Evaluation of Optimal Hybrid Distributed Generation Systems for an Isolated Rural Settlement in Masirah Island, Oman

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ABSTRACT

This paper summarizes the findings from a study that has been conducted to evaluate the feasibility of using renewable energy sources such as solar and wind in combination with the conventional power system; diesel systems in an isolated island of Masirah in Oman. The study has been conducted to determine the best sustainable generation system to meet the electrical load requirements for a small community of 500 residential buildings. A series of a simulation analyses have carried out to assess different distribution technologies including photovoltaics, wind and diesel for electrical generation in combination with storage batteries. It was found that the cost of energy could be reduced by as much as 48% compared to the cost under the idealized design currently used in the Masirah Island (i.e. Diesel Driven Generators). In particular, it was found that wind turbines in combination with storage batteries have a great impact in reducing the cost of generating electrical energy for the residential community. Moreover, solar PV panels were found unattractive at the current diesel price rates but could potentially become viable if the diesel prices increase. The paper outlines an optimal design for generating electricity for the community at lowest cost while minimizing carbon emissions. Other two options are also proposed to ensure a neutral carbon emission community with a cost of energy generation still more competitive than that of the currently used diesel generation system.

KEYWORDS: Cost of Energy, Hybrid Distributed Generation, Isolated communities, Renewable Energy

INTRODUCTION

Distributed electrical generation using renewable energy alone or in combinations with other conventional systems became a viable option for many isolated communities in the world. The benefits are many to governments, communities, or individuals such as the reduced cost of energy, sustainable communities, increase the reliability and diversity of energy sources. Many countries including fossil fuel rich countries are investigating the use of renewable energy to produce power for isolated rural communities. Oman looked into these potential in mid 90s when the Ministry of Water Resources installed an experimental 10 kW BWC Excel wind turbine at a remote agricultural research station in south of Oman where high wind potential was apparent [1]. In addition, 64 solar panels were installed in this site for the operation of desalination plant. Another study for the same site was conducted to analyze the potential of using 50 kW wind turbine in combination with diesel generators to produce electricity [2]. It was found that the cost of energy of wind turbine alone ranges from $ 0.074- 0.0845/kWh while the cost of energy from diesel generators are 1.7- 1.8 higher than those of wind turbine. Therefore, it was recommended to install a hybrid (wind/diesel) power system for this location. For a new city of Duqm which is located in the Middle region of Oman, a study has recommended to use a 5 wind turbines rated at 1.8 MW [3]. The cost of electricity was found to be $0.05 and $0.08 per kWh for discount rates of 5% and 10%, respectively. Although this value is higher than the existing COE (about $0.024 per kWh for this site for Gas power stations) in Oman, it was found that the wind turbines is sensitive to cost of gas and consequently attractive at higher gas price. Three studies have been conducted for Masirah Island to evaluate the feasibility of hybrid power system to meet the current power demand. Two studies have investigated wind/diesel power systems [4,5]. The third study has investigated a PV/diesel power system [6]. None of these studies have investigated the impact of new added settlement to the existing power systems except one evaluated the island for a marginal increase of power demand [6]. According to Al-Ismaily et al. [4], the cost of energy was found to be $ 0.123/kWh for 8 wind turbines rated at 100 kW and 7 diesel generators with total capacity of 5,461 kW at a diesel price of $ 0.48/L. Taking into account the economic and environmental benefits, Qian et al. [7] found that the cost of energy out of 10 wind turbines rated at 900 kW is $ 0.060/kWh compared to

$0.26/kWh for diesel base electrical generators when price of diesel is $ 0.53/L. On other hand, Bourdoucen et. al. [6] has studied the coupling of the existing 10 diesel generators at a diesel price of $ 0.468/L and a 2 MW PV station at a cost of $ 3/W with back up batteries (2000 kWh, 4000 kWh, 5000 kWh storage capacity) to cover the expected marginal increase of electrical load in the island. It was found that the 2 MW PV system with 5000 kWh storage capacity can give 1% excess electricity to the existing system.

Although the feasibility of hybrid power systems depends on many factors that are country or site dependent, literature has shown that even in countries with low diesel cost and high solar radiation or relatively similar to those in Oman, the cost of energy for a hybrid power system is high. For example, a study of a site (global solar radiation 5.839 kWh/m^2) in Saudi Arabia has found that the cost of energy is $ 0.179/kWh for a hybrid power system consisting of 4 kW PV system coupled with a diesel generator rated at 10 kW (diesel cost of $ 0.1/L) and a battery storage [8]. Another study in Saudi Arabia investigated the feasibility of using wind turbines combined with existing diesel generators for a remote village [9]. It was found that the existing power system is economically more feasible than when it is combined with a wind turbine option. The wind turbine option was only feasible under a wind speed of more than 6 m/s and a diesel price of more than $ 0.1/L. The thermal performance of hybrid (wind/solar/diesel) power systems in Saudi Arabia has been characterized by Elhadidy [10]. It was observed that the wind farm with a rated power close to peak load gives the best wind energy utilization factor. On the other hand, it was found that increasing the PV capacity yields a small decrease in diesel generated energy which makes the PV economically unfeasible for this village.

