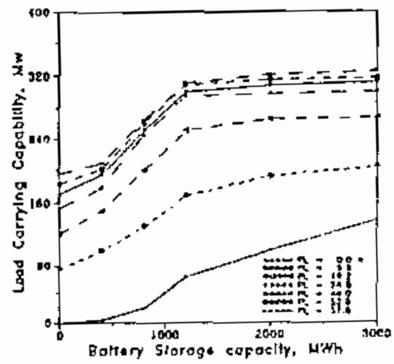


Fig.10.b : Load Carrying Capability vs. BSC and PL is taken as a parameter

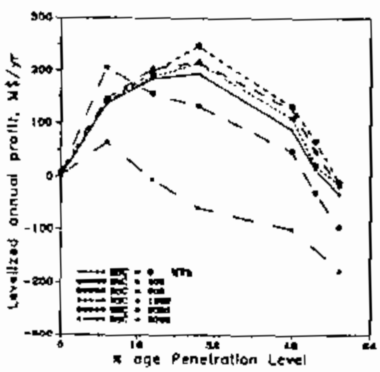


Fig.11.a : Levelized annual profit vs. PL and BSC is taken as a parameter

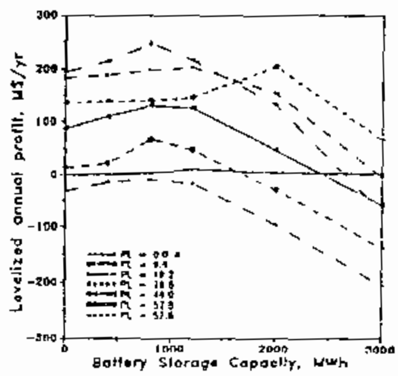


Fig 11.b : Levelized annual profit vs. BSC and PL is taken as a parameter

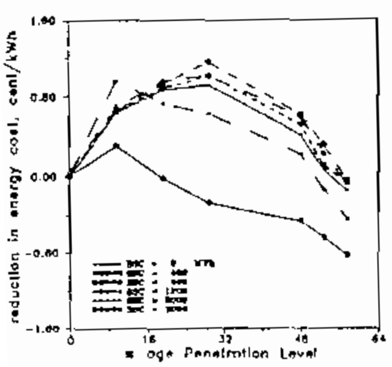


Fig.12.a : Levelized reduction in energy cost vs. PL and BSC is taken as a parameter

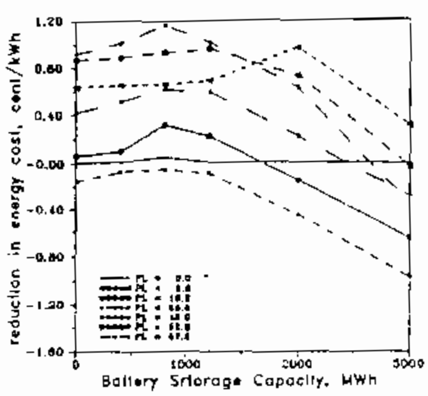


Fig.12.b : Levelized reduction in energy cost vs. BSC and PL is taken as a parameter

Table 1.a : The daily operation strategy at:
PL = 0.0 % and BSC = 0.0 MWh
(base case)

DAY-TIME (HOURS)	LOAD DEMAND (MW)	PV OUTPUT (MW)	BASE OUTPUT (MW)	MEDIUM OUTPUT (MW)	PEAK OUTPUT (MW)	BATTERY OUTPUT (MW)	DUMP LOAD (MW)
1	2160	0.0	1750	410.00	000.0	000.00	000.0
2	2040	0.0	1750	290.00	000.0	000.00	000.0
3	1800	0.0	1750	050.00	000.0	000.00	000.0
4	1740	0.0	1750	000.00	000.0	000.00	010.0
5	1680	0.0	1750	000.00	000.0	000.00	070.0
6	1860	0.0	1750	110.00	000.0	000.00	000.0
7	2040	0.0	1750	290.00	000.0	000.00	000.0
8	2160	0.0	1750	410.00	000.0	000.00	000.0
9	2280	0.0	1750	530.00	000.0	000.00	000.0
10	2400	0.0	1750	650.00	000.0	000.00	000.0
11	2520	0.0	1750	770.00	000.0	000.00	000.0
12	2760	0.0	1750	945.00	065.0	000.00	000.0
13	2820	0.0	1750	945.00	125.0	000.00	000.0
14	2880	0.0	1750	945.00	185.0	000.00	000.0
15	3000	0.0	1750	945.00	305.0	000.00	000.0
16	3120	0.0	1750	945.00	425.0	000.00	000.0
17	3060	0.0	1750	945.00	365.0	000.00	000.0
18	3000	0.0	1750	945.00	305.0	000.00	000.0
19	2880	0.0	1750	945.00	185.0	000.00	000.0
20	2820	0.0	1750	945.00	125.0	000.00	000.0
21	2520	0.0	1750	770.00	000.0	000.00	000.0
22	2280	0.0	1750	530.00	000.0	000.00	000.0
23	2220	0.0	1750	470.00	000.0	000.00	000.0
24	2160	0.0	1750	410.00	000.0	000.00	000.0

