Estimating the Optimal Design of a Hybrid Renewable Energy System in Basrah City

Abbas Hafiz Abbas[1], Abdul Baqi Khalaf Ali[2], Mustafa Jawad Kadhim[3]

[1]University of Basrah, College of Engineering, Electrical Engineering Department, Iraq
[2]University of Basrah, College of Engineering, Mechanical Engineering Department, Iraq
[3]Basrah Oil Training Institute, Mechanics Department, Iraq

Abstract: ***In this paper, a methodology for estimating the optimal design of a stand-alone hybrid wind/photovoltaic (wind/PV) system is developed. The system plan was developed by using the direct algorithm to achieve a minimum cost of energy production (COE) while satisfying the energy demand with a minimum value of loss of power supply probability (LPSP). The collected hourly data for one year 2012 of solar radiation, wind speed and temperature in Basrah city were used in the optimization. Results of the simulation illustrate that the most economic configuration is a stand-alone PV system with LPSP of 1% and cost of energy production equal to 0.5$/kWh.***

Keywords: Optimal design, stand-alone hybrid (wind/PV) system, minimum cost of energy production and loss of power supply probability (LPSP)

Nomenclature

a Constant, kg/s
b Constant
C_I Installation costs of the components, $
C Capital costs of the components, $
E_{bat} (t) Charge capacity of battery at (t) time, W.hr
E_{bat} (t-1) Charge capacities of battery at (t-1) time, W.hr
$E_{bat.max}$ The maximum allowable storage capacity, W.hr
$E_{bat.min}$ The minimum allowable storage capacity, W.hr
$E_{bat.n}$ Nominal capacity of Battery, W.hr
E_l (t) The load requirement during the time interval, W.hr
E_{pv} The energy from PV system during the time interval, W.hr
E_{tot} The total energy, W.hr
E_{wt} The energy from wind turbines system during the time interval, W.hr
G_{ref} Irradiance at (STC), W/m^2
G Incident irradiance, W/m^2
h_r Reference height, m
h Height of hub, m
i,j,k Components factor
K_T Temperature coefficient of the max. power, 1/˚C
M Maintenance costs of the components. $
P_{PV} Output power from the PV module at irradiance (G), W
P_{RPV} Rated power of the PV module at (STC), W
P_r Rated power of wind turbine, W
P_{wt} Output power from the wind turbine, W
T_{amb} Ambient temperature, ˚C
T_c Cell temperature, ˚C
T_{ref} Reference cell temperature, ˚C
v_{ci} Cut-in wind speed of wind turbine, m/s
v_{co} Cut-out wind speed of wind turbine, m/s
v_r Rated wind speed of wind turbine, m/s
v(t) Speed of air, m/s

Greek Symbols

α Ground surface friction coefficient, the one seventh- power law ratio
σ Self discharge rate
η_{inv} Efficiency of inverter
η_{bat} Efficiency of battery (in charging status)

1. Introduction

The world faces a rapid depletion of fossil fuel resources due to increasing of power consumption for both people and industries. So that, the oil reserves of the world are predicted that they will be exhausted within this century [1]. In Iraq, Electrical power generation stations fail to comply with the demand for power because of limited production capabilities and numerous defects due to deterioration. According to the Ministry of Electricity, the peak demand in 2008 was 12000 MW of power; however, only 6000MW was supplied. This deficit is likely to grow to more than 25000 MW by 2020 [2]. Iraq receives solar energy equivalent to an average of 275 W/m^2 with a land area of over 1.5 million km^2 [3]. So, all these reasons push forward more thinking in renewable energy investment in Iraq. Hybrid PV–Wind or PV–Wind systems with batteries storage have been widely studied in the technical literature. Razak et, al. (2008) [4] reviewed optimization procedure by using HOMER of renewable hybrid system which contains wind turbines, PV panels, diesel generator and hydro turbine. This system feeds a typical house in Malaysia as load. Khalifa (2011) [5] discussed a method to provide energy for a Reverse Osmosis (RO) desalination unit in a small community in the south of Iraq. He concluded that the lowest water cost was 1.8$/m^3 for RO unit powered by either a diesel generator or by a combination of diesel, wind, and solar power. Chedid el al. (2005) [6] minimized the total cost of the system using linear programming techniques. Katsigiannis et, al. (2010) [7] optimized the design of the hybrid renewable power system based on cost and reliability using binary genetic algorithm in order to solve the optimal sizing problem.

