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# Small Wind Turbine Hybrid System for Remote Application: Egyptian Case Study

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***Abstract*—**The objective of this research is to study the technical and economic performance of wind/diesel/battery (W/D/B) system supplying a remote small gathering of six families using HOMER software package. The electrical energy is to cater for the basic needs for which the daily load pattern is estimated. Net Present Cost (NPC) and Cost of Energy (COE) are used as economic criteria, while the measure of performance is % of power shortage. Technical and economic parameters are defined to estimate the feasibility of the system under study. Optimum system configurations are estimated for two sites. Using HOMER software, the simulation results showed that W/D/B systems are economical for the assumed community sites as the price of generated electricity is about 0.308 $/kWh, without taking external benefits into considerations. W/D/B systems are more economical than W/B or diesel alone systems, as the COE is 0.86 $/kWh for W/B and 0.357 $/kWh for diesel alone.

***Keywords*—**Optimum energy systems, Remote electrification, Renewable energy, Wind turbine systems.

## I. Introduction

ENERGY is a vital factor for social and economic development. As a result of the automation of agricultural, industrial and domestic activities the demand for energy has increased remarkably, especially in developing countries. It is a need of today's world to concentrate on renewable energy sources to satisfy the demand and conserve our finite natural resources for the generation to come.

Renewable energy supplies 19 percent of the world's primary energy consumption [1]. Renewable energy technologies provide an excellent opportunity for mitigation of greenhouse gas emission and reducing global warming through substituting conventional energy sources [2].

The variable electricity output of RES feeding variable load and storage system needs to be carefully designed (sized) to optimize system operation [3]. To allow a real penetration of the huge dispersed naturally renewable resources (wind, sun, etc.) intermittent and more or less easily predictable, optimal sizing of hybrid renewable power generation systems prove to be essential. That recommends an optimal sizing model based on iterative technique, to optimize the capacity sizes of different components of hybrid photovoltaic/wind power generation system using a battery bank. Hybrid Solar-Wind System Optimization Sizing (HSWSO) model was developed to optimize the capacity sizes of different components of hybrid solar-wind power generation systems employing a battery bank [4]. The HSWSO model consists of three parts: the model of the hybrid system, the model of Loss of Power Supply Probability (LPSP) and the model of the Levelized Cost of Energy (LCE).

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Abdel Hamid Kaabeche et al. proposed an integrated PV/wind hybrid system optimization model, which utilizes the iterative optimization technique following the Deficiency of Power Supply Probability, the Relative Excess Power Generated, the Total Net Present Cost, the Total Annualized Cost and Break-Even Distance Analysis for power reliability and system costs [5].

The optimum size of wind system supplying a load of typical house in south of Algeria (desert area) was calculated. The study methodology was based on a given load and a mixed multiple-criteria integer programming problem, the types and sizes of wind WTG was calculated based on the minimum cost of system [6]. The author investigated the genetic algorithm (GA) for optimally sizing a wind power system. The objective function is the total cost; also an optimal configuration of wind generating systems was determined.

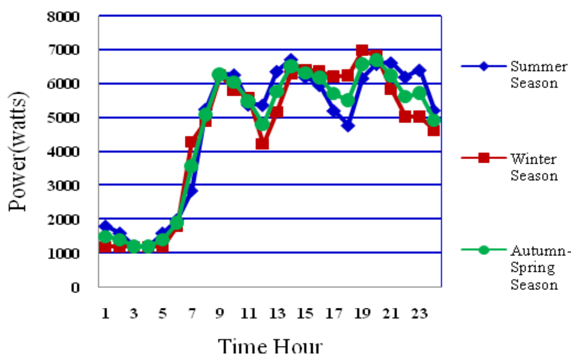



Fig. 1 Seasonal Load Profile

## II. Simulation of Hybrid Energy System

### *A. Load Profile*

Load profile estimations are the first steps for the technical design of any electric power system. Natures of operation of loads and consumers behavior are the parameters that determine the load profile. In Ras Sudr on the Red Sea Coast and Siwa Oasis in the western desert cases, most of loads are lighting fixtures, radio/TV and refrigerator, etc. Nature of operation of these loads is ON and OFF.

