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# Cost Analysis of Hybrid Wind Energy Generating System Considering $CO_2$ Emissions

M. A. Badr, M.N. El Kordy, A. N. Mohib, M. M. Ibrahim

***Abstract*****—**The basic objective of the research is to study the effect of hybrid wind energy on the cost of generated electricity considering the cost of reduction $CO_2$ emissions. The system consists of small wind turbine(s), storage battery bank and a diesel generator (W/D/B). Using an optimization software package, different system configurations are investigated to reach optimum configuration based on the net present cost (NPC) and cost of energy (COE) as economic optimization criteria. The cost of avoided $CO_2$ is taken into consideration. The system is intended to supply the electrical load of a small community (gathering six families) in a remote Egyptian area. The investigated system is not connected to the electricity grid and may replace an existing conventional diesel powered electric supply system to reduce fuel consumption and $CO_2$ emissions. The simulation results showed that W/D energy system is more economic than diesel alone. The estimated COE is 0.308$/kWh and extracting the cost of avoided $CO_2$, the COE reached 0.226 $/kWh which is an external benefit of wind turbine, as there are no pollutant emissions through operational phase.

***Keywords*****—**Hybrid wind turbine systems, remote areas electrification, simulation of hybrid energy systems, techno-economic study.

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## 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. This lead to rapid increase of fuel consumption, and consequently the amount of greenhouse gases emissions. As fossil fuel resources are depleting in the near future, fuel price is expected to increase rapidly. These are the main reasons for focusing on utilizing alternative energy sources effectively and efficiently [1]. Wind energy is gaining increasing importance throughout the world. Wind energy systems are often assumed to deliver energy without pollutant emissions during operational stage [2]. The built environment offers a new challenging opportunity for generating electricity from the wind. In contrast to large scale production in wind farms, the built environment requires a totally different design, small wind turbines (sometimes vertical axis) where wind is highly turbulent. Small vertical axis wind turbines, specially designed or modified provide good solution to visually integrate with the surrounding buildings [3].

The new concepts have evolved which are much better equipped for application on (existing) buildings. Typical dimensions are around 10 to 20% of the characteristic building height. Technically a system which is entirely dependent on renewable energy sources only, cannot be considered a reliable electricity supply, especially for isolated loads in remote areas. This is because the availability of the renewable energy sources is intermittent. Therefore, wind turbine and diesel generator systems are the suitable choice for isolated loads. A hybrid system using wind turbine, diesel generator, a battery bank and adequate control strategy is expected to: satisfy the load demands, minimize the costs, maximize the utilization of renewable sources, optimize the operation of battery bank, ensure efficient operation of the diesel generator, and reduce the environment pollution emissions from diesel generator if it is used as a standalone power supply. The high capital cost of hybrid systems is affected by technical factors such as efficiency, technology, reliability, location, as well as some nontechnical factors. The effect of each of these factors was considered in a performance study of the hybrid system. One of the important factors, which directly affect the electricity cost, is sizing of the system's components [4].

Zhao et al. introduced the current development situation of the renewable energy, analyzed the subsidy policy and discussed the problems of the electricity price mechanisms and policies in China [5]. The author concluded that government should formulate more policies to encourage private and foreign enterprises to invest in renewable energy industries as well as to apply the Clean Development Mechanism (CDM). The recent statements of both the European Union and the US Presidency pushed in the direction of using renewable forms of energy, in order to act against climate changes induced by the growing concentration of carbon dioxide in the atmosphere. A survey regarding methods and tools presently available to determine potential and exploitable energy in the most important renewable sectors was presented [6].

Optimal sizing model may be based on iterative technique, to optimize the capacity sizes of different components of hybrid energy systems. Hybrid solar/wind energy systems allow improving the system efficiency and power reliability and reduce the energy storage requirements for stand-alone applications. Wei Zhou et al presented a review of the current state of the simulation, optimization and control technologies for the stand-alone hybrid solar–wind energy systems with battery storage [7]. A simplified algorithm to estimate the

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yearly wind fraction, the fraction of energy demand provided by wind generator, in a hybrid-wind system (typically a PV-wind) with battery storage was developed by Çelik [8]. The model was based on the simulation results, using 8-year long measured hour-by-hour wind speed data from five different locations throughout the world.

## II. SIZING OF W/D/B SYSTEM COMPONENTS

Long term measurement of wind speeds is necessary for the simulation study of wind turbine system performance. Wind data in this study were obtained from Central Laboratory for Agricultural Climate. The average wind speeds are calculated for each month.

It should be noted that using monthly wind speed has some limitations such as loosing extremely low or high wind speeds within the month as well as inability to observe diurnal variations in the wind speed. However, monthly average wind speed, which is available for most locations, can be used to study the seasonal changes in wind speed and facilitates wind data analysis. Table I shows the monthly average wind speed at the site selected for the study which is Ras-Sudr on the Red Sea cost of Egypt. Hybrid Optimization Model for Electric Renewals (HOMER) simulation software is applied to analyze the operation of the hybrid wind system using two economic performance criteria; NPC and COE.

TABLE I
MONTHLY AVERAGE FOR 2 YEARS WIND SPEED AT RAS-SUDR SITE

| Month | Jan | Feb | Mar | Apr | May | June | July | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Average wind Speed (m/s) | 8.7 | 9.9 | 11.3 | 10.0 | 9.5 | 8.2 | 9.4 | 8.7 | 9.6 | 9.7 | 8.8 | 10.0 |

### A. Load Pattern

Load profile estimation is based on the assumption of expected electrical consuming appliances, natures of operation of each of them and consumers' behavior. For a small gathering the load consists of energy saving lighting fixtures, radio/TV, washing machine, fan and refrigerator, [9]. Other appliances such as mixers and water pumps may be used according to load management schedule based on periods of excess wind energy. The estimated seasonal basic load profiles are presented in Fig. 1.