2. System Model

In this paper, the configuration used to be evaluated in this work has a DC bus which combines the DC output of the PV module, the DC output of the wind turbine, and the battery bank. The AC bus of this configuration combines the output of the bidirectional inverter and the load.

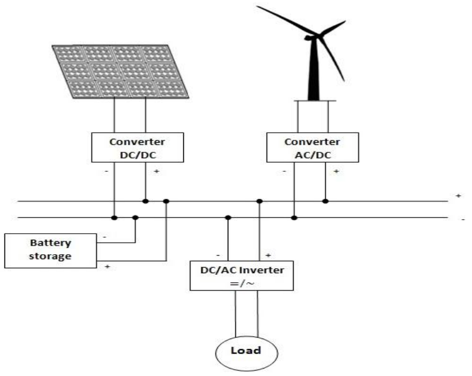

Figure 1: General diagram of a hybrid (wind–PV) system

2.1 Wind turbine Modeling

Each wind turbine has its own characteristic known as wind speed power curve. The shape of this curve is influenced by the blades area, the choice of airfoil, the number of blades, the blade shape, the optimum tip speed ratio, the speed of rotation and the cut-in wind speed. A mathematical model for the power curve of a wind turbine taking into account these parameters is as follows [8]:

$$P_{WT}(t) = \begin{cases} a.v^3(t) - b.P_r & v_{ci} < v(t) < v_r \\ P_r & v_r < v(t) < v_{co} \\ 0 & othetwise \end{cases} \quad (1)$$

Where:

$$a = \frac{P_r}{v_r^3 - v_{ci}^3} \quad (2)$$

$$b = \frac{v_{ci}^3}{v_r^3 - v_{ci}^3} \quad (3)$$

P_{WT}: Output power from wind turbine (W)
P_r: Rated power (W)
v_{ci}: Cut-in wind speed (m/s)
v_{co}: Cut-out wind speed (m/s)
v_r: Rated wind speeds of the wind turbine (m/s)

However, when calculating the output of the wind generator, the measured data of average hourly wind speed must be converted to the corresponding values at the hub height. The most commonly used formula is power law, expressed as [8]:

$$\frac{v(t)}{v_r(t)} = \left(\frac{h}{h_r}\right)^{\alpha} \quad (4)$$

Where:
v(t): is wind speed (m/s) at desired height h (m),
$v_r(t)$: is wind speed (m/s) at the reference height h_r (m)
α: is the ground surface friction coefficient, the one seventh-power law ratio is used corresponds to most common surfaces [8].

2.2 PV Panels Modeling

The output power from the PV cell is affected by the variation of cell temperature and variation of incident solar radiation. The maximum power output from the PV cell can be calculated using the following equation [9]:

$$P_{PV} = P_{RPV}\left(\frac{G}{G_{ref}}\right)[1 + K_T(T_c - T_{ref})] \quad (5)$$

Where:
P_{PV}: Output power from the PV module at radiation (W)
P_{RPV}: Rated power of the PV module at (STC) (W)
STC: Standard test condition at $(T_{ref} = 25\ C)$ and $G_{ref} = 1000\ W/m$
G: Incident radiation. (W/m)
T_c: Cell temperature (C)
K_T: Temperature coefficient of the maximum power (1/°C)

The solar cell temperature (Tc) can be found by the following equation [10]:

$$T_c = T_{amb} + \left(\frac{NOCT - 20}{800}\right)G \quad (6)$$

Where:
T_{amb} : ambient temperature (°C)

NOCT: Normal Operating Cell Temperature which is defined as the cell temperature when the module operates under the following conditions. (42 – 50)°C.

2.3 Modeling of Battery Storage

The output power from the wind turbine varies with wind speed variations through the day. Also the maximum power output of the PV generator varies according to variations in solar radiation and temperature. So the PV generator and the wind turbine may not be able to meet the load demands at all times. A battery between the DC bus of the hybrid system and the load will compensate and act as a power supply during these times.