The estimated seasonal load profiles for six families are presented in Fig. 1.

### *B. Wind Turbine Modeling and Sizing*

The power output of a wind turbine is determined by its power curve and the instantaneous wind speed at the site of installing this wind turbine. The current study is concerned with small scale wind turbine (0.5-50 kW), thus different models of wind turbines with different sizes are considered. The turbines used in the optimization of the studied case are in the range from 0.5 to 10 kW. A mathematical model for the power curve of a wind turbine is shown below [7]:

$$P_W = \begin{cases} 0 \\ a * V^3 - b * Pr \\ Pr \end{cases} \begin{cases} V < Vci \\ Vci < V < Vr \quad and\ 0\ for\ V > Vco \\ Vr < V < Vco \end{cases} \tag{1}$$

where, Pw (in W/m2): is the output power density generated by a wind turbine,

$$a = {}^{P_r}\!/_{VC_i^3} \tag{2}$$

$$b = \frac{VC_i^3}{Vr^3} - VCO^3 \tag{3}$$

and, $P_r$, V, $V_{ci}$, $V_r$ and $V_{co}$, are rated power (w) , instantaneous, cut-in, rated and cut-out wind speeds in (m /s) respectively.

### *C. Battery Bank Modeling and Sizing*

A battery bank is used to support the load when the output power from wind turbine is not sufficient. If the output power from the wind turbine generator exceeds the load requirement, excess energy is stored in the battery to supply load when energy from wind generator is not enough. The ampere-hour efficiency of a battery ($\eta_{Ah}$) is the ratio of amount of total Ampere-hours the battery provides during discharge to that required to charge it back to its original condition. The battery efficiency can be specified as Watt-hour efficiency ($\eta_{Wh}$) and it has values lower than $\eta_{Ah}$ because the variation in voltage is taken into account [7]. A minimum storage level is specified for a battery so that should not be exceeded it. This level is a function of battery depth of discharge.

So that:

$$E_{min} = EBN \times (1 - DOD) \tag{4}$$

where: $E_{min}$ is minimum allowable capacity of the battery bank, EBN: is the nominal capacity of battery bank, DOD: is the depth of discharge.

The ampere-hour capacity (CAh) and watt-hour capacity (CWh) of a battery bank required to supply a load for a certain period (day) when energy from renewable resources is not available or not enough can be specified as follows:

$$C_{wh} = (E_L \times AD)/(\eta_v \times \eta_{Wh} \times DOD) \tag{5}$$

where AD is the daily autonomy, $E_L$ is the load requirement during the time interval, $\eta_v$ and $\eta_{Wh}$ are the efficiency of inverter and battery bank respectively.

It is obvious from above relation that total capacity of the battery depends on daily autonomy which represents number of days that battery will be capable to supply the load in case of shortage of the renewable sources. Each battery has a specific discharge curve that gives the battery capacity relative to the discharge current.

### *D. Diesel Generator Ratings and Sizing*

A back up Diesel Generator (D.G.) is required in case of incapability of the renewable sources to supply the load. D.G.is used in the system for following tasks: To supply load when the output power from wind is not enough to operate this load, as well as to bring the State of Charge (SOC) of batteries to an acceptable level. The diesel generator should be selected to cover the load so its ratings are determined according to load specifications. The optimum selection of the generator rating is such that the generator with other sources shall provide load power it needed at all cases [7].

### *E. Converter Modeling and Sizing*

A bi-directional inverter is essential in the hybrid system where a storage system and a backup D. G. are included in the generating system. It can transfer power simultaneously in both directions.

