# ECONOMIC PERSPECTIVE OF HYBRID WIND-DIESEL TECHNOLOGY FOR COMMERCIAL LOADS OF DHAHRAN, SAUDI ARABIA
## A Step Towards Sustainable Future

by

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*The governments world-wide are deliberating to promote renewable energy sources such as wind to mitigate increasing demand of energy and to overcome effects of pollution due to to use of fossil fuels. Integration of wind turbine generators with diesel plants is pursued widely to reduce dependence on fossil-fuels and to reduce carbon emissions. Literature indicates that commercial/residential buildings in the Kingdom of Saudi Arabia consume an estimated 10-40% of the total electric energy generated. The aim of this study is to analyze wind-speed data of Dhahran (East-Coast) to assess the economic feasibility of utilizing hybrid wind-diesel power systems to meet the load requirements of a typical commercial building (with annual electrical energy demand of 620,000 kWh). The monthly average wind speeds in the range from 3.3 to 5.6 m/s. The hybrid systems simulated consist of different combinations of 100 kW commercial wind turbine generations supplemented with diesel generators. NREL's HOMER software has been employed to perform the techno-economic analysis.*

*The simulation results indicate that for a hybrid system comprising of 100 kW wind capacity together with 175 kW diesel system, the wind penetration (at 37 m hub-height, with 0% annual capacity shortage) is 25%. The cost of generating energy from this hybrid wind-diesel system has been found to be 0.121 $/kWh (assuming diesel fuel price of 0.1$/liter). The study exhibits that for a given hybrid configuration, the number of operational hours of diesel gensets decreases with increase in wind farm capacity. Emphasis has also been placed on wind penetration, un-met load, energy production and cost of generating energy, excess electricity generation, percentage fuel savings and reduction in carbon emissions (relative to diesel-only situation) of different hybrid systems, cost break-down of wind-diesel systems, COE of different hybrid systems, etc.*

Keywords: *hybrid wind-diesel systems, commercial loads, diesel generators, carbon emissions*

## Introduction

Renewable energy holds the key to future prosperity and is considered as a promising way to solve the problem of environmental pollution. In the light of rising cost of oil and threats of its depletion coupled with increased pollution, renewable energy source such as wind is ex-

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ploited/used world-wide. Unless ways and means are explored to curb global warming, our life and planet are in danger. Wind is developing into a mainstream power source in several countries, and is playing a key role in meeting the energy challenges. Literature indicates that wind energy (being in-exhaustible, site-dependent, environment-friendly) is being pursued by a number of countries with average wind speeds in the range of 4-10 m/s [1-7]. Cumulative global wind energy capacity reached 93.849 MW in December 2007. The price of generating energy using wind turbine generators (WTG) has dropped dramatically over the last decade and currently it is in the range of 4 to 5 cents per kWh. The technology of the WTG has improved remarkably over the last five years. WTG in the range of 3.2 MW are commercially available. The rate of increase in installed capacity during the last ten years is in the range of 25-30% per year [8]. By and large, typical wind power applications include lighting, electrical appliances, military installations, communication and gas stations, electricity for remote settlements (which are far from existing utility grid), water pumping for irrigation, cathodic protection of oil pipe lines, *etc*.

Stand-alone WTG are not economically competitive because of their intermittent nature (associated with high cut-in speeds) and because they require large storage capacity to meet the load. Stand-alone diesel systems contribute in atmospheric pollution. The diesel generator efficiency drops when it operates at less than 40% of full load, its lifespan shortens and frequency of maintenance increases [9, 10]. More often, it appears to be difficult to achieve realizable electricity cost savings with respect to the diesel-alone situations (due to high O & M + fuel costs) in a long term. However, integration of WTG with diesel mini-grids has several advantages. It reduces pollution, may reduce the cost of generating energy (COE) [$/kWh], in a long-run, and provides the reliability of the diesel system as well as the cost-effectiveness of the wind-generated energy. Introduction of WTG into the diesel grid leads to an appreciable reduction in the diesel consumption. A hybrid wind-diesel driven power system (with/without battery) is a viable/cost-effective technology for electric supply. Many projects deployed around the world use hybrid wind-diesel system although it requires a sophisticated control system [11-26]. Literature points out that wind-diesel technology is ready for wide spread deployment and to complement existing diesel plants.