At any hour, the charge of battery is a function to the previous charge level and to the difference between the load demand and energy production of the system during the time from (t-1) to (t). During the charging process, when the total outputs of the renewable generators are greater than the load demand, the battery charge at hour t can be described by [11]:

$$E_{bat}(t) = E_{bat}(t-1).(1-\sigma) + \left(E_{pv}(t) + E_{wt}(t) - \frac{E_l(t)}{\eta_{inv}}\right)\eta_{bat} \quad (7)$$

When the load demand is greater than the available energy generated, the battery charge at hour t can be described by:

$$E_{bat}(t) = E_{bat}(t-1).(1-\sigma) - \left(\frac{E_l(t)}{\eta_{inv}}(E_{pv}(t) - E_{wt}(t))\right) \quad (8)$$

Where:
$E_{bat}(t)$ and $E_{bat}(t-1)$: The charge capacities of battery bank (Wh) at the time t and (t-1) respectively,
σ : Hourly self discharge rate.

$E_{wt}(t)$: The energy from wind turbine during the time interval (Wh)
$E_{pv}(t)$: The energy from PV system during the time interval (Wh)
$E_l(t)$: The load requirement during the time interval (Wh)
η_{inv} and η_{bat} : the efficiency of inverter and battery bank respectively as stated before. They equal 0.92 and 0.75 respectively.

At any hour, the storage capacity is subject to the following constraints [11]:

$$E_{bat.min} < E_{bat}(t) < E_{bat.max} \quad (9)$$

Where $E_{bat.max}$ and $E_{bat.min}$ are the maximum and minimum allowable storage capacity respectively.

For backup batteries, SOC is considered important terms during the operation.

$$SOC = E_{bat}(t) / E_{bat,max} \quad (10)$$

2.4 Modeling of System Reliability

While designing a hybrid renewable energy system HRES, the reliability of supply of the system must be kept in mind to ensure that the load will be met by the supply at all times. A common parameter used to measure the system integrity and reliability is Loss of Power Supply Probability (LPSP). This is the probability that load will encounter an insufficient load supply. Three scenarios may appear during the operation:

A. The renewable generated power is greater than the power demand. The battery will be charged.
B. The renewable generated power is less than the power demand. The power deficit is compensated by the backup batteries. If the battery capacity decreases to their minimum allowable level, the control unit disconnects the load and the energy deficit, loss of power supply for hour (t) can be expressed as follows [11]:

$$LPS(t) = E_l(t) - \left(E_{pv}(t) + E_{wt}(t) + E_{bat}(t) - E_{bat,min}\right)\eta_{inv} \quad (11)$$

C. In case of inverter input and total power equality, the storage capacity remains unchanged.

The loss of power supply probability, LPSP, for a considered period T, can be defined as [11]:

$$LPSP = \sum_{t=1}^{8760} LPS(t) \Big/ \sum_{t=1}^{8760} E_l(t) \quad (12)$$

3. Costs of System Components

The optimal configuration can be identified finally from this set of configurations by achieving the minimum total cost of the system. The costs of a hybrid system include the capital costs, operating costs, maintenance costs and replacement costs. The optimization procedure is achieved by minimizing the system total cost function consisting of the sum of the individual system devices capital, the 20-year round maintenance costs and the installation costs [8].

$$TC(Npv, Nwt, Nbt) = \sum_{i=1}^{n_{PV}} Npv^i \left(C_{pv}^i + 20.M_{pv}^i + C_{I,pv}^i\right) + \sum_{J=1}^{n_{WT}} Nwt^j \left(C_{WT}^j + 20.M_{WT}^j + C_{I,WT}^j\right) + \sum_{k=1}^{n_{bat}} Nbt^k \Big(\big(1 + ybatkCbatk + CI,batk + 20 - ybatk - 1.Mbatk \quad (13)$$

Where:

TC: total cost per life cycle ($)
Npv, Nwt, Nbt: number of PV panels, wind turbines and backup batteries respectively.
C_{pv}^i, C_{WT}^j **and** $C_{I,bat}^k$: Capital cost of PV panels, wind turbines and battery respectively ($).
M_{pv}^i, M_{WT}^j **and** M_{bat}^k :Maintenance cost of PV panels, wind turbines and battery respectively ($)
$C_{I,pv}^i, C_{I,WT}^j$ **and** $C_{I,bat}^k$: Installation cost of PV panels, wind turbines and battery respectively ($)
y_{bat}^k : The expected number of battery replacements during the 20-year system operation, because of limited battery lifetime.