OBJECTIVES

Omani government has an economical vision to develop many remote areas by promoting new investments. Masirah Island is an example of those remote rural areas in Oman that has the government attention. To develop this area further, additional infrastructure such as expanding the power station capacity is important to meet any future demand. This could be done either by installing more diesel powered generators or by using potential distributed generation techniques.

Therefore, the objectives of this study are twofold:

1. Evaluate the economic feasibility of using different (diesel/wind/solar) power generations systems to produce electricity for a new rural settlement in Masirah Island.

2. Define those that have optimal economic benefits and propose a hybrid power system for this settlement.

LOCATION AND ELECTRICAL LOAD

Location

Masirah is an isolated island in the eastern side of Oman at Arabian Sea as shown in Figure 1. The Supreme Committee for Town Planning in Oman is responsible for town planning with coordination of the Min-

Figure 1. Map of Oman and Location of Masirah Island

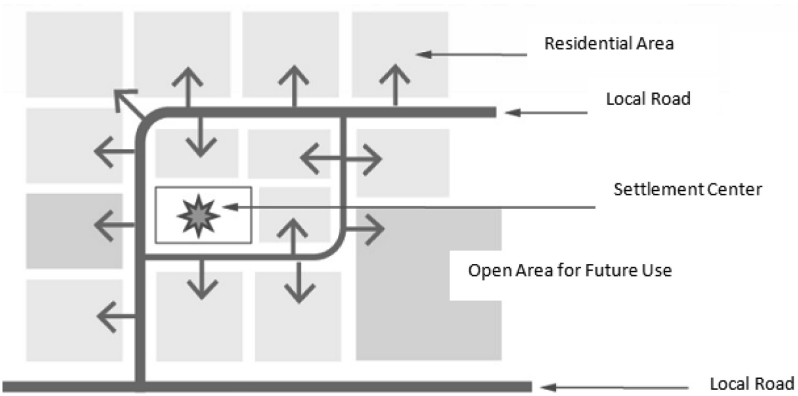

Figure 2. Typical Planning of a new Settlement in Oman [6]

istry of Housing in Oman. A typical new settlement as per the Omani town planning guidelines is shown in Figure 2 [11]. The typical new settlement is composed of 500 plots representing 50 plots per residential area in a total of 10 residential areas blocks. Therefore, a typical settlement in Masirah Island is as that per the guideline and are distributed to locals. Many of these plots are not with basic infrastructure and it might take years before the community is connected to utilities.

Power System and Electrical Load

At present, all electric power demand at Masirah Island is met by ten diesel powered generators located at a central power station. The individual generator power rating ranges from 265 to 3,136 kW with a total site power capacity of 8,478 kW as per Table 1 [6]. The power system for Masirah Island consists of 54% residential load demands, 40%

Table 1. Rated Power Capacity of Diesel Generators

Engine No.	Engine Ref.	Engine Rated Capacity(KW)	Engine Site Capacity (KW)
G1	MBS	265	212
G2	MBS	265	212
G3	MBS	265	212
G4	MBS	265	212
G5	MBS	265	212
G6	KHD	3136	2509
G7	KHD	3136	2509
G8	Caterpillar	1000	800
G9	Caterpillar	1000	800
G10	Cummins	1000	800

commercial and governmental usage and 6% industrial loads [2]. The electrical load in Masirah Island for a typical year is shown in Figure 3 [12]. In particular, Figure 3 shows that the peak power demand is around 7 MW and an excess of 1.4 MW is available.

Although, there is no data on the electrical load for this additional community, an hourly energy simulation program was utilized to generate the electrical load for one typical building and project the energy demand for the whole community [13]. A typical residential building is assumed to be representative of similar Omani construction practice [14]. Figure 4 shows the daily average electrical load for 500 residential buildings in this community. It is clear that the daily average peak electrical load could reach 16 MW in May. The monsoon season starts

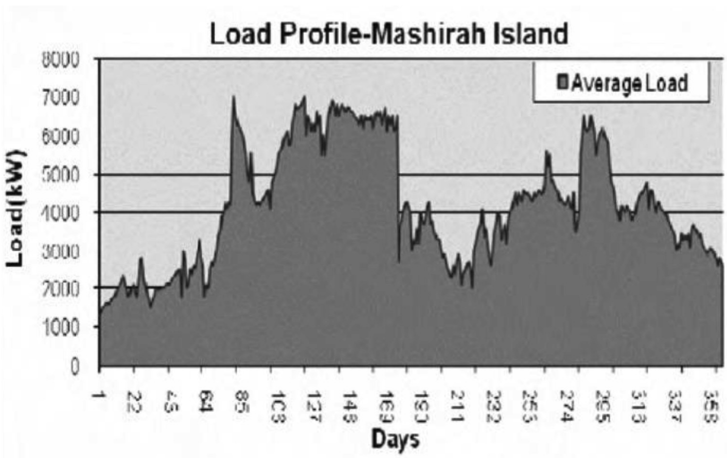

Figure 3. Annual electric load demand for Masirah Island [7]