The demand for electrical power in Saudi Arabia is increasing at an unprecedented rate. This demand is driven by high population growth and a large number of mega industrial projects. The number of consumers grew from 300,000 in early 1970 to about 4.2 million in 2003 [27]. The installed generating capacity of the power plants reached 30,000 MW in 2003 [27]. The demand for electricity is expected to reach about 55,000 MW by 2020. In particular, Dhahran's peak demand has escalated substantially from 7317 MW in year 1995 to 8332 MW in year 2001. Also, the above significant increases can be attributed to rapid growth in residential, commercial, and industrial sectors. Since, Saudi Arabia's wind regime is reasonable, an appreciable fraction of its energy needs may be harnessed from wind energy. Moreover, use of alternative sources of energy reduces $CO_2$ emission which is the principal cause of global warming. Literature indicates that addition of 1.5 MW of wind energy conversion system (WECS), capable of producing about 4 million kWh of energy per year, would eliminate 5.6 million tons of $CO_2$ [28, 29]. Also investments in mobilization of wind power can stimulate the local economy by making use of available local indigenous resources [4].

The research on feasibility of renewable energy systems at Dhahran, has been the subject matter of several earlier studies [30-33]. In the present work, wind-speed data (of the year 1997) of Dhahran (26° 32' N, 50° 13' E) has been analyzed to assess the economic feasibility of utilizing hybrid wind-diesel power systems to meet the load requirements of a typical commercial building (with annual electrical energy demand of 620,000 kWh). Load influences the power system design markedly. The hybrid systems simulated consist of different combinations of 100 kW commercial WTG supplemented with diesel gensets. Specifically, the merit of hybrid wind-diesel system has been evaluated in a broad sense with regards to its size, operational requirements, cost, *etc*. National Renewable Energy Laboratory's (NREL's) and HOMER Energy's HOMER (Hybrid Optimization Model for Electric Renewables) software has been utilized to carry out the economic feasibility of hybrid wind-diesel power systems. HOMER is a sophisticated tool or computer-model that facilitates design of stand-alone electric power systems [34].

## Background information and load data

Climatic conditions dictate the availability of wind energy at a site. Dhahran is located just north of the Tropic of Cancer on the eastern coastal plain of Saudi Arabia and is nearly 10 km inland from the Arabian Gulf Coast. Although it is in the vicinity of the coast, but is situated in very much a desert environment. Two distinct seasons are noticed in this region: a very hot season (May to October) and a cold season (November to April). Monthly mean temperatures reach close to 37 °C for hot months and in cooler months the mean temperatures drop by about 20 °C as compared to the hot months. The relative humidity exhibits a large diurnal cycle on the order of 60% round the year. Typical long-term annual mean precipitation is about 80 mm. The winds blow from 270° to 360° direction range (north to north-westerly winds) for most of the time during the year [35-36].

An important driving element of any power generating system is load. Load has substantial impact on system design. The present work focuses attention on commercial loads. As a case study and as a representation of commercial buildings, the measured annual average electric energy consumption of a typical air-conditioned supermarket (located in Dhahran, floor area of 945 $m^2$) has been considered as yearly load 620,000 kWh in the present study [37]. This load could also be a representation of many remotely located commercial buildings which lack access to the utility grid (even today, there are many communities living or dwelling in small pockets in remote locations of the Kingdom of Saudi Arabia (K. S. A.). The K. S. A. area is large, with large number of settlements (far from electric grids) scattered all over the Kingdom. The supply of electricity to these remote villages through diesel generators alone or by connecting into the nearest grid could be an expensive option. The retrofitting of wind turbines along with the diesel systems may result in reduced fuel transport/storage/consumption, lower diesel emissions, fewer diesel spills, and possibly longer engine life. The raw electrical load data for a complete year is presented in fig. 1. As illustrated in this figure, the load seems to peak during June to September. The peak requirements of the load dictate the system size.

In the present study, the selection and sizing of components of hybrid power system has been done using NREL's HOMER software. HOMER is a hybrid system design software that facilitates design of electric power systems for stand-alone applications. Input information to be provided to HOMER includes: electrical load data, renewable resources data (wind speed data), component technical details/costs, constraints, controls, type of dispatch strategy, *etc*.

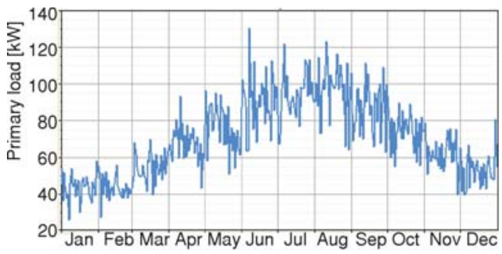



**Figure 1. Daily average load [kW] for a complete year**

HOMER designs a optimal power system to serve the desired loads. HOMER is an simplified optimization model/code, which performs hundreds or thousands of hourly simulations over and over (to ensure best possible matching between supply and demand) in order to design the optimum system. It uses life cycle cost to rank order these systems. It offers a powerful user interface and accurate sizing with detailed analysis of the system. The software also performs automatic sensitivity analysis to account for the sensitivity of the hybrid system design to key parameters, such as the resource availability or component costs [34].