Comparison of different configurations that supply the load at a required LPSP is based on calculating the cost of electricity production in ($/kWh). COE is the ratio between the total cost (TC) and the total energy required by the load (E_l).

$$COE = \frac{TC/20}{E_l} \quad (14)$$

4. Data Acquisition

In order to design a HRES, a reliable, trusted and feeds the loads without deficit and continuity and at the same time get a cheaper cost of this system, it has to be to get enough data for finding the optimal number of wind turbines, solar panels and storage batteries. These necessary data are summarized by hourly solar radiation, temperature, wind speed, load demand and the required LPSP as shown in the optimization algorithm. The solar radiation and wind speed were got by installing power predictor in Basrah city, Basrah located in the southern of Iraq, situated at latitude of 30.46˚ and longitude of 47.7˚. The power predictor contains hardware and software components www.powerpredictor.com. Power predictor was installed at a mist height at least 10 m so as to avoid the violation of air path, and the solar sensor facing the south so that it will face the sun at the peak radiation time, the so-called ecliptic is the apparent path that the Sun traces out in the sky while it goes from east to west during the day.

5. Load Demand

Load profile study and determination is the first step for design of any electric power system. In this study, a small secondary school in a rural region in the west of Basra is used as load consumer, it situated at latitude (30.33) and longitude (47.50) and away from Al-Rumaila site about 30 km. This school serves more than 120 pupils.

The school contains six classes and management rooms and bath rooms. Each classroom has eight indoor lights (fluorescent) and two fans. The management sector contains eight indoor lights (fluorescent), computer, copy machine and two ceiling fan. The bath room contains five ventilator and seven indoor lights (fluorescent). Also, there are two water cooler, water pump and six outdoor lights. It should be noted that the study in the school starts in October and ends with the end of June, five days per week and six hours per day. Total power consumed per day is 46.18 kWh. See figure (3).

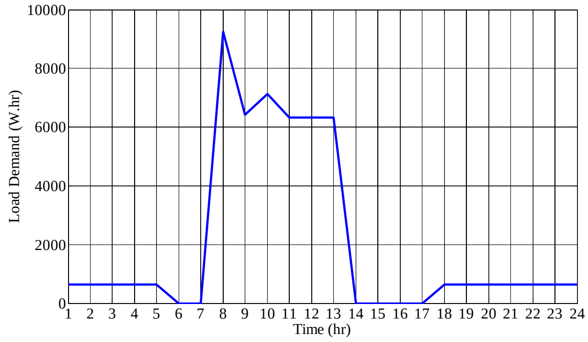

Figure 2: Maximum predictable load profile per day

6. Results and Discussions

The developed optimization methodology was applied for sizing the hybrid energy system supplying an hourly variable.

6.1 Climatic Data

Climatic characteristics in Basra city vary quarterly and monthly depending on the variation amounts of solar radiation received as a result of variation of brightness hours which is resulted due to the sun movement. Figure (3) shows a graphical representation of the hourly solar irradiance in Basra city in 2012. Basra receives large amounts of solar radiation, the annual rate of radiation reaches to (0.208 kWh/m^2) during the 8760 hours. Basra city lives along and hot summer during the year. The annual rate of temperature is 28˚C. See Fig. (4).

Figure (5) illustrates the hourly values of wind speed for Al-Rumaila site in 2012. The measured values will be helpful in the future to choose a specified wind turbine with required cut-in speed according to these data. Data shows that the wind had been activated in the hot months (July, August and September) so that it recorded (6.4, 5.6 and 5.8) m/s, respectively. Data illustrated that the lowest averages were in the cold months (December and January) so that it recorded (4.1 and 3.7) m/s, respectively. The annual average speed was 4.8 m/s. For this site, the strong gale force winds are rare, while moderate winds are quite common. Figure (6) show a graphical representation of the percentage of occurrence for different ranges of wind speed for Al-Rumaila. The area under the curve is always exactly 8760. The most repeated range in Al-Rumaila was (3-4) m/s which occurred 1606 hour per the year.