The bi-directional inverter can be modeled as follows [7]:

$$Pdi = P_{Gout} \times \eta_{di} \tag{6}$$

where $P_{di}$ is output power of bidirectional inverter in its charge mode, $P_{Gout}$ is Diesel generator output power, and $\eta_{di}$ is the efficiency of bidirectional inverter in its charge mode.

The charger is characterized by its nominal AC voltage and voltage range, nominal DC output voltage that shall matched with DC bus voltage and it's charging current.

The efficiency of converting the direct current to alternative current of most inverters today is 90% or more. Many inverters claim to have higher efficiencies. Two converter sizes are investigated in this study; 4 kW and 10 kW.

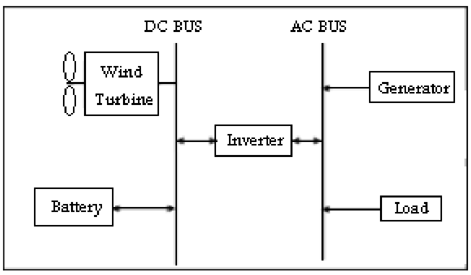



Fig. 2 Block diagram of the hybrid stand-alone system

### *F. Wind/Diesel/Battery System*

The design of a stand-alone wind-diesel power system supplying the predefined load schedule, (ac load of primary type with average of daily demand of 111kWh/day) was carried out based on the previously mentioned input/output mathematical relations of each of the system components. A schematic diagram of the standalone power supply system required is shown in Fig. 2.

## III. Optimization Model

The objective of optimizing micropower system is to minimize the net present cost, in the same time minimizing the cost of produced electrical energy. The model constraints (defined by user) are: maximum annual capacity shortage, minimum renewable fraction, percent of renewable fraction and annual real interest rate. Decision variables are: wind turbine (size, number), site wind speed, battery (size, number), diesel generator (size), converter (size) and if the system is off-grid or connected to the grid.

In the present study; these assumptions are stated:

- Maximum Annual Capacity Shortage = 15%
- Minimum Renewable Fraction = 60%
- Wind Power Output (as percent of renewable fraction) = 100%
- Annual Real Interest Rate= (interest rate (11%) –inflation rate (3%)) = 8%

As it was mentioned earlier, the RES could be off-grid or grid connected. If the system is connected to grid, the cost of grid extension 1000 $/km is added as a part of capital cost. The grid power price is taken equal to 0.1 $/kWh [8]. If the system is off-grid, the costs of extension and grid electricity price are used for the comparison of the renewable produced electricity.

### *A. HOMER Software Inputs*

The data used as input to HOMER are as follows:

- Load profile: the load required at each hour for the intended application (6 families' electrical energy requirements).
- A number of wind turbines covering the range (0.5-10 KW) four types were selected as following. These are: skystream3.7 (1.8 KW), WES 5 Tulipo (2.5 KW), Whisper 500 (3KW), and BWCXL-R (8KW).
- Two series of batteries are considered: Vision 6FM200D (12V, 200 Ah), and Trojan T-105 (6V, 225Ah)
- Diesel generator: 8 kW D.G. (fuel consumption curve & efficiency curve are supplied).
- Converter (two converters are considered: 4 &10kW, converter efficiency 95%)
- Wind resources: Monthly average wind speed for two sites, Ras Sudr and Siwa Oasis are calculated from the daily wind speed data. This data are collected for two years (2009 and 2010) Annual average wind speed for Ras Sudr and Siwa Oasis are 9.484 and 7.544 m/s respectively.
- The anemometer height above the ground at which the wind speed data were measured and site elevation above sea level (used to calculate air density).
- The autocorrelation factor of hourly wind speed is taken equals to 0.90 as the selected areas are of averagely uniform topography [7]. A typical range for the autocorrelation factor is 0.8 – 0.95.
- The diurnal pattern strength (a measure of how strongly the wind speed tends to depend on the time of day) of 0.2 have been selected for calculation. Typical values for diurnal pattern strength range from 0 to 0.4.