## Wind data and characteristics of hybrid wind-diesel system

The monthly average wind speeds for Dhahran of the year 1997 are presented in fig. 2. Wind speeds are higher in summer months (May to Aug.) as compared to other months. This indicates that a WTG would produce appreciably more energy during summer months as compared to the other months (this is a favorable characteristic because the load is high in summer in this part of the world). The monthly behavior of wind speed matches the higher electrical load requirements during summer period. The data also indicates that there is noticeable variation of monthly average wind speed from one month to another month. These variations indicate that the monthly energy output from WTG would be subjected to considerable differences.

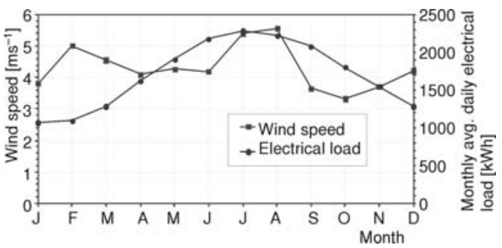



**Figure 2. Monthly average wind speed and monthly average daily commercial load**

An earlier study on WTG at Dhahran has analyzed long-term (1986-1997) wind speed data [38]. In the present study, wind-speed data of the year 1997 has been considered as a representative year for assessing the performance of hybrid wind-diesel systems using HOMER software. The monthly average wind speeds during 1997 have been found to range from 3.3 to 5.6 m/s. The yearly average wind speed of 1997 is 4.31 m/s at 10 m height.

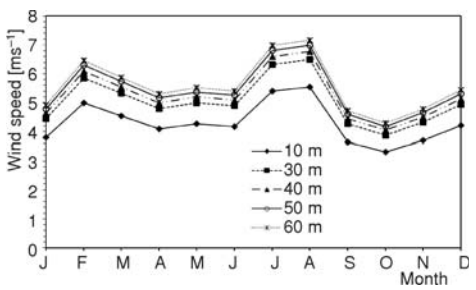



**Figure 3. Monthly average wind speed at different hub-heights**

The monthly average wind speeds corresponding to the year 1997 at different hub-heights (by using 1/7$^{th}$ power law) are presented in fig. 3. Wind is faster, less turbulent and yields more energy at 30 m or more heights above the ground. With increase in height from 10 m to 50 m, the wind speed increases by about 26%. The raw daily wind speed data of the year 1997 is shown in fig. 4. The cumulative frequency distribution of wind speed is illustrated in fig. 5.

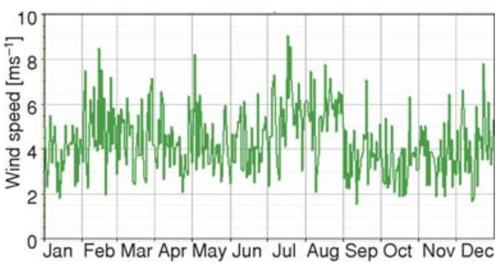



**Figure 4. Daily wind speed data for one complete year**

The calculations of wind energy (in HOMER) are made by matching the power-wind speed characteristics of commercial wind turbine generators (CWTG) with the hub-height wind speed data. The characteristics of the 100 kW CWTG considered in this study are presented in tab. 1. The technical and performance characteristics of diesel generators assumed in the study are tabulated in tab. 2. The power-curve of the 100 kW WTG is shown in fig. 6. Today's best WTG can achieve an overall efficiency of about 35% [39 ,40]. However it may be mentioned that further technological milestones, may change the scenario.

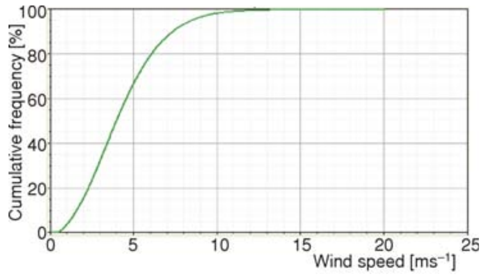



**Figure 5. Cumulative frequency distribution of wind speed**

**Table 1. Power-wind characteristics of 100 kW commercial wind turbine generator**

| Wind turbine generator model | Rated power Rp [kW] | Rated speed Vs [ms$^{-1}$] | Cut-in speed Vci [ms$^{-1}$] | Cut-out speed Vco [ms$^{-1}$] | Rotor diameter [m] | Hub height [m] |
|---|---|---|---|---|---|---|
| NW100 | 100 | 15.0 | 3 | 25 | 21 | 37 |