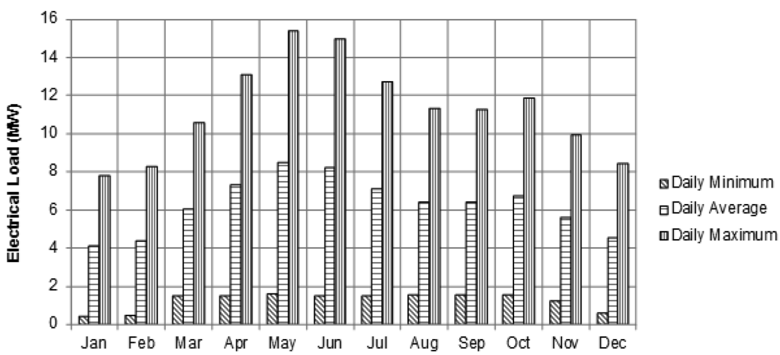

Figure 4. Monthly Electrical Load for 500 Residential Buildings

in July and ends in September which reduces the cooling load and subsequently the overall electrical load.

In light of the above results, the total electrical load in the island will increase from the current load at 7 MW to more than 23 MW in the future which wouldn't be met by the current 8.5 MW maximum capacity of the diesel generators. Therefore, either additional diesel generators are added or other source of power generation is sought.

ENERGY RESOURCES AND ELECTRICAL PRICES IN OMAN

Energy Resources

Oman has limited fossil fuel resources compared to other GCC countries in the region. Oman exports more than 90% of its oil production with the remaining used domestically and exports 40% of its gas production [5]. In Oman, gas is the main source fuel for the majority of power stations while others are running by diesel especially those in rural area. Due to its low fossil fuel reserves and its long term obligations for gas export, Oman now is looking for alternatives such as coal gasification power stations. However, Oman lies on solar belt and with strong wind during the summer due to the monsoon season, renewable energy has a high potential to generate electricity in this peak season. Studies have been conducted to evaluate the climatic data of Oman for different purposes including the potential to generate electricity [14-16].

Masirah is an isolated and remote island located in Arabian Sea about 15-20 km from the main land which is either accessed through sea or by air. Therefore, all products including fossil fuels (i.e. diesel) used for power generation are transported by trucks and then on ships to the island. This raises the cost of transportation and subsequently the cost of electricity. Despite the abundant renewable energy resources such as wind and solar in this island, still there is no utilization of this free energy. Recent studies have indicated that the wind speed and consequently the wind power are among the highest in Oman with very low variations between the minimum and maximum [15]. Figure 5 shows the average wind speed for Masirah for year 2006 [5]. It is clear that the wind highest speed is in summer months during the monsoon season.

Solar radiation for this island was also analyzed for solar desalination project and was averaged for three years; 1988, 1989 and 1990 [7,

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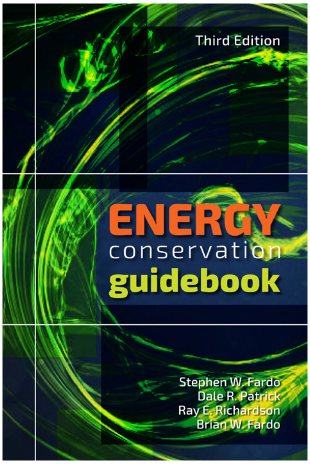

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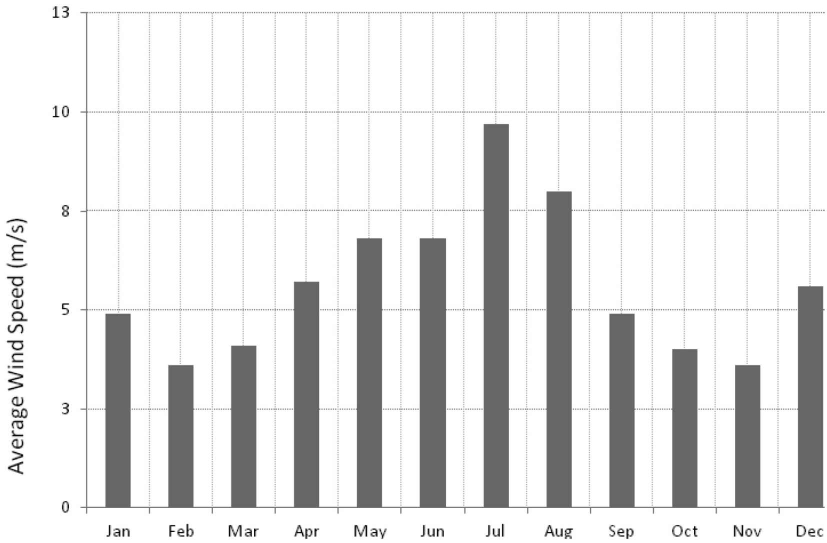

Figure 5. Measured Monthly Average Wind Speed for Masirah for Year 2006

Table 2. Solar Radiation data for Masirah Island

Month	Average Monthly Global Solar Radiation on Horizantal Surface (kWh/m²)
Jan	3.99
Feb	4.27
Mar	5.54
Apr	6.09
May	6.80
Jun	6.23
Jul	5.40
Aug	5.45
Sep	5.34
Oct	4.86
Nov	4.14
Dec	3.61

15]. Table 2 shows that the direct solar radiation peaks in May which coincides with peak electrical demand in the island.