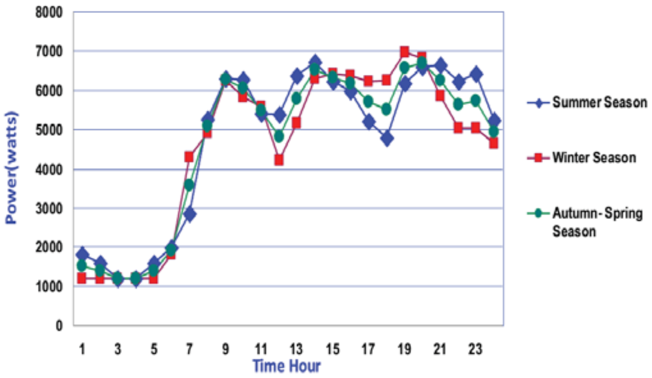

Fig. 1 Daily load curve for six families

### B. Generating Power Units

1) Wind Turbines

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. Three turbines are used in the optimization of the studied case with rated power in the range from 1.8 to 8 kW**.** The wind speed- power curve of each turbine is an input of HOMER simulation program.

2) Diesel Generator

Optimal unit sizing of a D.G. should consider several factors such as load fluctuations, and conditions for feasible and reliable diesel operation. Sizing diesel units based on annual peak and/or average load values, with reasonable safety margins, diesel units will generally be oversized. This is due to the fact that the peak loads; especially in small community, are much higher than average load. Number of diesel working hours depends its size, wind turbine size and site wind speeds [6].

3) Battery Bank

The ampere-hour capacity of a battery is the quantity of discharge current available for a specified length of time at a certain temperature and discharge rate, [6]. High discharge current would result in reduction of the battery capacity and will decrease its life time. 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. 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, [6].

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

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.

4) Converter

A bidirectional inverter is essential in the hybrid energy generating system. It can transfer power simultaneously in both directions. Shape of the output waveform, power rating and efficiency are the parameters that shall be considered to choose a certain bi-directional inverter for certain application, [6].

## III. RESULTS AND DISCUSSION

Using HOMER software; different system configurations were simulated to reach the optimum configuration, to supply six families electrical load at Ras-Sudr site. Optimization results are shown in the following subsections. These results are obtained based on two decision variables; maximum

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allowable shortage, and minimum renewable fraction, in addition to a particular set of inputs such as load pattern, diesel price, and system lifetime and wind resource data for the site. The diesel price is 0.25 $/L, which is the current unsubsidized price of diesel in the country.

### A. Basic Load Results: Case I

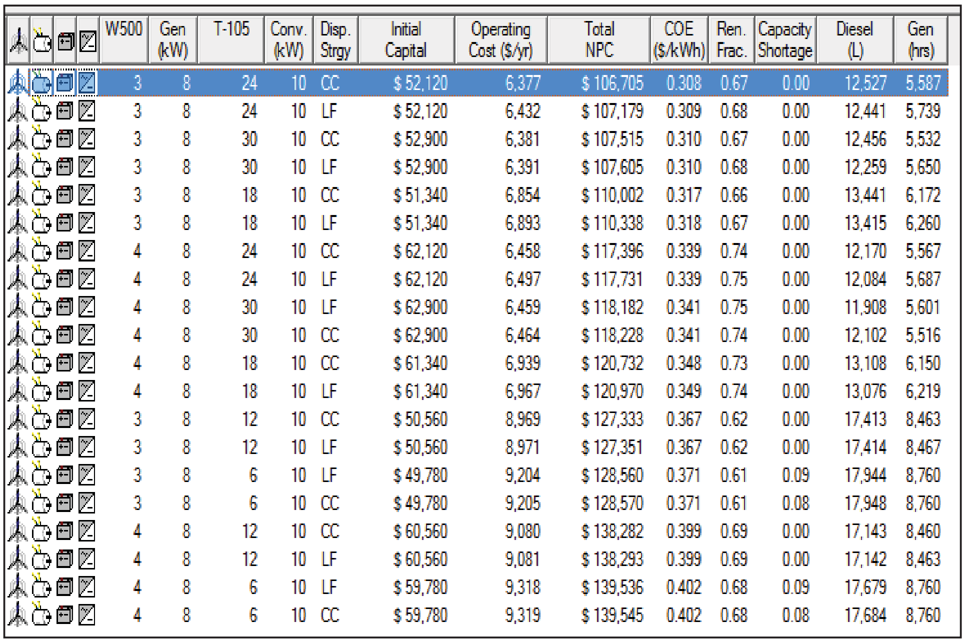
The optimum system configuration is used to supply the energy requirements of 6 families to investigate the effect of higher load on the utilization of excess energy and modified COE, as shown in Fig. 1. In this case, the daily energy consumption is 111 kWh (40515 kWh/year) and the peak load is 10 kW. Fig. 2. exhibits the optimization results of W/D/B system.

From Fig. 2, it is shown that the optimum system configuration in this case is as follows:

- 3 wind turbines, Whisper 500, 3 KW rated power each.
- 24 battery bank, Trojan T-105, 6V-225Ah each.
- Generator, 8 KW size.
- Converter, 10 KW size.