The project life time is 15 or 20 year based on wind turbine life time, and the interest rate modified to include inflation rate is assumed to be the present rate, 8%.

### *B. Control Approach*

In this approach the renewable energy sources (wind) plus the energy stored in the battery are used to cover the demand. Diesel generator is switched on when the battery is discharged to a predefined level. For each hour step the simulation program compares the required energy demand and the supplied energy, and according to the difference, a decision to operate the diesel generator or to charge the battery or discharge it will be taken. The use of renewable energy to supply load has priority over using batteries or diesel generator. The surplus energy is used to charge batteries. Different configurations of WT/G/B system are considered. Two of the wind turbines used is AC and the other two are DC. For AC-WTs a converter of 4 kW is used. In case of DC WTs, 10 kW' converter is used. Although the system reliability was assumed to be 85-90% no shortage was detected in the case of 10 KW' converter.

## IV. Results

The alternative system configurations considered in optimization are shown in Table I. The below mentioned configurations are applied for the two selected sites. In the current study the backup generator is fueled by diesel. The investigated diesel prices are 0.3, 0.35, 0.4 and 0.5 US dollars per liter. The current diesel price considered is 0.25 USD per liter. Case 1 represents Ras Sudr while case 2 represents Siwa Oasis site.

<u>Case 1: Ras Sudr</u>

According to Table I, eight systems configurations were simulated. The summary of results is shown in Table II, and the optimum system configuration is case 1.6 (highlighted).

<u>Case 2: Siwa Oasis</u>

According to Table I, eight systems configurations were simulated. The summary of results is shown in Table III, and the optimum system configuration is case 2.6 (highlighted).

TABLE I
ALTERNATIVE SYSTEM CONFIGURATIONS USED FOR SIMULATION

| Wind Turbine | | | Battery | Generator | Converter |
|---|---|---|---|---|---|
| Model | Current | Power (KW) | | | |
| Whisper 500 | DC | 3 | Trojan T-105, Vision 6FM200D | 8 KW | 10 KW |
| BWXL-R | DC | 8 | Trojan T-105, Vision 6FM200D | 8 KW | 10 KW |
| Skystream 3.7 | AC | 1.8 | Trojan T-105, Vision 6FM200D | 8 KW | 4 KW |
| WES Tulipo 5 | AC | 2.5 | Trojan T-105, Vision 6FM200D | 8 KW | 4 KW |

TABLE II
OPTIMIZATION RESULTS FOR RAS SUD SITE

| Case No | Opt No of WT | Gen (KW) | Opt No of Batt. | Conv (KW) | Disp. Strat. | Initial Capital Cost ($) | Operating Cost ($/yr) | Total NPC ($) | COE ($/KWh) | Ren. Frac. (%) | Capacity Shortage | Diesel (L) | Gen (hrs.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.1 | 3 | 8 | 12 | 10 | LF | 54,280 | 7,258 | 116,408 | 0.336 | 62 | 0.00 | 13,433 | 6,057 |
| 2.2 | 2 | 8 | 24 | 10 | CC | 80,120 | 7,202 | 150,829 | 0.379 | 75 | 0.00 | 12,561 | 5,601 |
| 2.3 | 7 | 8 | 6 | 4 | LF | 117,740 | 10,192 | 217,806 | 0.548 | 66 | 0.03 | 17,881 | 8,760 |
| 2.4 | 4 | 8 | 6 | 4 | LF | 60,880 | 9,733 | 144,193 | 0.416 | 63 | 0.08 | 17,875 | 8,760 |
| 2.5 | 2 | 8 | 12 | 10 | LF | 82,280 | 7,529 | 156,199 | 0.393 | 75 | 0.00 | 12,794 | 5,919 |
| 2.6 | 3 | 8 | 24 | 10 | CC | 52,120 | 6,917 | 111,329 | 0.321 | 62 | 0.00 | 13,156 | 5,633 |
| 2.7 | 7 | 8 | 6 | 4 | LF | 115,880 | 10,088 | 214,924 | 0.540 | 66 | 0.08 | 17,881 | 8,760 |
| 2.8 | 4 | 8 | 6 | 4 | LF | 62,740 | 9,818 | 146,778 | 0.423 | 63 | 0.03 | 17,875 | 8,760 |