Electricity Prices

Electrical cost in Oman is largely subsidized by the government. The price of gas from Ministry of Oil and Gas resources is 1.5 USD/MMBtu for all power generators compared to international market price of more than 3 USD/MMBtu and the price of diesel is $ 0.38/L [15].

However, the actual cost of diesel for rural areas such as Masirah Island is $ 0.468/L [6]. In addition, the government of Oman subsidizes the cost of electricity to the end users. For example in rural areas, the average cost of electricity in 2008 is $ 0.248/kWh where the government has to subsidize this value by 83% and the final electrical cost to residential users is $ 0.042/kWh [12].

BASE CASE SCENARION OF POWER SYSTEM

For any renewable energy project to be attractive to Omani government in rural areas, the price of electricity should be below $ 0.2/kWh, the value that is paid currently as subsides. The base case design proposed for Masirah Island is shown in Figure 6. The base case cost assumptions are listed in Table 3. Table 4 shows the search domain that describes the different design options to be considered for the design of optimal hybrid power system. In this study, Homer simulation tool is used to design the hybrid power system for the residential settlement [17]. Two types of wind turbines were used for this site; the GE 1.5 rated at 1.5 MW and Vestas V82 rated at 1.65 MW.

ANALYSIS OF RESULTS

Base Case Results

The base case design with many variables was totaled 18,200 alternatives. Table 5 shows that the total net present cost of the optimum

Table 3. Base Case Cost Assumptions

	Capital Cost ($/kW)	O & M Cost ($/year)	Replacement Cost ($)
PV	4000	22.5	2000
Wind Turbines	2000	57	2000
Diesel Generator	780	224	500
Storage Batteries (S4KS25P)	300		300
Converter	350		350
Economic	Project Life Time (years)	25	
	Interest Rate (%)	7.5	
Diesel Fuel Cost	$ 0.468/L		

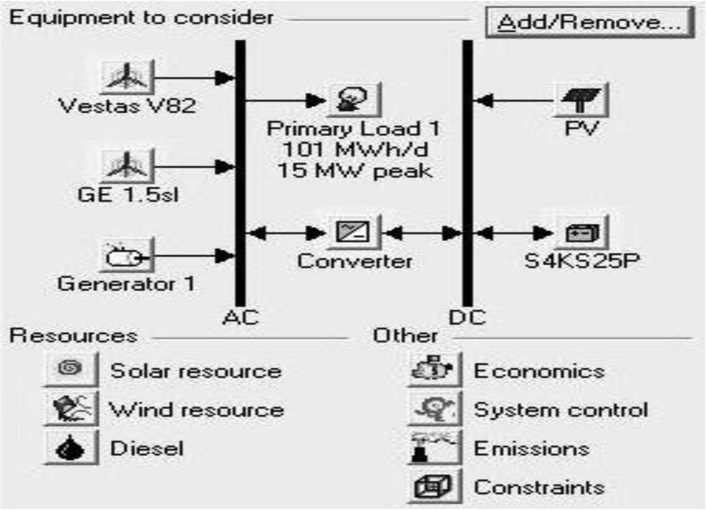

Figure 6. Base Case Hybrid Power System for Masirah Island

Table 4. Search Domain for Homer Design Optimization

PV Array (kW)	V82 (Quantity)	1.5sl (Quantity)	Deisel Generator (kW)	S4KS25P (Strings)	Converter (kW)
0	0	0	0	0	0
100	2	2	265	50	10000
500	3	3	1000	100	15000
5000	5	5	3000	150	
10000	10	10	4000	200	
15000	15	15	5000	250	
20000	20	20	6000	300	
25000	25	30	7000	500	
30000		40	8000	1000	
			9000	1500	
			10000	2500	
			15000		

design is 60 Mill USD and cost of energy is $ 0.154/kWh. This option utilizes 5 wind turbines (total capacity 8 MW), 3 MW Diesel generator, 10,000 S4KS25P storage batteries and 10 MW convertor. The total renewable utilization is 67%. If only diesel generators are only to be used (Case#9), the COE is $ 0.273/kWh. Since the cost of energy to end users is limited to $0.042/kWh, the government has to subsidize this by

$ 0.231/kWh (i.e. 85% subside). However, with the optimized design (i.e. Case#1), the government will only subsidize this by $ 0.112/kWh which is a cost saving of more than 48.5% per kWh produced compared to the diesel only design. It is interesting to note that it is possible to solely depend on renewable energy to supply electricity to this settlement but at a higher COE compared to the optimum design but still below than the current system. For example, Case#5 is using 15 Vestas wind turbines (V82; 24.75 MW), 500 kW PV with storage batteries and COE is $ 0.181/kWh while Case#6 is for 15 GE (1.5 sl: 22.5 MW) but with high storage batteries and the COE is $ 0.180/kWh.