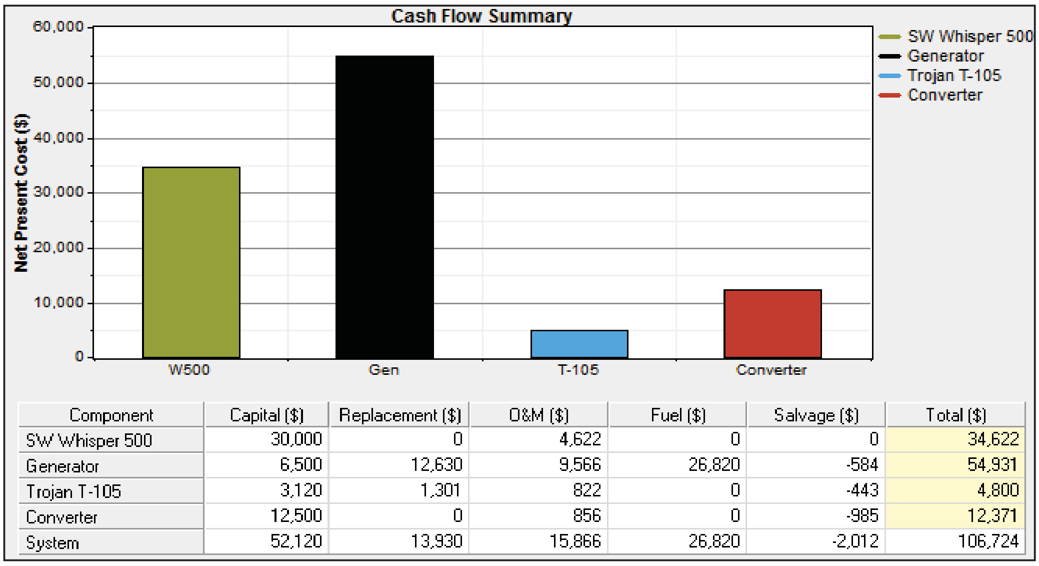
System NPC is $106,705 and COE is 0.308$/kWh. In this case, the amount of $CO_2$ emissions is 33,004 kg/year.

W500 is Whisper 500, 3 KW rated power. T-105 is Trojan battery 6V-225Ah. Fig. 3 represents the cash flow summary of the system, while Fig. 4 shows the system energy summary.



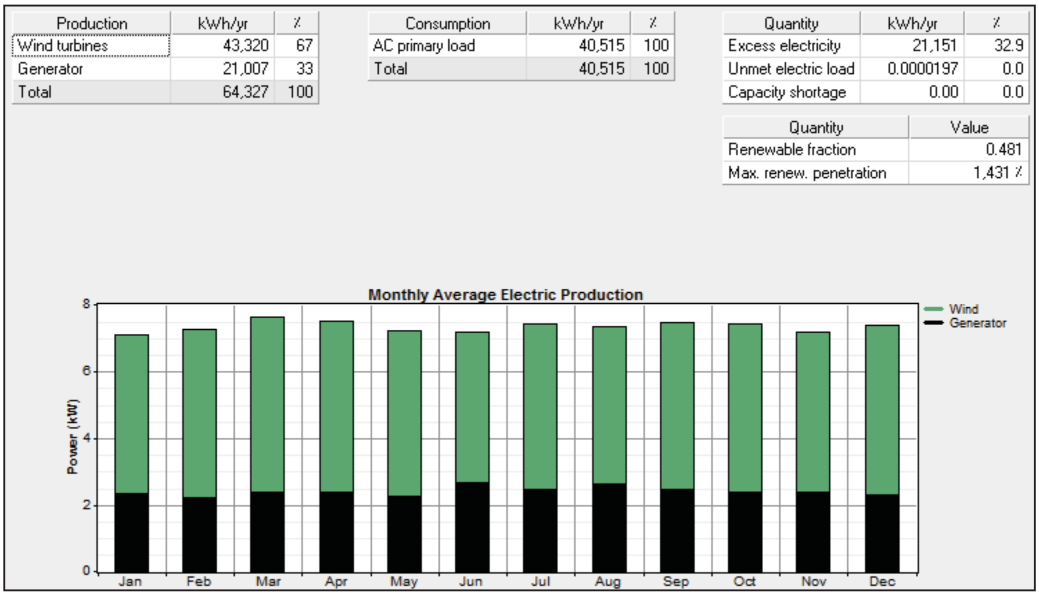
| W500 | Gen (kW) | T-105 | Conv. (kW) | Disp. Strgy | Initial Capital | Operating Cost ($/yr) | Total NPC | COE ($/kWh) | Ren. Frac. | Capacity Shortage | Diesel (L) | Gen (hrs) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 8 | 24 | 10 | CC | $ 52,120 | 6,377 | $ 106,705 | 0.308 | 0.67 | 0.00 | 12,527 | 5,587 |
| 3 | 8 | 24 | 10 | LF | $ 52,120 | 6,432 | $ 107,179 | 0.309 | 0.68 | 0.00 | 12,441 | 5,739 |
| 3 | 8 | 30 | 10 | CC | $ 52,900 | 6,381 | $ 107,515 | 0.310 | 0.67 | 0.00 | 12,456 | 5,532 |
| 3 | 8 | 30 | 10 | LF | $ 52,900 | 6,391 | $ 107,605 | 0.310 | 0.68 | 0.00 | 12,259 | 5,650 |
| 3 | 8 | 18 | 10 | CC | $ 51,340 | 6,854 | $ 110,002 | 0.317 | 0.66 | 0.00 | 13,441 | 6,172 |
| 3 | 8 | 18 | 10 | LF | $ 51,340 | 6,893 | $ 110,338 | 0.318 | 0.67 | 0.00 | 13,415 | 6,260 |
| 4 | 8 | 24 | 10 | CC | $ 62,120 | 6,458 | $ 117,396 | 0.339 | 0.74 | 0.00 | 12,170 | 5,567 |
| 4 | 8 | 24 | 10 | LF | $ 62,120 | 6,497 | $ 117,731 | 0.339 | 0.75 | 0.00 | 12,084 | 5,687 |
| 4 | 8 | 30 | 10 | LF | $ 62,900 | 6,459 | $ 118,182 | 0.341 | 0.75 | 0.00 | 11,908 | 5,601 |
| 4 | 8 | 30 | 10 | CC | $ 62,900 | 6,464 | $ 118,228 | 0.341 | 0.74 | 0.00 | 12,102 | 5,516 |
| 4 | 8 | 18 | 10 | CC | $ 61,340 | 6,939 | $ 120,732 | 0.348 | 0.73 | 0.00 | 13,108 | 6,150 |
| 4 | 8 | 18 | 10 | LF | $ 61,340 | 6,967 | $ 120,970 | 0.349 | 0.74 | 0.00 | 13,076 | 6,219 |
| 3 | 8 | 12 | 10 | CC | $ 50,560 | 8,969 | $ 127,333 | 0.367 | 0.62 | 0.00 | 17,413 | 8,463 |
| 3 | 8 | 12 | 10 | LF | $ 50,560 | 8,971 | $ 127,351 | 0.367 | 0.62 | 0.00 | 17,414 | 8,467 |
| 3 | 8 | 6 | 10 | LF | $ 49,780 | 9,204 | $ 128,560 | 0.371 | 0.61 | 0.09 | 17,944 | 8,760 |
| 3 | 8 | 6 | 10 | CC | $ 49,780 | 9,205 | $ 128,570 | 0.371 | 0.61 | 0.08 | 17,948 | 8,760 |
| 4 | 8 | 12 | 10 | CC | $ 60,560 | 9,080 | $ 138,282 | 0.399 | 0.69 | 0.00 | 17,143 | 8,460 |
| 4 | 8 | 12 | 10 | LF | $ 60,560 | 9,081 | $ 138,293 | 0.399 | 0.69 | 0.00 | 17,142 | 8,463 |
| 4 | 8 | 6 | 10 | LF | $ 59,780 | 9,318 | $ 139,536 | 0.402 | 0.68 | 0.09 | 17,679 | 8,760 |
| 4 | 8 | 6 | 10 | CC | $ 59,780 | 9,319 | $ 139,545 | 0.402 | 0.68 | 0.08 | 17,684 | 8,760 |