For the two case studies the optimum system configuration is found to be: 9 kW wind turbines, 8 kW diesel generator, and 4400 Ah storage batteries in addition to a converter of 10 kW rating. In Ras Sudr case wind turbines cover 67% of the required load. The estimated price of system generated electricity is about 0.308 $/kWh. This price is equivalent to the price of grid electricity if the grid extended along 72 km (breakeven grid extension distance). While for Siwa case the wind turbines cover 62% of the required load. The estimated price of system generated electricity is about 0.321 $/kWh. The break even distance in this case is 76.7 km.

TABLE III
OPTIMIZATION RESULTS FOR SIWA OASIS

| Case No | Opt No of WT | Gen (KW) | Opt No of Batt. | Conv (KW) | Disp. Strategy | Initial Capital Cost ($) | Operating Cost ($/yr) | Total NPC ($) | COE ($/KWh) | Ren. Frac. (%) | Cap.y Short. | Diesel (L) | Gen (hrs) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.1 | 3 | 8 | 12 | 10 | LF | 54,280 | 6,669 | 111,363 | 0.321 | 68 | 0.00 | 12,77 | 5,902 |
| 1.2 | 1 | 8 | 24 | 10 | CC | 51,120 | 6,652 | 116,429 | 0.293 | 61 | 0.00 | 13,12 | 5,655 |
| 1.3 | 5 | 8 | 6 | 4 | LF | 87,740 | 9.431 | 180,334 | 0.453 | 62 | 0.03 | 17,82 | 8,760 |
| 1.4 | 4 | 8 | 6 | 4 | LF | 60,880 | 9,174 | 139,405 | 0.402 | 65 | 0.08 | 17,76 | 8,760 |
| 1.5 | 1 | 8 | 12 | 10 | LF | 53,280 | 6,964 | 121,656 | 0.306 | 61 | 0.00 | 13,37 | 6,001 |
| 1.6 | 3 | 8 | 24 | 10 | CC | 52,120 | 6,377 | 106,705 | 0.308 | 67 | 0.00 | 12,52 | 5,587 |
| 1.7 | 5 | 8 | 6 | 4 | LF | 58,880 | 9,327 | 177,452 | 0.446 | 62 | 0.08 | 17,82 | 8,760 |
| 1.8 | 4 | 8 | 6 | 4 | LF | 62,740 | 9,259 | 141,990 | 0.409 | 65 | 0.03 | 17,76 | 8,760 |

*A. Cost- Effective Summary*

Tables IV (A) & (B) exhibit optimum cost-effective summary, for the systems installed in Ras Sudr and Siwa Oasis sites. Figs. 3 (a), (b), show that the WT contribution in the produced system electricity is higher in case of Ras Sudr than Siwa Oasis (43,317 and 36,742 kwh/yr, respectively). Clearly due to high wind speed in Ras Sudr. Also excess electricity in case of Ras Sudr is about 33% while it is equal to 27.6% for Siwa Oasis.