Table1.b : The daily operation strategy at :
PL = 9.6 % AND BSC = 0.0 MWh

DAY-TIME (HOURS)	LOAD DEMAND (MW)	PV OUTPUT (MW)	BASE OUTPUT (MW)	MEDIUM OUTPUT (MW)	PEAK OUTPUT (MW)	BATTERY OUTPUT (MW)	DUMP LOAD (MW)
1	2160	000.00	1750	410.00	000.00	000.00	000.00
2	2040	000.00	1750	290.00	000.00	000.00	000.00
3	1800	000.00	1750	050.00	000.00	000.00	000.00
4	1740	000.00	1750	000.00	000.00	000.00	010.00
5	1680	000.00	1750	000.00	000.00	000.00	070.00
6	1860	000.00	1750	110.00	000.00	000.00	000.00
7	2040	054.40	1750	235.60	000.00	000.00	000.00
8	2160	105.00	1750	305.00	000.00	000.00	000.00
9	2280	148.50	1750	381.50	000.00	000.00	000.00
10	2400	181.86	1750	468.14	000.00	000.00	000.00
11	2520	202.80	1750	567.20	000.00	000.00	000.00
12	2760	210.00	1750	800.00	000.00	000.00	000.00
13	2820	202.80	1750	867.20	000.00	000.00	000.00
14	2880	181.86	1750	945.00	003.14	000.00	000.00
15	3000	148.50	1750	945.00	156.50	000.00	000.00
16	3120	105.00	1750	945.00	320.00	000.00	000.00
17	3060	054.40	1750	945.00	310.60	000.00	000.00
18	3000	000.00	1750	945.00	305.00	000.00	000.00
19	2880	000.00	1750	945.00	185.00	000.00	000.00
20	2820	000.00	1750	945.00	125.00	000.00	000.00
21	2520	000.00	1750	770.00	000.00	000.00	000.00
22	2280	000.00	1750	530.00	000.00	000.00	000.00
23	2220	000.00	1750	470.00	000.00	000.00	000.00
24	2160	000.00	1750	410.00	000.00	000.00	000.00

Table 1.c : The daily operation strategy at :
PL = 0.0 % and BSC = 800 MWh

DAY-TIME (HOURS)	LOAD DEMAND (MW)	PV OUTPUT	BASE OUTPUT (MW)	MEDIUM OUTPUT (MW)	PEAK OUTPUT (MW)	BATTERY OUTPUT (MW)	DUMP LOAD (MW)
1	2160	000.00	1750	672.90	000.00	-262.90	000.00
2	2040	000.00	1750	290.00	000.00	000.00	000.00
3	1800	000.00	1750	050.00	000.00	000.00	000.00
4	1740	000.00	1750	000.00	000.00	-010.00	000.00
5	1680	000.00	1750	000.00	000.00	-070.00	000.00
6	1860	000.00	1750	110.00	000.00	000.00	000.00
7	2040	000.00	1750	290.00	000.00	000.00	000.00
8	2160	000.00	1750	410.00	000.00	000.00	000.00
9	2280	000.00	1750	530.00	000.00	000.00	000.00
10	2400	000.00	1750	650.00	000.00	000.00	000.00
11	2520	000.00	1750	770.00	000.00	000.00	000.00
12	2760	000.00	1750	945.00	000.00	065.00	000.00
13	2820	000.00	1750	945.00	000.00	125.00	000.00
14	2880	000.00	1750	945.00	000.00	185.00	000.00
15	3000	000.00	1750	945.00	120.00	185.00	000.00
16	3120	000.00	1750	945.00	425.00	000.00	000.00
17	3060	000.00	1750	945.00	365.00	000.00	000.00
18	3000	000.00	1750	945.00	305.00	000.00	000.00
19	2880	000.00	1750	945.00	185.00	000.00	000.00
20	2820	000.00	1750	945.00	125.00	000.00	000.00
21	2520	000.00	1750	945.00	000.00	-175.00	000.00
22	2280	000.00	1750	812.14	000.00	-282.14	000.00
23	2220	000.00	1750	470.00	000.00	000.00	000.00
24	2160	000.00	1750	410.00	000.00	000.00	000.00