Fig. 2 Optimization Results of W/D/B System at *Ras-Sudr Site*



| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Salvage ($) | Total ($) |
|---|---|---|---|---|---|---|
| SW Whisper 500 | 30,000 | 0 | 4,622 | 0 | 0 | 34,622 |
| Generator | 6,500 | 12,630 | 9,566 | 26,820 | -584 | 54,931 |
| Trojan T-105 | 3,120 | 1,301 | 822 | 0 | -443 | 4,800 |
| Converter | 12,500 | 0 | 856 | 0 | -985 | 12,371 |
| System | 52,120 | 13,930 | 15,866 | 26,820 | -2,012 | 106,724 |

Fig. 3 Cash flow summary



| Production | kWh/yr | % |
|---|---|---|
| Wind turbines | 43,320 | 67 |
| Generator | 21,007 | 33 |
| Total | 64,327 | 100 |

| Consumption | kWh/yr | % |
|---|---|---|
| AC primary load | 40,515 | 100 |
| Total | 40,515 | 100 |

| Quantity | kWh/yr | % |
|---|---|---|
| Excess electricity | 21,151 | 32.9 |
| Unmet electric load | 0.0000197 | 0.0 |
| Capacity shortage | 0.00 | 0.0 |

| Quantity | Value |
|---|---|
| Renewable fraction | 0.481 |
| Max. renew. penetration | 1,431 % |

Fig. 4 Energy summary

The cash flow summary shows that while wind turbine total cost is $34,622 over the system lifetime, the total cost of the diesel generator; (price of the first generator and its replacements in addition to fuel, operation and maintenance cost) is $54,931. Fig. 4 shows that although wind turbine output energy is more than 43,000 kWh/year, wind generated energy only covers 67% of the required load energy (40515 kWh), this is due to mismatch between the daily profiles of wind turbine output and load. Hence, about 33% of the wind generated energy is wasted as excess.

Increasing the RF increased the COE as most of extra generated wind electricity was wasted as excess energy. The daily load curve, wind turbine output and excess power curves are plotted for the 24 hours, Fig. 5. Wind turbine and excess powers are calculated as the hourly average of 15 simulated days in July.