**Table 2. Technical data and study assumptions of diesel units**

| Description | Data |
|---|---|
| *Diesel generator units:* | |
| Rated power of diesel unit 1 (D1) | 120 kW |
| Minimum allowed power (min. load ratio) | 30% of rated power |
| No load fuel consumption | 39.6 L per hour |
| Full load fuel consumption | 10.09 L per hour |
| Rated power of diesel unit 2 (D2) | 55 kW |
| Minimum allowed power (min. load ratio) | 30% of rated power |
| No load fuel consumption | 18.15 L per hour |
| Full load fuel consumption | 4.63 L per hour |
| *Dispatch/operating strategy:* | Multiple diesel load following |
| *Spinning reserve:* | |
| Additional online diesel capacity (to shield against increases in the load or decreases in the wind power output) | 10% of the load |

In general, the cut-in wind speed (speed at which wind machine starts producing useable energy) of most of the CWTG ranges from 3 to 4 m/s [30]. The wind duration analysis indicates that the wind speeds are less than 3 m/s for about 40% (at 10 m height) of the time during the year as shown in fig. 5. This implies that a stand-alone WTG (if installed at Dhahran) will not produce any energy for about 40% of the time (during the year) and hence cannot meet the required load distribution on a continuous basis. In this regard (to cope-up with the down-time of WTG), integration of WTG with diesel systems can meet the required load distribution on a 24-hour basis.

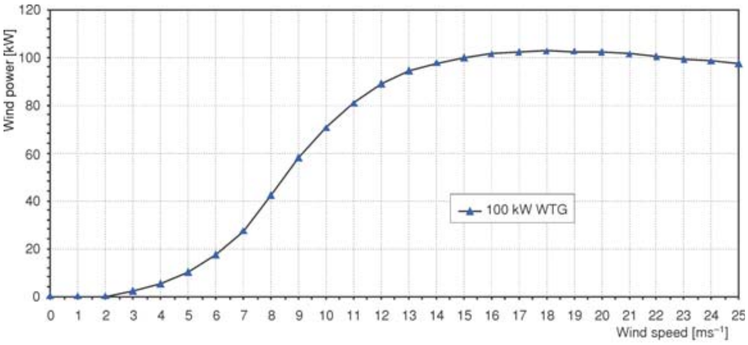



**Figure 6. Power curve of commercial 100 kW wind turbine generator**

The hybrid wind-diesel system configuration is shown in fig. 7. The dispatch strategy of the hybrid system is as follows: in normal operation, WTG feeds the load demand. The excess energy from the WTG is drained or fed to some dump load. The diesel gensets are operated at times when WTG fails to satisfy the load.

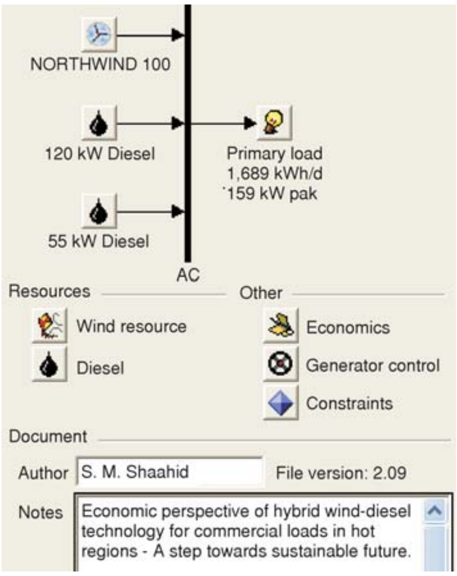



**Figure 7. Schematic of hybrid wind-diesel power system**

## Results and discussions

The hybrid systems simulated consist of different combinations of 100 kW wind machines (clustered into wind farms of different capacities) supplemented with diesel generators. HOMER allows use of three diesel units for simulation of hybrid systems. As a rule of thumb, diesel generators are generally sized to meet the peak demand of the power. The peak demand of the present case-study is 159 kW as depicted in fig. 7. In this regard, two diesel generator sets with a combined power of 175 kW (to cover peak load and to cover spinning/operating reserve of about 10% to overcome rapid changes in load) have been considered for carrying out the technical and economic analysis of the hybrid systems. The capacities of the two diesel gensets (D1, D2) are 120 kW and 55 kW, respectively. The spinning reserve is surplus electrical generation capacity (over and above that required to cover the load) that is instantly available to cover additional loads. It provides a safety margin that helps ensure reliable electricity supply even if the load were to suddenly increase or the renewable power output were to suddenly decrease.