Table 1.d : The daily operation strategy at :
PL = 9.6 % and BSC = 800 MWh

DAY-TIME (HOURS)	LOAD DEMAND (MW)	PV OUTPUT (MW)	BASE OUTPUT (MW)	MEDIUM OUTPUT (MW)	PEAK OUTPUT (MW)	BATTERY OUTPUT (MW)	DUMP LOAD (MW)
1	2160	000.00	1750	672.90	000.00	-262.90	000.00
2	2040	000.00	1750	290.00	000.00	000.00	000.00
3	1800	000.00	1750	050.00	000.00	000.00	000.00
4	1740	000.00	1750	000.00	000.00	-010.00	000.00
5	1680	000.00	1750	000.00	000.00	-070.00	000.00
6	1860	000.00	1750	110.00	000.00	000.00	000.00
7	2040	054.40	1750	235.60	000.00	000.00	000.00
8	2160	105.00	1750	305.00	000.00	000.00	000.00
9	2280	148.50	1750	381.50	000.00	000.00	000.00
10	2400	181.86	1750	468.14	000.00	000.00	000.00
11	2520	202.80	1750	567.20	000.00	000.00	000.00
12	2760	210.00	1750	800.00	000.00	000.00	000.00
13	2820	202.80	1750	867.20	000.00	000.00	000.00
14	2880	181.86	1750	945.00	000.00	003.14	000.00
15	3000	148.50	1750	945.00	000.00	156.50	000.00
16	3120	105.00	1750	945.00	000.00	320.00	000.00
17	3060	054.40	1750	945.00	230.24	080.36	000.00
18	3000	000.00	1750	945.00	305.00	000.00	000.00
19	2880	000.00	1750	945.00	165.00	000.00	000.00
20	2820	000.00	1750	945.00	125.00	000.00	000.00
21	2520	000.00	1750	945.00	000.00	-175.00	000.00
22	2280	000.00	1750	812.14	000.00	-282.14	000.00
23	2220	000.00	1750	470.00	000.00	000.00	000.00
24	2160	000.00	1750	410.00	000.00	000.00	000.00

Table 4.b : The parameters A_6 , B_6 , C_6 and CF_6 for different batttery storage capacities .

BSC (MWh)	A_6	B_6	C_6	CF_6
0000.0	01.07701	5.30139	0.0391965	0.9832
0400.0	09.79315	5.35717	0.0390953	0.9985
0800.0	17.46190	5.49602	0.0404541	0.9985
1200.0	27.47140	5.24013	0.0369677	0.9983
2000.0	48.39560	4.68184	0.0320653	0.9985
3000.0	64.88140	3.52278	0.0142999	0.9982

Table 5.a : The parameters A_7 , B_7 , C_7 , and CF_7 for different penetration levels .

P.L. %	A_7	B_7	C_7	CF_7
00.0	-009.68739	0.0538171	1.13006 E-06	0.9801
09.6	070.93530	0.0946303	1.69571 E-05	0.9848
19.2	113.94400	0.1343680	2.79686 E-05	0.9981
28.8	145.00600	0.1469167	3.21008 E-05	0.9898
48.0	162.17600	0.1342930	2.83120 E-05	0.9968
52.8	173.20200	0.1313590	2.79702 E-05	0.9826
57.6	184.50100	0.1211890	2.48559 e-05	0.9756

Table 5.b : The parameters A_8 , B_8 , C_8 , and CF_8 for different batttery storage capacities .

BSC (MWh)	A_8	B_8	C_8	CF_8
0000.0	006.92252	07.04261	0.069193	0.9999
0400.0	014.11210	08.50258	0.092774	0.9991
0800.0	026.93010	11.10270	0.125662	0.9989
1200.0	067.44000	11.60360	0.132136	0.9977
2000.0	105.55200	09.83791	0.109822	0.9959
3000.0	138.93400	07.83069	0.082911	0.9991

Table 6.a : The parameters A_9 , B_9 , C_9 and CF_9 for different penetration levels .

P.L. %	A_9	B_9	C_9	CF_9
00.0	-0.705988	0.0100300	3.22873 E-06	0.9989
09.6	115.5780	0.0841399	3.18695 E-05	0.9994
19.2	174.6310	0.0748068	4.45790 E-05	0.9995
28.8	194.9810	0.0941148	6.12663 E-06	0.9992
48.0	092.7183	0.0665039	3.97766 E-05	0.9994
52.8	015.0427	0.0701792	4.11850 E-05	0.9975
57.6	-026.8592	0.0419919	3.44520 E-05	0.9993

Table 6.b : The parameters A_{10} , B_{10} , C_{10} , and CF_{10} for different batttery storage capacities .