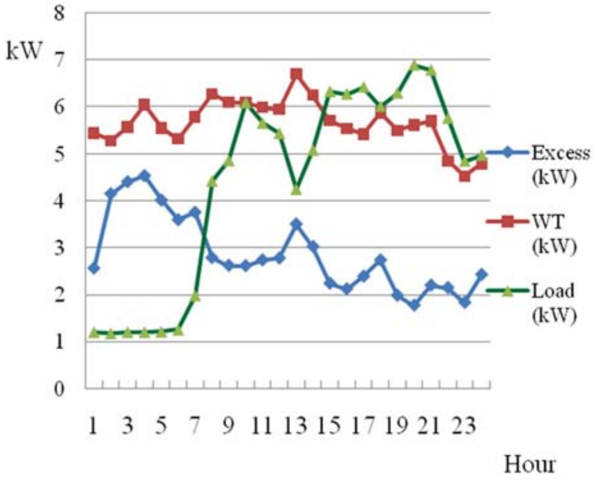


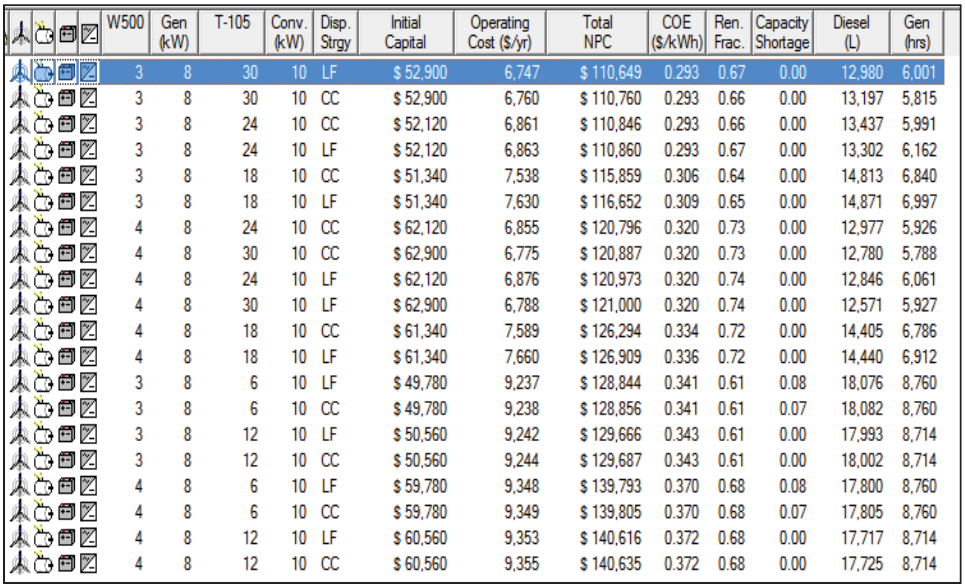
Fig. 5 Daily load curve, wind turbine output and excess power, Case I

In Fig. 5, it could be seen that during the period from 1 a.m. to 7 a.m. the load curve is at its minimum value while the wind turbine output is high. Hence, the excess power value is high. Thus, it is advisable to use this energy for water pumping.

### *B. Basic Load and Water Pumping Results: Case II*

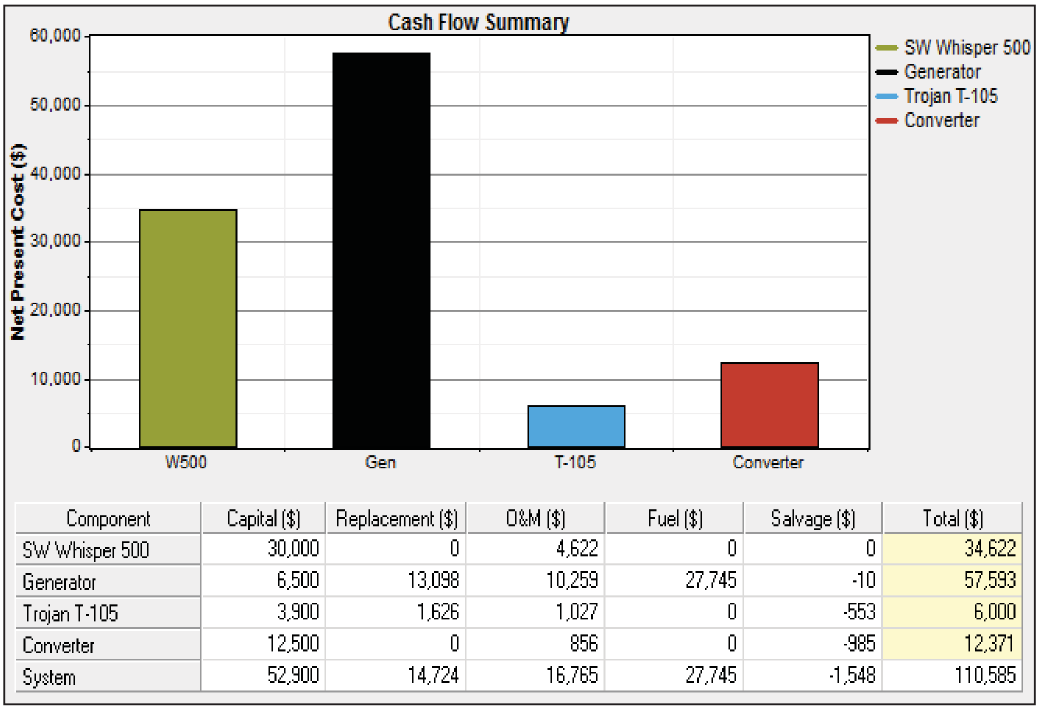
The power required for pumping water is calculated as the required water quantity Q in cubic meters multiplied by the height. For six families, Q is taken as 42 $m^3$in winter and 50 $m^3$in summer. Water is going to be elevated 41 m. Thus, the required pump power is 1.3 kW in winter (1.5 kW in summer) for 7 hours from 1 to 7 a.m. to make use of part of the excess power. Fig. 6 shows the optimization results and Figs. 7 and 8 exhibit the cash flow and energy summaries for Case II, respectively.