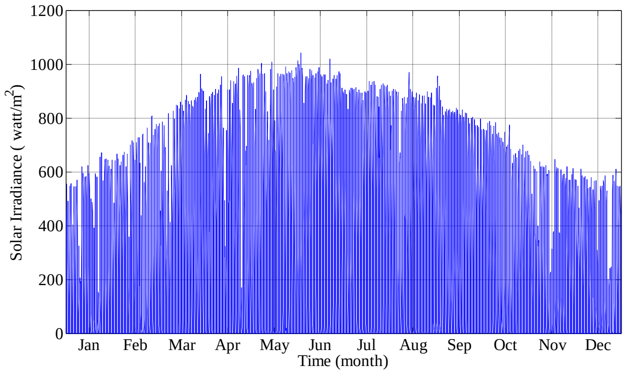

Figure 3: Hourly solar irradiance in Basra city during 2012

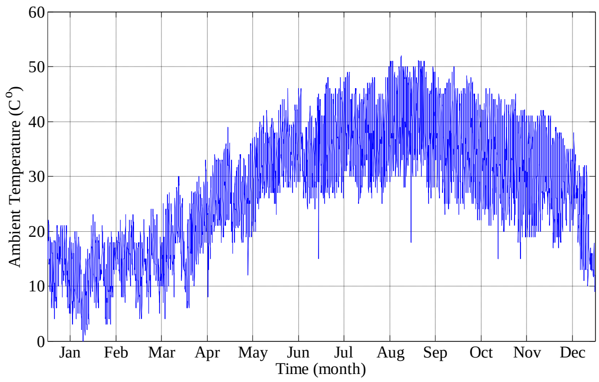

Figure 4: hourly temperature in Basra city during 2012 [12]

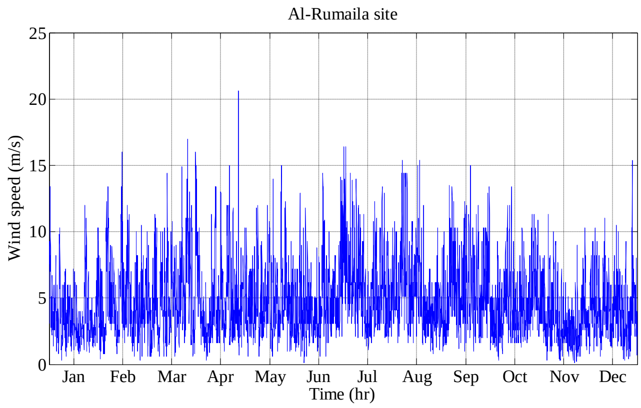

Figure 5: Hourly wind speed in Al-Rumaila site

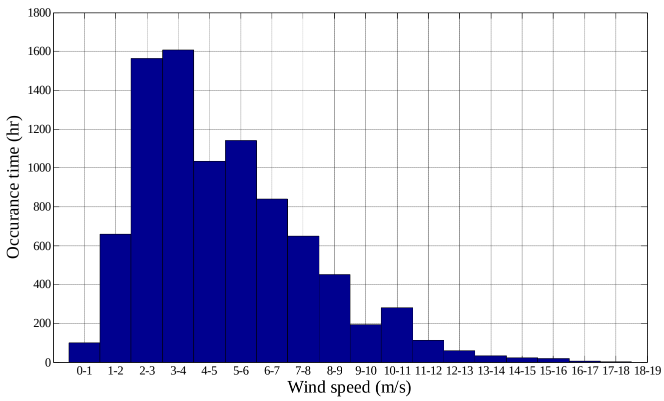

Figure 6: Number of hours per year for each wind speed range in Al-Rumaila site

6.2 Optimization Results

The optimization algorithm was run using the hourly values of climatic data from the power predictor and load data. The cost was minimized whilst keeping an LPSP equal or less than of 1%. This means that the load will not be supplied 1% (3.65 days) in year.

In this paper, the specifications and the related capital, maintenance and installation costs of the components of the system are shown in table (1, 2 and 3). The maintenance cost of each unit per year and the installation cost of each component have been set at 1% and 10% respectively of the corresponding capital cost.