SENSITIVITY ANALYSIS

Wind Speed and Cost of Wind Turbine

A sensitivity analysis was performed for the optimized design: wind turbines, diesel generator and the storage batteries for wind speed and wind turbine capital cost. The wind speed was varied from 0 to 12 m/s (base case is 5.77 m/s vertical dash line) with interest rate varied from 5 to 10% (base case is 7.5%) as shown in Figure 7. It is clear that this option is very attractive even at lower wind speed (up to 4 m/s) and at higher interest rate compared to the ideal power system (i.e. diesel option only). The minimum cost of energy achieved is at a wind speed of 9 m/s after which the COE starts to pick up because of the power curve of these wind turbines.

The capital cost of wind turbines (multipliers) was varied from 0.4 to 1.6 to evaluate the impact of wind turbine costs on the cost of energy at different interest rate as shown in Figure 8. The cost of energy drops as the cost of the wind turbine reduces. In addition, the cost of energy for this optimized design does not cross the cost of energy for the diesel option even at higher interest rate which further supports the feasibility of this hybrid design.

Solar Radiation and Cost of PV

For the optimal design, the wind turbine was deleted and PV was added at higher power rate. Subsequently, the new design will be the diesel generators with PV and batteries. The solar radiation was varied from 3 to 12 kWh/m^2/day with a base case for this site set to be 5.15 kWh/m^2/day (vertical dash line) as shown in Figure 9. For this option

Table 5. Optimized Designs for Masirah Island

Case #	PV (kW)	V82	1.5sl	DG (kW)	S4KS25P	Converter (kW)	Initial capital	Operating cost ($/yr)	Total NPC	COE ($/kWh)	Renewable fraction	Capacity shortage	Diesel (L)	DG (hrs)
1		**5**		**3,000**	**10,000**	**10,000**	**27,340,000**	**2,923,319**	**59,926,072**	**0.154**	**0.67**	**0.08**	**5,066,110**	**5833**
2			**10**	**5,000**			**33,900,000**	**2,364,652**	**60,258,648**	**0.155**	**0.82**	**0.08**	**4,635,643**	**4188**
3	**100**	**5**		**3,000**	**10,000**	**10,000**	**27,740,000**	**2,922,302**	**60,314,740**	**0.155**	**0.67**	**0.08**	**5,049,832**	**5827**
4	100		10	5,000		10,000	37,800,000	2,545,830	66,178,228	0.17	0.82	0.08	4,623,271	4176
5	500	15			15,000	10,000	62,500,000	515,646	68,247,872	0.181	1	0.10		
6			15		25,000	10,000	61,000,000	681,619	68,597,968	0.18	1	0.09		
7				5,000	10,000	10,000	12,400,000	6,863,074	88,902,304	0.232	0	0.1	12,874,720	7919
8	100			5,000	15,000	10,000	15,300,000	6,916,092	92,393,296	0.24	0	0.09	12,877,375	7805
9				10,000			7,800,000	8,965,775	107,741,000	0.273	0	0.07	17,178,086	8760
10	100			10,000		10,000	11,700,000	9,151,807	113,714,696	0.288	0	0.07	17,174,670	8760