Several simulations have been made by considering different combinations of wind farm capacities. The number of geogorapically separated wind turbines (100 kW) has been allowed to vary from 0 to 6. The study assumptions made for making simulations on HOMER are furnished in tabs. 1 and 2. The simulation results of HOMER (based on diesel price of 0.1 \$/L) for hub-height (37 m) of NW100 WECS are shown in fig. 8. In this figure, the 1$^{st}$ column shows the presence of wind turbines in a given hybrid system, 2$^{nd}$-3$^{th}$ columns indicate the presence of diesel units, 4$^{th}$ column highlights number of 100 kW wind turbines considered in a particular case, 5$^{th}$ column highlights number of 120 kW diesel units considered in a particular case, 6$^{th}$ column highlights number of 55 kW diesel units considered in a particular case, 7$^{th}$ column indicates the total capital cost ($) of a given hybrid system, 8th column indicates the total net present cost (NPC, $) of a given hybrid system, 9th column shows cost of generation (COE, $/kWh) of 1 kWh of energy, 10th column indicates the renewable energy fraction (% of wind) in a given hybrid system, 11th column shows the diesel fuel consumption (in liters) in a given hybrid system, 12th-13th columns indicate the operational hours of the two diesel units (D120 or 120 kW and D55 or 55 kW) in a given hybrid system.

| | | | Nw100 | D120 [kW] | D55 [kW] | Total capital | Total NPC | COE [$kW$^{-1}$h$^{-1}$] | Ren. frac. | Diesel [L] | D120 [h] | D55 [h] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| | | | | 120 | 55 | $ 46,000 | $ 838,110 | 0.087 | 0.00 | 228,024 | 6,801 | 2,534 |
| | | | 1 | 120 | 55 | $ 296,000 | $ 1,161,463 | 0.121 | 0.25 | 186,197 | 5,731 | 3,298 |
| | | | 2 | 120 | 55 | $ 546,000 | $1,506,335 | 0.156 | 0.45 | 160,279 | 4,831 | 3,713 |
| | | | 3 | 120 | 55 | $ 796,000 | $ 1,862,761 | 0.193 | 0.58 | 141,955 | 4,244 | 3,650 |
| | | | 4 | 120 | 55 | $ 1,046,000 | $ 2,235,814 | 0.232 | 0.67 | 129,130 | 3,850 | 3,527 |
| | | | 5 | 120 | 55 | $ 1,296,000 | $ 2,615,058 | 0.272 | 0.74 | 118,571 | 3,502 | 3,413 |
| | | | 6 | 120 | 55 | $ 1,546,000 | $ 3,003,859 | 0.312 | 0.78 | 110,505 | 3,245 | 3,306 |

**Figure 8. Technical and economic parameters of wind-diesel systems (at 37 m hub-height)**

It can be noticed from the results (fig. 8) that in general, the wind penetration (renewable energy fraction, column 10) has varied from 0 to 78%. In an isolated system, renewable energy contribution of 78% is considered to be high. Such a system might be very difficult to control while maintaining a stable voltage/frequency. It can be noticed that as wind fraction (number of wind machines, column 4) increases, the cost of energy (9th column) increases, diesel fuel consumption (11th column) decreases, and operation hours of the diesel units (12th-13th columns) decrease. The level of wind penetration in hybrid wind-diesel systems (deployed around the world) is generally in the range of 11 to 25% [41]. A trade-off need to be established between different feasible options. To consolidate, the COE from a hybrid wind-diesel system (100 kW wind capacity together with 175 kW diesel system, 37 m hub height, for given wind-regime/load data of 1997, 0% annual capacity shortage) with 25% wind penetration has been found to be is 0.121 US$/kWh as shown in fig. 8. It can be depicted from fig. 8, that COE increases with increase in penetration of wind.

In general, the total operational hours/time of diesel system (*i. e.* sum of operational hours of diesel unit # 1 and diesel unit # 2) decrease with increase in renewable energy fraction or wind farm capacity . It is also evident from fig. 8 that as penetration of wind increases, the diesel engine operation time decreases (which eventually reduces emission of green house gases in the atmosphere). It is worth mentioning that for diesel-only situation, the operational hours of the two diesel units are 6801 and 2534, respectively. However, for wind-diesel hybrid system (100 kW wind machine, 175 kW diesel system, for a given hub-height of 37 mm, 0% annual capacity shortage, as shown in fig. 8), the operational hours of the two diesel units are 5731 and 3298, respectively. This clearly reflects that operational hours of the bigger diesel generator (D1, 120 kW) of hybrid wind-diesel (25% wind penetration) system decrease by 16% as compared to diesel-only (zero % wind energy) situation. This indicates that with introduction of wind machines, load on the first diesel generator has decreased substantially.