TABLE IV
OPTIMUM COST-EFFECTIVE REPORT FOR THE SYSTEMS INSTALLED IN BOTH SITES (A) RAS SUDR

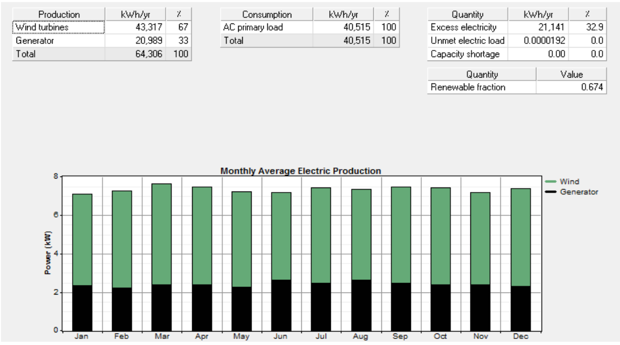
| System architecture | | Sensitivity case | | Annual Electric Production (kwh/yr) | | | Annual Electric consumption (kWh/yr) | | | Emissions (Kg/yr) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Wind turbine | 3 Whisper (3KW) | Sensitivity case | | Wind turbine | 43,317 | 67% | AC primary load | 40,515 | 100% | Carbon Dioxide | 32,987 |
| Diesel Generator | 8 KW (Gen) | | | Generator | 20,989 | 33% | Cost summery | | | Carbon Monoxide | 81.4 |
| Battery | 24 Trojan T-105 (6V, 225Ah) | Average wind speed | 9.484 m/s | Total | 64,306 | 100% | Total net present cost | 106,705$ | | Unburned hydrocarbons | 9.02 |
| Inverter | 10 KW | Diesel price | 0.25 $ | Excess | 21,141 | 32.9% | Levelized cost of energy | 0.308 $/ KWh | | Particulate matter | 6.14 |
| Rectifier | 7.5 KW | | | Unmet electric Load | 0.0000192 | 0% | Operating cost | 6,377 $/yr | | Sulfur dioxide | 66.2 |
| Dispatch Strategy | Cycle Charging | | | Capacity Shortage | 0.00 | 0% | | | | Nitrogen oxides | 727 |

(B) SIWA OASIS

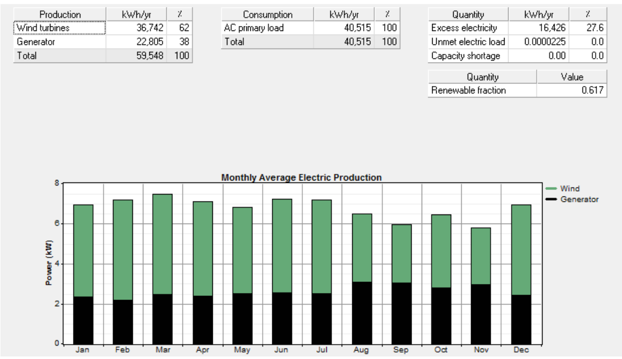
| System architecture | | Sensitivity case | | Annual Electric Production (kwh/yr) | | | Annual Electric consumption (kWh/yr) | | | Emissions (Kg/yr) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Wind turbine | 3 Whisper (3KW) | Sensitivity case | | Wind turbine | 36,472 | 62% | AC primary load | 40,515 | 100% | Carbon Dioxide | 34,643 |
| Diesel Generator | 8 KW (Gen) | | | Generator | 22,805 | 38% | Cost summery | | | Carbon Monoxide | 85.5 |
| Battery | 24 Trojan T-105 (6V,225Ah) | Average wind speed | 7.544 m/s | Total | 59,548 | 100% | Total net present cost | 111,329 | | Unburned hydrocarbons | 9.47 |
| Inverter | 10 KW | Diesel price | 0.25 $ | Excess | 16,426 | 27.6% | Levelized cost of energy | 0.321 $/ KWh | | Particulate matter | 6.45 |
| Rectifier | 7.5 KW | | | Unmet electric Load | 0.0000225 | 0% | Operating cost | 6,917 $/yr | | Sulfur dioxide | 69.6 |
| Dispatch Strategy | Cycle Charging | | | Capacity Shortage | 0.00 | 0% | | | | Nitrogen oxides | 763 |

### *B. Energy Performance*

Figs. 3 (a) and (b) show the energy performance of the optimum system for both sites.