From Fig. 6, it could be seen that NPC is $110,649 and COE is 0.293 $/kWh. The increase in the system NPC is due to the increase in fuel consumption and operation and maintenance cost of the diesel generator. From Fig. 6, it is seen that the excess energy has decreased to 27%. The value of excess energy could be further decreased if other appliances; such as mixers, computers, vaccum cleaners, etc, are used if needed during scheduled times. The daily load pattern, wind turbine output and excess power curves are plotted for the 24 hours, Fig. 9. Similar to Case I, wind turbine and excess powers are calculated, as the hourly average of 15 simulated days in July.



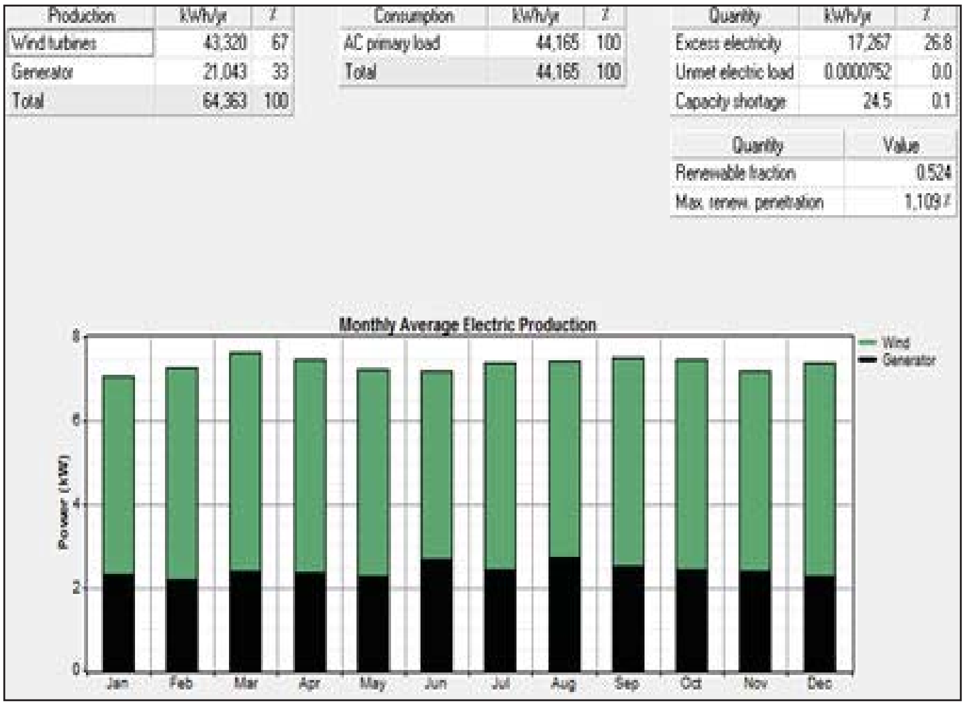
| W500 | Gen (kW) | T-105 | Conv. (kW) | Disp. Strgy | Initial Capital | Operating Cost ($/yr) | Total NPC | COE ($/kWh) | Ren. Frac. | Capacity Shortage | Diesel (L) | Gen (hrs) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 8 | 30 | 10 | LF | $ 52,900 | 6,747 | $ 110,649 | 0.293 | 0.67 | 0.00 | 12,980 | 6,001 |
| 3 | 8 | 30 | 10 | CC | $ 52,900 | 6,760 | $ 110,760 | 0.293 | 0.66 | 0.00 | 13,197 | 5,815 |
| 3 | 8 | 24 | 10 | CC | $ 52,120 | 6,861 | $ 110,846 | 0.293 | 0.66 | 0.00 | 13,437 | 5,991 |
| 3 | 8 | 24 | 10 | LF | $ 52,120 | 6,863 | $ 110,860 | 0.293 | 0.67 | 0.00 | 13,302 | 6,162 |
| 3 | 8 | 18 | 10 | CC | $ 51,340 | 7,538 | $ 115,859 | 0.306 | 0.64 | 0.00 | 14,813 | 6,840 |
| 3 | 8 | 18 | 10 | LF | $ 51,340 | 7,630 | $ 116,652 | 0.309 | 0.65 | 0.00 | 14,871 | 6,997 |
| 4 | 8 | 24 | 10 | CC | $ 62,120 | 6,855 | $ 120,796 | 0.320 | 0.73 | 0.00 | 12,977 | 5,926 |
| 4 | 8 | 30 | 10 | CC | $ 62,900 | 6,775 | $ 120,887 | 0.320 | 0.73 | 0.00 | 12,780 | 5,788 |
| 4 | 8 | 24 | 10 | LF | $ 62,120 | 6,876 | $ 120,973 | 0.320 | 0.74 | 0.00 | 12,846 | 6,061 |
| 4 | 8 | 30 | 10 | LF | $ 62,900 | 6,788 | $ 121,000 | 0.320 | 0.74 | 0.00 | 12,571 | 5,927 |
| 4 | 8 | 18 | 10 | CC | $ 61,340 | 7,589 | $ 126,294 | 0.334 | 0.72 | 0.00 | 14,405 | 6,786 |
| 4 | 8 | 18 | 10 | LF | $ 61,340 | 7,660 | $ 126,909 | 0.336 | 0.72 | 0.00 | 14,440 | 6,912 |
| 3 | 8 | 6 | 10 | LF | $ 49,780 | 9,237 | $ 128,844 | 0.341 | 0.61 | 0.08 | 18,076 | 8,760 |
| 3 | 8 | 6 | 10 | CC | $ 49,780 | 9,238 | $ 128,856 | 0.341 | 0.61 | 0.07 | 18,082 | 8,760 |
| 3 | 8 | 12 | 10 | LF | $ 50,560 | 9,242 | $ 129,666 | 0.343 | 0.61 | 0.00 | 17,993 | 8,714 |
| 3 | 8 | 12 | 10 | CC | $ 50,560 | 9,244 | $ 129,687 | 0.343 | 0.61 | 0.00 | 18,002 | 8,714 |
| 4 | 8 | 6 | 10 | LF | $ 59,780 | 9,348 | $ 139,793 | 0.370 | 0.68 | 0.08 | 17,800 | 8,760 |
| 4 | 8 | 6 | 10 | CC | $ 59,780 | 9,349 | $ 139,805 | 0.370 | 0.68 | 0.07 | 17,805 | 8,760 |
| 4 | 8 | 12 | 10 | LF | $ 60,560 | 9,353 | $ 140,616 | 0.372 | 0.68 | 0.00 | 17,717 | 8,714 |
| 4 | 8 | 12 | 10 | CC | $ 60,560 | 9,355 | $ 140,635 | 0.372 | 0.68 | 0.00 | 17,725 | 8,714 |