For a given hub-height of 37 m and for a given wind farm capacity of 100 kW (together with 175 kW diesel system), the information related to energy generated by wind and diesel systems, excess electricity, un-met load [kWh], capacity shortage [kWh] and the cost breakdown of wind-diesel power systems is presented in figs. 9 and 10. It can be seen from fig. 9 that with the above system configuration, un-met load is zero kWh, capacity shortage is zero kWh per year and excess energy generated is about 4%. It should be mentioned over here, that this excess energy produced goes un-used due to lack of demand (there are ways and means to utilize excess energy, sometimes it is fed to some dump load). Figure 9 indicates that monthly average wind-diesel generated power is high during summer months (May-August) as compared to other months. This is a favorable characteristic because the load is higher during summer months. HOMER hybrid model indicates that the total initial capital cost of the hybrid system (100 kW wind machine, 175 kW diesel system, 37 m hub-height) is US$ 296,000 while the net present cost (NPC) is US$ 1,161,702 (figs. 9 and 10). It can be noticed from (fig. 10) that the initial capital cost of WECS is about 76% of the total initial capital cost. This highlights that cost of wind turbines in hybrid system is predominant. Regarding operation and maintenance cost of WECS, it is about 12% of the total O & M + fuel cost, whereas the O & M + fuel cost of the diesel system is about 88%.

The percentage of fuel savings by using hybrid system (100 kW wind machine, 175 kW diesel system, for 37 m hub height) as compared to the diesel only case is about 14% as shown in fig. 8. Moreover, percentage fuel savings increase by increasing the wind farm capacity. The diesel fuel savings may only be quantifiable by means of justifying the additional capital expenditure invested in WECS. It has also been observed that the carbon emissions for diesel-only situation are 165 tons per year. However, with wind-diesel hybrid system (175 kW diesel, 100 kW WECS, 37 m hub-height) the carbon emissions are 135 tons per year (fig. 9). This reflects that the percentage

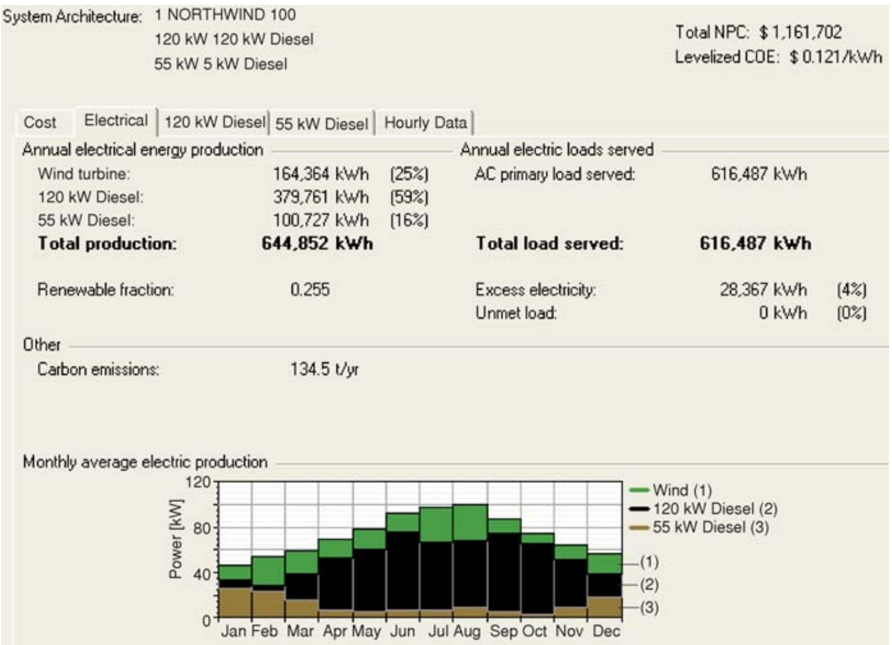
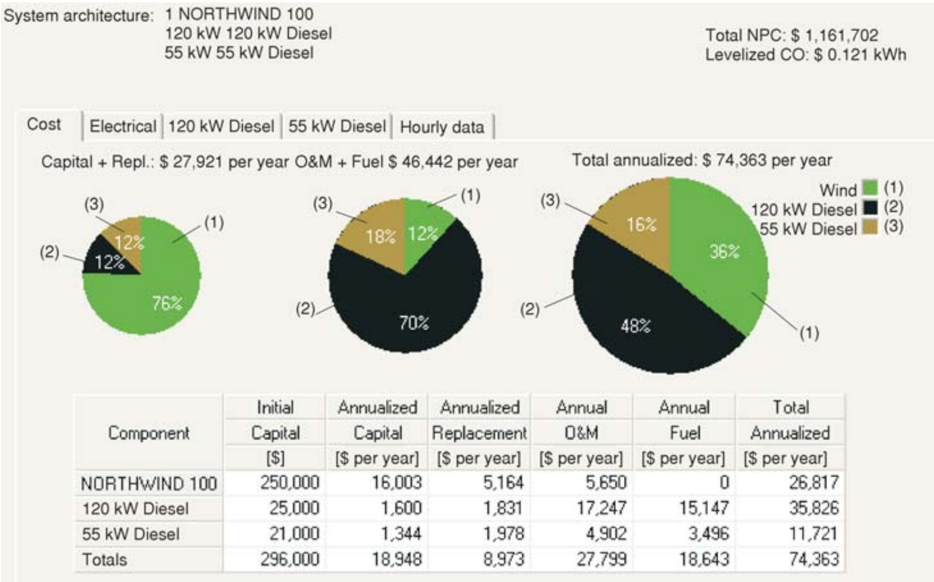