Table 1: the specifications of 10 kW wind turbine.

Rated Output	10000 W
Rated Wind speed	10 m/s
Cut-in Wind speed	3.0 m/s
Cut-out Wind speed	25 m/s
Rotor Diameter	8.0 m
Number of Blades	3
Tower Height	12-18m
Life time	20 year
Capital cost	20000 $

Table 2: The specification of BP1325 PV panel

Rated power	125 W
Nominal voltage	12 V
Voltage at Rated power (V_{mp})	17.4 V
Current at Rated power (I_{mp})	7.2 A
Short circuit current (I_{sc})	8.1A
Open circuit voltage (V_{oc})	22.0 V
K_T	-(0.5±0.05)%/°C
NOCT	47±2°C
Capital cost ($)	500

Table 3: Concorde (PVX-2120L) specifications

Nominal Capacity	253 Ah
Voltage	12 Ah
Minimum charge	20 %
Cost	465 $

Figure 7 shows the influence of incorporating the number of wind turbines (Nwt) and the number of backup batteries (Nbt) on the LPSP value. The value of LPSP will decrease if (Nwt) and (Nbt) increase because the total produced renewable power and the storing energy in batteries increased as a function of components number. Adding several units of backup batteries shows a clear impact on the LPSP.

Figure (8) shows the influence of incorporating the number of PV panels (Npv) and the number of backup batteries (Nbt) on the LPSP value. If the load demand is feed from wind turbines, PV panels and backup batteries, many configurations satisfy the load with at least LPSP of 1%. Table (4) shows the economical configurations of the system at different with different Nwt, Npv and Nbt. the economical configuration is formed by Npv = 147 and Nbt = 16 with TC of 144719 $ and COE = 0.5 $/kWh.

Fig. (9) shows a graphical representation of SOC of backup batteries of the economical configuration. In the first months the SOC varies between its maximum and minimum level because the PV panels start to charge the batteries and supply the load at the same time.

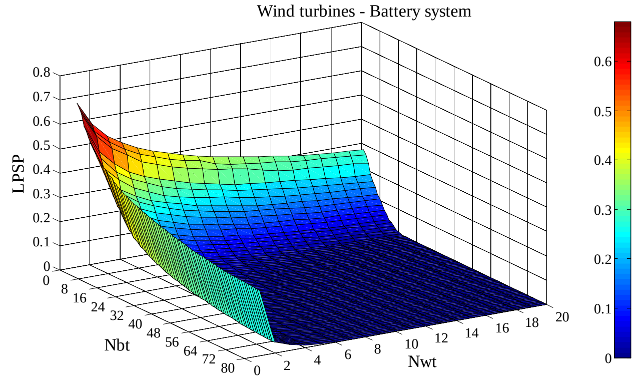

Figure 7: 3D plots of different size combinations of wind turbines and battery at different LPSP values

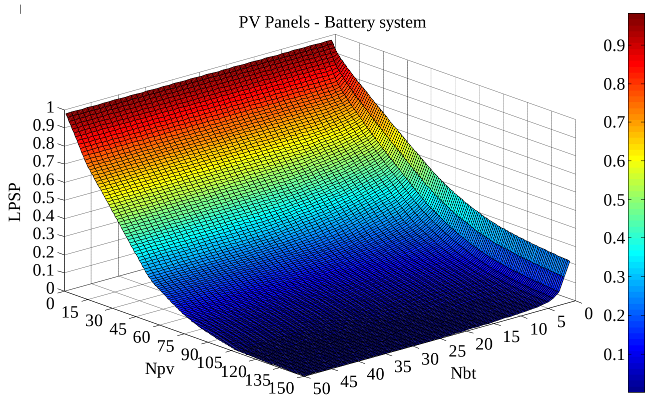

Figure 8: 3D plots of different size combinations of PV panels and battery at different LPSP values

Table 4: different configurations of optimal sizes with their TC and COE

Wind - PV - Battery system				
Npv	Nwt	Nbt	TC ($)	COE ($/kWh)
0	6	48	303377	0.910
89	1	23	154502	0.707
88	2	15	155300	0.710
89	3	12	172743	0.790
80	4	12	192893	0.883
72	5	12	213693	0.978
147	0	16	144719	0.500