Fig. 6 Optimization Results of W/D/B System Supplying Basic Load and Water Pump



| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Salvage ($) | Total ($) |
|---|---|---|---|---|---|---|
| SW Whisper 500 | 30,000 | 0 | 4,622 | 0 | 0 | 34,622 |
| Generator | 6,500 | 13,098 | 10,259 | 27,745 | -10 | 57,593 |
| Trojan T-105 | 3,900 | 1,626 | 1,027 | 0 | -553 | 6,000 |
| Converter | 12,500 | 0 | 856 | 0 | -985 | 12,371 |
| System | 52,900 | 14,724 | 16,765 | 27,745 | -1,548 | 110,585 |

Fig. 7 Cash flow summary for Case II



| Production | kWh/yr | % |
|---|---|---|
| Wind turbines | 43,320 | 67 |
| Generator | 21,043 | 33 |
| Total | 64,363 | 100 |

| Consumption | kWh/yr | % |
|---|---|---|
| AC primary load | 44,165 | 100 |
| Total | 44,165 | 100 |

| Quantity | kWh/yr | % |
|---|---|---|
| Excess electricity | 17,267 | 26.8 |
| Unmet electric load | 0.0000752 | 0.0 |
| Capacity shortage | 24.5 | 0.1 |

| Quantity | Value |
|---|---|
| Renewable fraction | 0.524 |
| Max. renew. penetration | 1,109 % |

Fig. 8 Energy summary for Case II

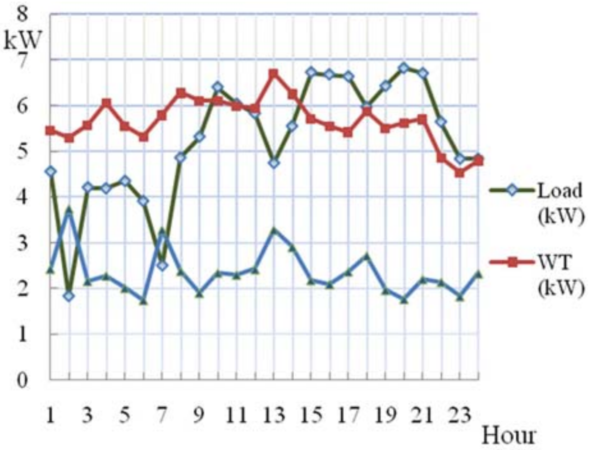
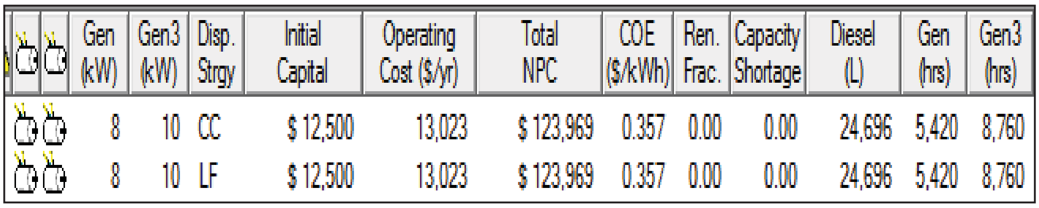