**Figure 9. Power generated wind and diesel systems at 37 m hub-height**




| Component | Initial Capital [$] | Annualized Capital [$ per year] | Annualized Replacement [$ per year] | Annual O&M [$ per year] | Annual Fuel [$ per year] | Total Annualized [$ per year] |
|---|---|---|---|---|---|---|
| NORTHWIND 100 | 250,000 | 16,003 | 5,164 | 5,650 | 0 | 26,817 |
| 120 kW Diesel | 25,000 | 1,600 | 1,831 | 17,247 | 15,147 | 35,826 |
| 55 kW Diesel | 21,000 | 1,344 | 1,978 | 4,902 | 3,496 | 11,721 |
| Totals | 296,000 | 18,948 | 8,973 | 27,799 | 18,643 | 74,363 |

**Figure 10. Cost of wind and diesel power systems at 37 m hub-height**
(for color image see journal web site)

decrease in carbon emissions with 25% wind penetration is about 18% as compared to diesel-only case. The effect of wind penetration on operational hours of diesel generators, diesel fuel consumption, carbon emissions, COE, excess energy is demonstrated more explicitly in figs. 11 to 13.

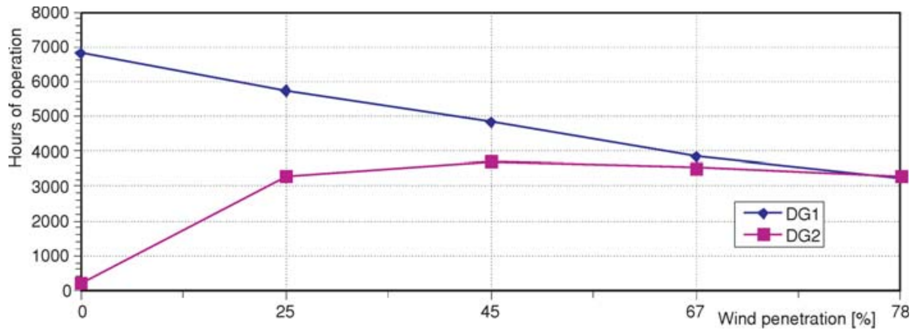



**Figure 11. Impact of wind penetration on diesel engine operation time**

Attempt has also been made to perform the sensitivity analysis on average wind speed and diesel price using HOMER. The wind speed was allowed to vary from 4.0 to 8.0 m/s and the diesel price was varied from 0.1 to 2.0 $/L. The chart of sensitivity analysis is demonstrated in fig. 14. This analysis examines the effect of fluctuations in external factors (such as: fuel price, wind speed) on the system design. This figure is a concise representation of a great deal of computations. The diamonds correspond to the points were HOMER actually solved for the optimal system. It is evident in fig. 14, that for a given wind speed of 5 m/s, the wind-diesel system starts becoming optimal for diesel fuel price greater than 0.42 $/liter.