BSC (MWh)	A_{10}	B_{10}	C_{10}	CF_{10}
0000.0	08.72645	14.1474	0.261289	0.9999
0400.0	07.76157	14.9037	0.269438	0.9999
0800.0	02.76222	16.4907	0.289221	0.9986
1200.0	16.06050	15.0925	0.271902	0.9976
2000.0	42.08610	11.1843	0.271902	0.9878
3000.0	18.99500	00.5133	0.067951	0.9677

Table 4.b : The parameters A_6 , B_6 , C_6 and CF_6 for different batttery storage capacities .

BSC (MWh)	A_6	B_6	C_6	CF_6
0000.0	01.07701	5.30139	0.0391965	0.9832
0400.0	09.79315	5.35717	0.0390953	0.9985
0800.0	17.46190	5.49602	0.0404541	0.9985
1200.0	27.47140	5.24013	0.0369677	0.9983
2000.0	48.39560	4.68184	0.0320653	0.9985
3000.0	64.88140	3.52278	0.0142999	0.9982

Table 5.a : The parameters A_7 , B_7 , C_7 , and CF_7 for different penetration levels .

P.L. %	A_7	B_7	C_7	CF_7
00.0	-009.68739	0.0538171	1.13006 E-06	0.9801
09.6	070.93530	0.0946303	1.69571 E-05	0.9848
19.2	113.94400	0.1343680	2.79686 E-05	0.9981
28.8	145.00600	0.1469167	3.21008 E-05	0.9898
48.0	162.17600	0.1342930	2.83120 E-05	0.9968
52.8	173.20200	0.1313590	2.79702 E-05	0.9826
57.6	184.50100	0.1211890	2.48559 e-05	0.9756

Table 5.b : The parameters A_8 , B_8 , C_8 , and CF_8 for different batttery storage capacities .

BSC (MWh)	A_8	B_8	C_8	CF_8
0000.0	006.92252	07.04261	0.069193	0.9999
0400.0	014.11210	08.50258	0.092774	0.9991
0800.0	026.93010	11.10270	0.125662	0.9989
1200.0	067.44000	11.60360	0.132136	0.9977
2000.0	105.55200	09.83791	0.109822	0.9959
3000.0	138.93400	07.83069	0.082911	0.9991

Table 6.a : The parameters A_9 , B_9 , C_9 and CF_9 for different penetration levels .

P.L. %	A_9	B_9	C_9	CF_9
00.0	-0.705988	0.0100300	3.22873 E-06	0.9989
09.6	115.5780	0.0841399	3.18695 E-05	0.9994
19.2	174.6310	0.0748068	4.45790 E-05	0.9995
28.8	194.9810	0.0941148	6.12663 E-06	0.9992
48.0	092.7183	0.0665039	3.97766 E-05	0.9994
52.8	015.0427	0.0701792	4.11850 E-05	0.9975
57.6	-026.8592	0.0419919	3.44520 E-05	0.9993

Table 6.b : The parameters A_{10} , B_{10} , C_{10} , and CF_{10} for different batttery storage capacities .

BSC (MWh)	A_{10}	B_{10}	C_{10}	CF_{10}
0000.0	08.72645	14.1474	0.261269	0.9999
0400.0	07.76157	14.9037	0.269438	0.9999
0800.0	02.76222	16.4907	0.289221	0.9986
1200.0	16.06050	15.0925	0.271902	0.9976
2000.0	42.08610	11.1843	0.271902	0.9878
3000.0	18.99500	00.5133	0.067951	0.9677

CONCLUSIONS

This paper introduces approaches for determining the reliability indices , levelized annual profit and levelized reduction in energy unit cost of the conventional generation system integrated with PV / BS one . The degree of improvement in LOLE and EUE , levelized annual profit , and levelized reduction in kWh price of the combined system are dependent essentially upon :

a- proposed operation strategy ,
b- conventional generation system ,
c- penetration level of PV and its installation site ,
d- battery storage capacity and its operation characteristics and
e- supplied load curve .

Therefore , it is impossible to represent the improvement in LOLE and EUE , levelized annual profit and levelized reduction in kWh price in universal manners . The numerical application presented in this paper investigates and analysis the improvement in LOLE and EUE , levelized annual profit and levelized reduction in kWh price for different penetration levels and battery storage capacities .

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