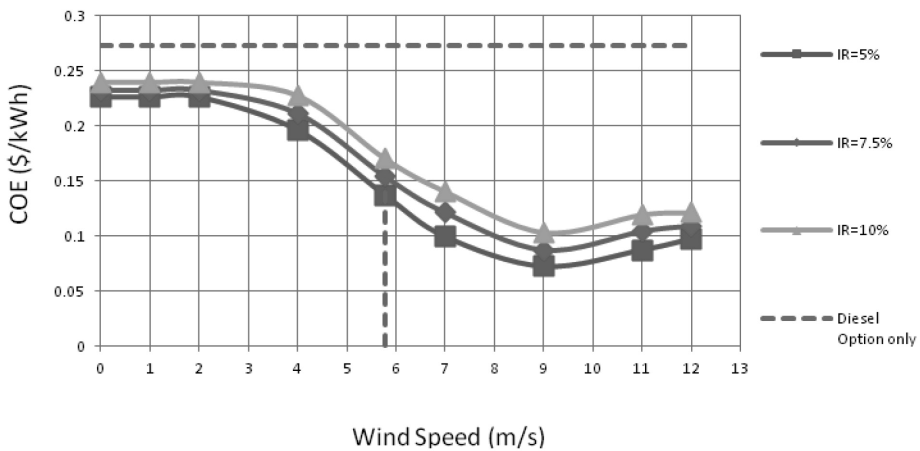

Figure 7. Sensitivity Analysis of Wind speed with COE at Various Interest Rates

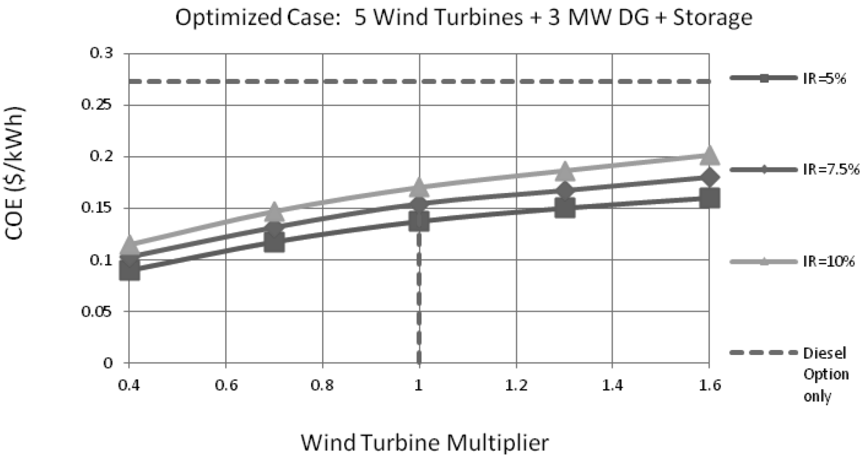

Figure 8. Sensitivity Analysis of Wind Cost Multipliers with COE at Various Interest Rates

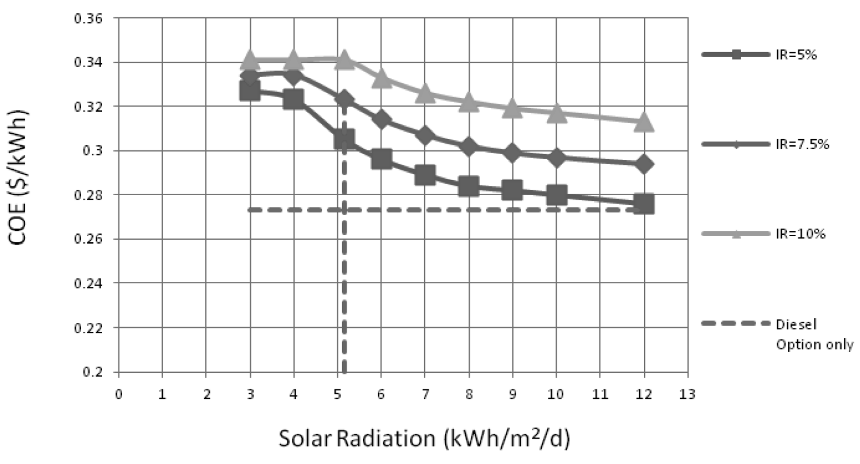

Figure 9. Sensitivity Analysis of Solar Radiation with COE at Various Interest Rates

to be attractive, the COE has to be the difference between the COE for the diesel option ($0.273/kWh for this case) and fixed customer tariffs ($0.042/kWh). Therefore, the COE has to be below $ 0.23/kWh to be attractive. From this figure, the COE will not drop below this threshold unless the interest rate is dropped to 5% and the solar radiation has to be more than the current base case.

The cost multiplier of PV was then varied from 0.4 to 1.6 with different rate of interest as shown in Figure 10. The PV with diesel generators and batteries will be only attractive when the cost of PV dropped by 60% of the current value at 7.5%. However, at lower interest rate the PV becomes more attractive than the 7.5%. At higher interest rate, the COE for this option will not go above the diesel option.

Sensitivity Analysis of Combination of Wind Speed/Solar Radiation and Diesel Prices on the COE

A sensitivity analysis was done for the diesel prices, solar radiation and wind speed. A total of 120 parameters and 432,000 different designs were evaluated. Figure 11 shows the variation of diesel prices with the wind speed. This figure corresponds to the case when the average yearly solar radiation is kept at the base case of 5.15 kWh/m^2/day. For any design to be attractive to the government, the COE should be less than what it will be paying for subsidize if diesel generators are used (i.e. $ 0.273/kWh). Figure 11 shows that the power system could be run 100% on renewable (i.e. wind turbines) if the wind speed is greater than 7 m/s. The PV systems will be attractive if wind speed is less than 2.5 m/s and diesel price is more than $0.57/L. It is also noticed that the storage batteries are sensitive and not attractive when the wind speed is above 6.0-7.0 m/s. The wind turbines in all cases are very attractive except when the wind speed falls below 2.5 m/s. It is observed that the 100% renewable can be achieved with wind turbines and batteries provided that the wind speed is above 6.5 m/s. However, as the prices