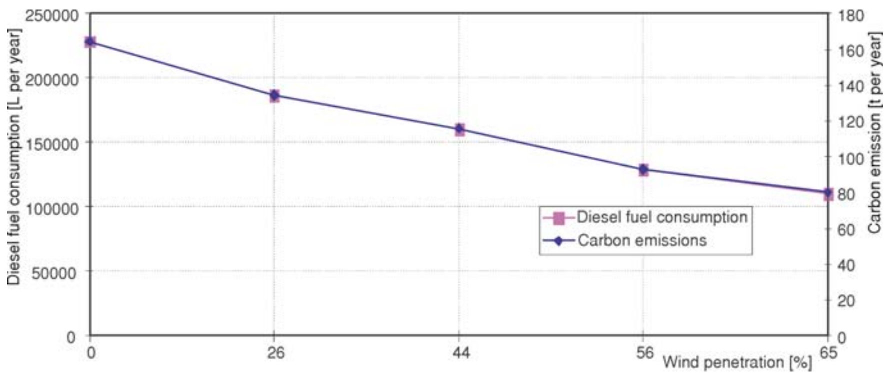



**Figure 12. Impact of wind penetration on diesel fuel consumption and carbon missions (for 37 mm hub-height)**

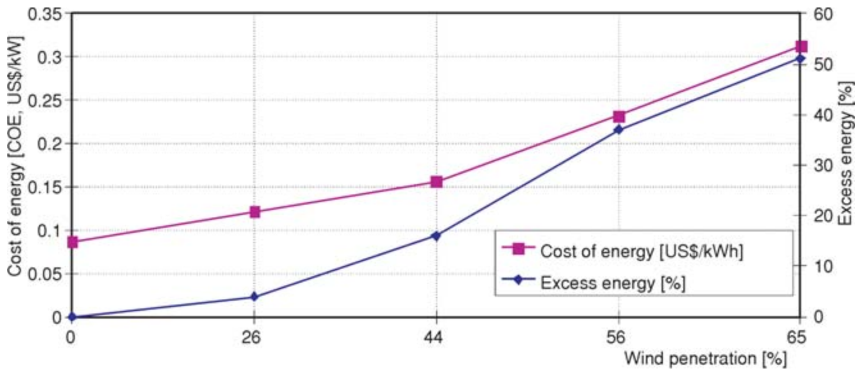



**Figure 13. Impact of wind penetration on COE and excess energy generated (at 37 m hub-heigh)**

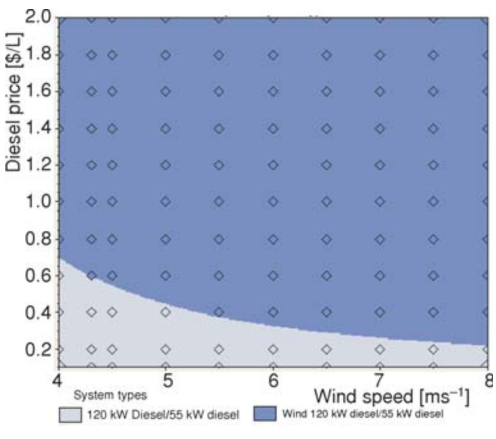



**Figure 14. Sensitivity analysis results of hybrid wind-diesel power systems**

## Conclusions and recommendations

The present study has discussed in appreciable depth the economic feasibility of utilizing hybrid wind-diesel power systems to meet the electricity requirements of a typical commercial buildings (with annual electrical energy demand of 620,000 kWh) of Saudi Arabia. Specifically, the merit of hybrid wind-diesel system has been evaluated in broader perspective with regards to its size, operational requirement, cost, *etc*.

The study indicates that for a hybrid system comprising of 100 kW wind capacity together with 175 kW diesel system (D1:120 kW, D2: 55 kW), the wind penetration (at 37 m hub-height, with 0% annual capacity shortage) is 25%. The cost of generating energy (COE) from this hybrid wind-diesel system has been found to be 0.121 $/kWh (assuming diesel fuel price of 0.1$/liter). The total net present cost of the above hybrid system has been found to be US$ 1,161,702. Also for this configuration, the un-met load is zero kWh. The percentage fuel savings by using the above hybrid system has been found to be about 14% relative to diesel-only situation. Additionally, the percentage reduction in carbon emissions is about 18% relative to zero % wind-energy case. The study also indicates that the operational hours of diesel generators decrease with increase in wind farm capacity.

From cost of energy point of view, the cheapest is the diesel only system, but the purpose of the study has been to find optimum configuration that provides the lowest cost of energy using renewable energy.

The present work shows that a fraction of Saudi Arabia's energy demand may be harnessed from wind systems. Also investments in mobilization of wind systems may stimulate the local economy (in a long-run) by exploitation of available local resources. The observations of this work can be employed as a reference/platform/benchmark to carry out economic feasibility of hybrid wind-diesel power systems for other locations having similar climatic/load conditions.

## Acknowledgment

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