Fig. 9 Daily load curve, wind turbine output and excess power, Case II

*C. Cost of Reduction in $CO_2$ Emission*

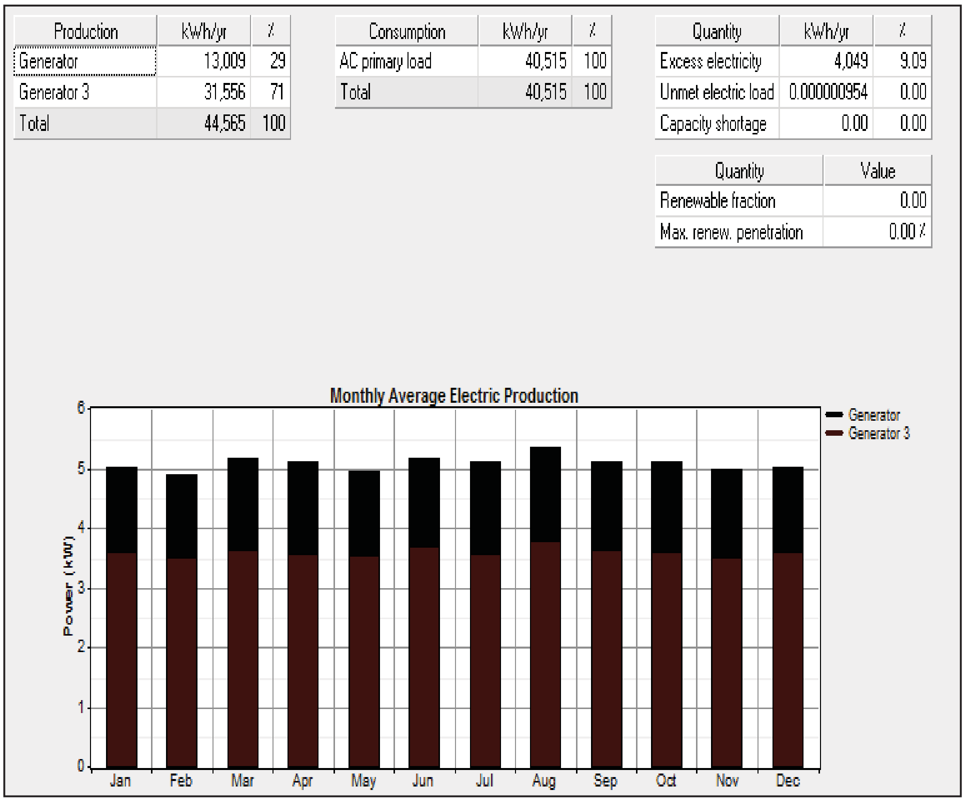
To estimate the amount of reduction in $CO_2$ emission, a simulation run is performed supplying the load by diesel generators only. The result of this run is shown in Fig. 10.

As it is shown in Fig. 10, two generators (8 and 10 kW) are used to supply the load. The NPC is $123,969 and COE is 0.357 $/kWh that are higher than the optimum W/D/B system. The amount of yearly consumed fuel is 24969 liters; which results in 949 ton of $CO_2$ as $CO_2$ emissions from diesel fuel = 10.1 kg/gallon = 38 kg/L [10]. The energy summary of this case showed 9% excess energy as shown in Fig. 11.



| | | Gen (kW) | Gen3 (kW) | Disp. Strgy | Initial Capital | Operating Cost ($/yr) | Total NPC | COE ($/kWh) | Ren. Frac. | Capacity Shortage | Diesel (L) | Gen (hrs) | Gen3 (hrs) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 8 | 10 | CC | $ 12,500 | 13,023 | $ 123,969 | 0.357 | 0.00 | 0.00 | 24,696 | 5,420 | 8,760 |
| | | 8 | 10 | LF | $ 12,500 | 13,023 | $ 123,969 | 0.357 | 0.00 | 0.00 | 24,696 | 5,420 | 8,760 |

Fig. 10 Simulation Results in Case of Diesel Generators alone



| Production | kWh/yr | % |
|---|---|---|
| Generator | 13,009 | 29 |
| Generator 3 | 31,556 | 71 |
| Total | 44,565 | 100 |

| Consumption | kWh/yr | % |
|---|---|---|
| AC primary load | 40,515 | 100 |
| Total | 40,515 | 100 |

| Quantity | kWh/yr | % |
|---|---|---|
| Excess electricity | 4,049 | 9.09 |
| Unmet electric load | 0.000000954 | 0.00 |
| Capacity shortage | 0.00 | 0.00 |

| Quantity | Value |
|---|---|
| Renewable fraction | 0.00 |
| Max. renew. penetration | 0.00 % |

Fig. 11 Energy summary for diesel alone

TABLE II
SUMMARY OF THE THREE CASES RESULTS

| | Fuel consumption (L) | $CO_2$ (kg/year) | Total NPC ($) | COE ($/kWh) | Modified COE ($/kWh) |
|---|---|---|---|---|---|
| Diesel Alone | 24,696 | 65,033 | 123,969 | 0.357 | --- |
| W/D/B Case I | 12,527 | 33,004 | 106,705 | 0.308 | 0.226 |
| W/D/B Case II | 12,980 | 34,144 | 110,649 | 0.293 | 0.205 |

The recorded COE in both cases does not take into consideration the cost of avoided $CO_2$ emissions. Deducing the cost of avoided $CO_2$ emissions, the COE is reduced from 0.308 \$/kWh to 0.226 \$/kWh for Case I, and from 0.293 to 0.205 \$/kWh for Case II.

$$\text{Avoided cost } CO_2 = RSL \times ACO_2 \times P\ CO_2$$

where: RSL: Renewable supplied load, i.e. Part of load supplied by WT (kWh). $ACO_2$: Amount of $CO_2$ emitted from one kWh, diesel generated electricity. $PCO_{2:}$ Penalty of $CO_2$ emission \$/kg. Penalty of $CO_2$ emission = 80\$/ton [11]

Table II represents a summary of the three cases results.

## IV. CONCLUSIONS

Based on the economic assumptions, site wind speeds and estimated load pattern used in the simulation of the energy system, the following conclusions are derived:

- Wind/Diesel/Battery energy system is more cost effective than conventional diesel generator systems.
- The optimum system configuration to support 10 kW peak load (6 families) was; 3 wind turbines (3 kW each), a diesel generator of 8 kW, and 24 battery storage of 225 Ah capacity. The optimization results summary is as follows: NPC = 106,705, COE = 0.308\$/kWh, Renewable Fraction (RF)= 67% and the recorded yearly excess energy is 21141 kWh.
- The emitted $CO_2$ is 32.987 ton/year; in Case I compared to 949 ton/year for diesel generator system. Calculating the cost of avoided $CO_2$, the estimated modified COE is 0.226 \$/kWh.
- Adding extra load (water pump) to make use of a part of the excess energy decreased the COE to \$0.293 and modified COE to \$0.205.

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