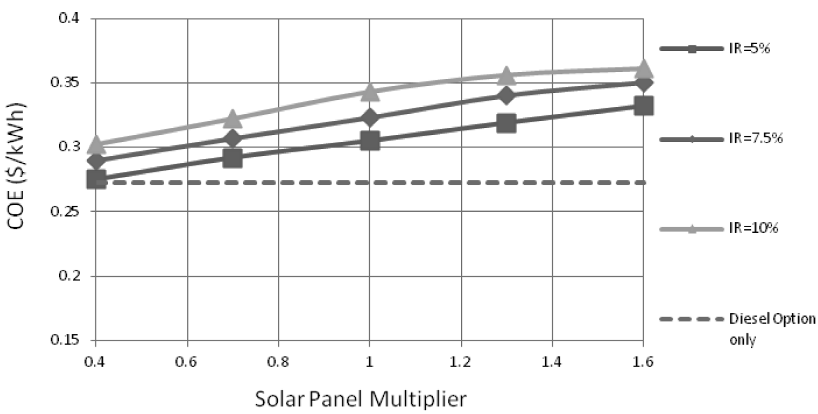

Figure 10. Sensitivity Analysis of Panel Cost Multiplier with COE at Various Interest Rates

of diesel drops below the current value the potential to use 100 % wind decreases and will be valuable at higher wind speed. For example, if the diesel price falls below $ 0.35/L, 100% wind turbine will be achieved at a wind speed of more than 8.0 m/s.

Figure 12 shows that variation of solar radiation with wind speed at constant diesel price of $ 0.468/L. At this current diesel price, PV systems will be attractive if solar radiation is above 6.8 kWh/m^2/d and wind speed is less than 3.0 m/s. It is noticed that the settlement can be run on 100% renewable resource (wind turbine) with batteries when the wind speed is above 7.0 m/s. The batteries are not attractive in wind speed range 6.0-6.9 m/s because the wind energy can be utilized directly. Figure 13 shows that variation of solar radiation with diesel prices when the wind speed is fixed. It is clear that the PV could be potentially attractive when the diesel prices are above $ 0.65/L.

OPTIMIZATION ANALYSIS

In order to propose a hybrid design that has a lower cost of energy compared to the ideal design option (i.e. diesel system), an optimization

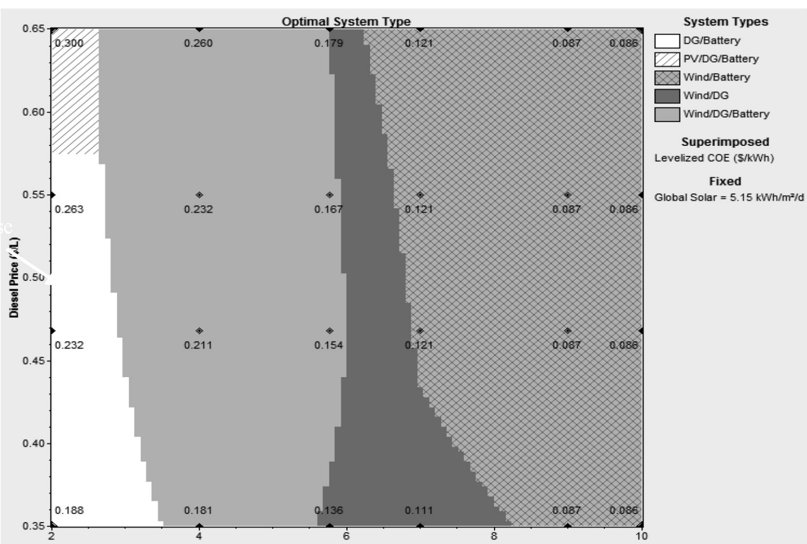

Figure 11. Sensitivity Analysis of Wind Speed and Diesel prices at fixed solar radiation

approach was performed and the results are shown in Figure 14. The main objective of this optimization is to find the design that has a lowest COE and maximum reduction of carbon emissions. For this analysis, the carbon contents of fuels are the defaults of Homer. The COE of energy

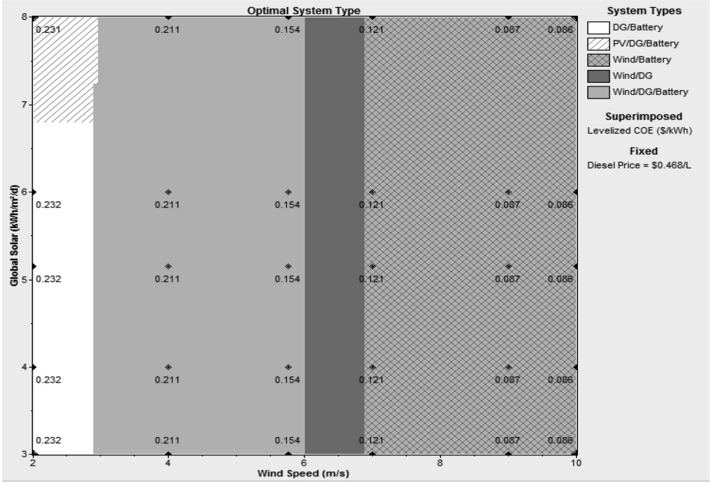

Figure 12. Sensitivity Analysis of Wind Speed and Global Solar Radiation at Constant Diesel Prices