(a) For RasSudr Site



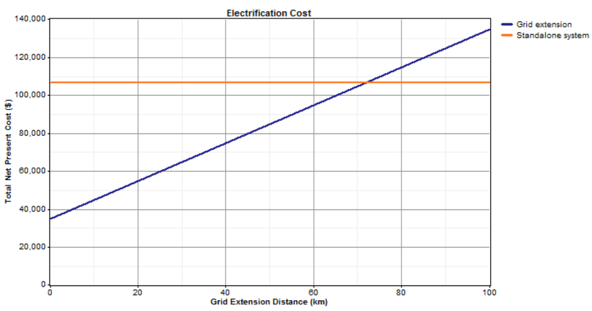

(b) For Siwa Oasis Site

Fig. 3 The energy performance of the optimum system

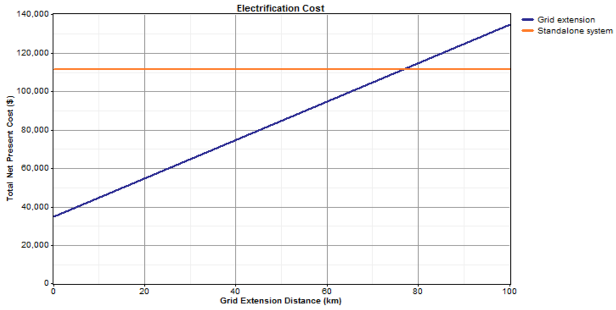
### *C. Break-Even Analysis*

Break-even analysis presents a simple and direct way for the comparison of the cost of electricity of stand-alone systems versus the grid extension for sites at different distances from the national grid. Figs. 4 (a) and (b) illustrate the break even analysis for both sites.

Figs. 4 (a) and (b) the breakeven point happen at grid extension distance 72 km for Ras Sudr and 76.7 km for Siwa Oasis. Obviously as WT output is higher for Ras Sudr, the break even with grid extension is located at shorter distance.




(a) Ras Sudr




(b) Siwa Oasis

Fig. 4 Breakeven analysis of energy generated from the system against the cost of electricity for the optimum system

## V. CONCLUSIONS

The results obtained give numerous alternatives of feasible hybrid systems with different levels of renewable resources penetration. The economic performance criteria are NPC of the system and the COE produced, while the technical performance criterion is the allowable percentage shortage.

Based on the economic assumptions used in the simulation of W/D/B system (applied on two case studies) in this research the following specific conclusions are derived:

- Two case studies were introduced optimizing wind/ diesel/battery energy system for two sites; Ras Sudr and Siwa Oasis. The optimization was carried out using HOMER simulation package to determine the optimal system; technically and economically, for each site. The results demonstrated that the W/D/B systems are viable alternative for grid extension for remote areas.
- The results also showed that for W/D/B system, the wind generated electricity is about 60-67% of load requirements (according to wind speeds), with yearly diesel generator operation limited to (5,587 hrs.) for Ras Sudr and (5,633 hrs.) for Siwa Oasis.
- The optimum system configuration to support 10 kW peak load (6 families) was; 3 wind turbines (3 kW each), a diesel engine of 8 kW, and 24 battery storage of 225 Ah capacity. The optimization results summary is in Table V.

TABLE V
SUMMARY OF OPTIMIZATION RESULTS

| Site | NPC ($) | COE ($/KWh) | RE (%) |
|---|---|---|---|
| Ras Sudr | 106,705 | 0.308 | 67 |
| Siwa Oasis | 111,329 | 0.321 | 62 |

- Economic evaluation of the system is highly sensitive to the assumed economic parameters, especially fuel price, changing this rate from $0.25 to $0.35 increased NPC about 10%. Hence specific economic decisions require conducting simulation experiments with the exact parameters.
- In the applied case study, should wind speed be increased by about 25%, causes a decrease of NPC of 22% on the average according to wind turbine performance curve.

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