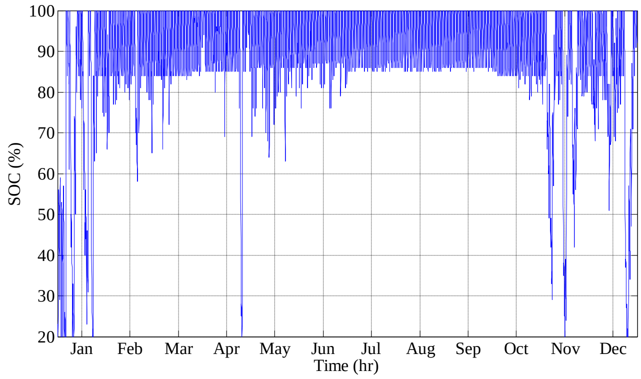

Figure 9: SOC of the optimal configuration system (Npv=147 and Nbt=16)

7. Conclusions and Recommendations

According to the results, the following conclusions can be summarized:

1. Basrah receives high solar energy density during the year. The maximum solar irradiance was in June and the lowest amount of radiation was in December.
2. The combination of PV panels and backup batteries forms the optimum design of the renewable system for the specified load demand.
3. The measured values of wind speed are encouraging and could be reliable to generate power in Basra city.
4. The total cost of this renewable power system could be minimized depending on other choices (less capital cost) of components under the same climate condition of the city.

The following recommendations are drawn out of this research:

1. More studies need to investigate the renewable resources such as biomass, hydropower, and geothermal powers.
2. Implementing the optimization by using the genetic algorithm and neural networks.
3. Find the optimal hybrid system for entire villages of Basrah and make a comparison with the traditional diesel units.

References

[1] Al-Shemmeri, T., **"Wind turbines"** Ventus Publishing APS, ISBN 97887-7681-692-6, 2010.
[2] Kazem, H. A., and Chaichan, M. T., **"Status and future prospects of renewable energy in Iraq"** Renewable and Sustainable Energy Reviews 16 6007–6012, 2012.
[3] Hassan, A. K., **"Design a solar energy system to supply a marsh village, southern Iraq with electrical energy"** Marina Mesopotamica, 20(1): 171-182, 2008.
[4] Razak, J. A., Sopian, K., Yusoff, M. Y., Alghoul, M. A., and Zaharem, A., **"Optimization of Renewable Energy Hybrid System"** ISSN: 1790-5117 8th WSEAS International Conference on POWER SYSTEMS (PS 2008).
[5] Khalifa, A. N., **"Evaluation of different hybrid power scenarios to Reverse Osmosis (RO) desalination units in isolated areas in Iraq"** Energy for Sustainable Development 15-49–54, 2011.
[6] Chedid, R., Karaki, S. and Rifai, A., **"A multi-Objective Design Methodology for Hybrid Renewable Energy Systems"** Proceedings of the IEEE PowerTech Conference, Saint Petersburg, Russia, June 29, 2005.
[7] Katsigiannis1, Y. A., Georgilakis, P. S., Karapidakis, E. S. **"Genetic Algorithm Solution to Optimal Sizing Problem of Small Autonomous Hybrid Power Systems"** S. Konstantopoulos et al. (Eds.): SETN 2010, LNAI 6040, pp. 327–332, 2010. Springer-Verlag Berlin Heidelberg 2010
[8] Belfkira, R., Nichita, C., Reghem, P., and Barakat, G., **"Modeling and optimal sizing of hybrid renewable energy system"** Proceedings of the International Conference on Electrical Machines, 2008.
[9] Lasnier, F. and Ang, T. G., **"Photovoltaic Engineering Handbook"** IOP Publishing Ltd., 1990, Adam Hilger, New York.
[10] T. Markvar, **Solar Electricity**, 2nd edition, J. Wiley & Sons, 2000.
[11] Ai, B., Yang, H., Shen, H., Liao, X. **"Computer-aided design of PV/wind hybrid system"** Renewable Energy 28-1491–1512, 2003.
[12] Iraqi Meteorological Organization and Seismology, unpublished data 2012, Basrah Airport