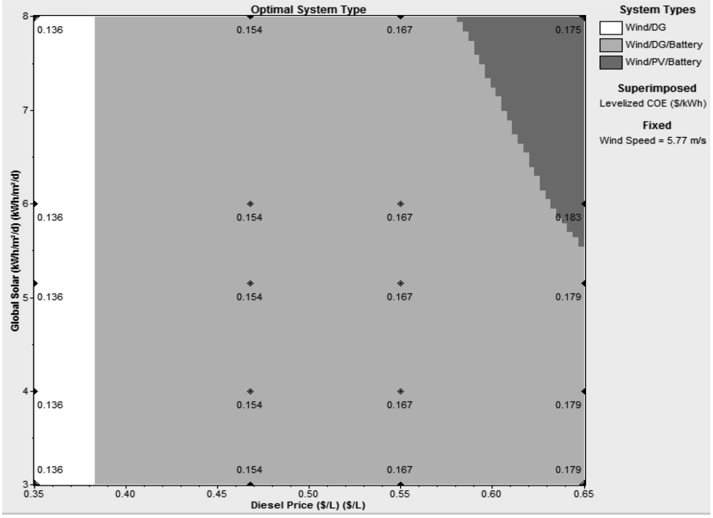

Figure 13. Sensitivity Analysis of Global Solar radiation and Diesel Prices at Fixed Wind Speed

for the diesel option design is \$ 0.273/kWh and the customer has to pay a fixed tariff of \$ 0.042/kWh with the remaining (\$ 0.23/kWh) to be paid by the government as subsides.

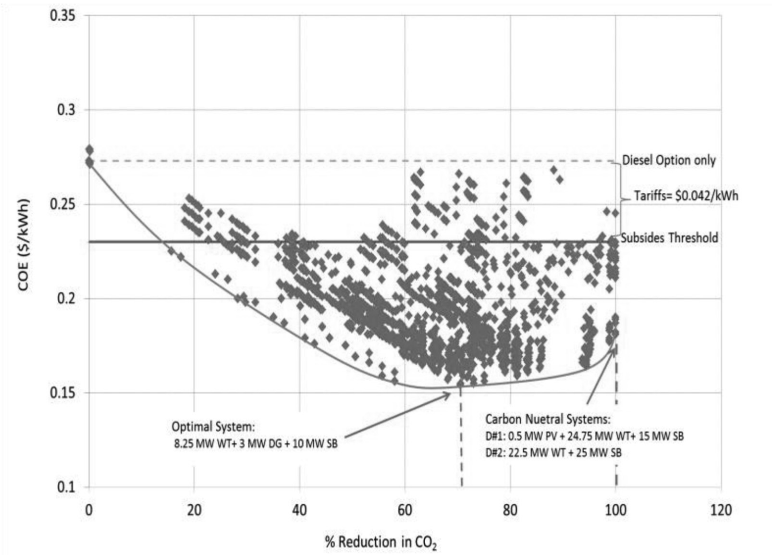

Figure 14. Optimum Designs for lowest COE and Maximum Carbone Reduction

Figure 14 shows that there are many designs that could be attractive to the government to reduce its subsidies. In other word, many designs are qualified to be considered as alternatives for current ideal design. However, it was found that the optimum design is 5 V82 (8.25 MW) wind turbines, 3 MW diesel generator and 10 MW storage batteries. The COE for this optimal design is \$ 0.154/kWh where the government has to pay \$ 0.112/kWh which is a 48.5% reduction from the value that is paid when diesel systems are used. However, if the government wants to go for neutral carbon design where the reduction of carbon is 100%, then there are two optimal designs:

Option#1: 0.5 MW of PV, 24.75 MW Wind Turbine and 15 MW Storage Batteries (COE \$0.181/kWh)

Option#2: 22.5 MW Wind Turbine and 25 MW Storage Batteries (COE \$0.18/kWh)

SUMMARY AND CONCLUSIONS

A typical settlement consists of 500 new residential buildings in Masirah Island was simulated using detailed whole-building modeling tool to estimate the additional electrical load to the existing power system in this island. It was found out that the additional peak electrical load is 16 MW which can't be met by the current maximum capacity of 8.4 MW. Homer software was used to study the feasibly of a hybrid power system for this settlement. The study reveals that storage batteries are very good option to be used with any combinations of power systems. Wind turbines were found very attractive reducing the overall COE by more than 48% compared to a case when diesel generators are only used. PV solar panels were found unattractive option unless the diesel prices are above $ 0.65/L and at very low wind speed. For a lowest COE and maximum reduction of carbon emissions, the optimum power system for this settlement was found to be 8.25 MW Wind Turbines, 3 MW Diesel generators and with 10 MW of storage batteries. In addition, a neutral carbon design was found for two options: Option#1: 0.5 MW of PV, 24.75 MW Wind Turbine and 15 MW Storage Batteries (COE $0.181/kWh) and Option#2: 22.5 MW Wind Turbine and 25 MW Storage Batteries (COE $0.18/kWh).

Acknowledgments

The first author gratefully acknowledges the financial support received from Sultan Qaboos University, Muscat, Oman, for supporting his PhD Study at the University of Colorado, Boulder, USA.

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