Economic Evaluation of Micro-Grid System (On/Off Grid): Egyptian Case Study

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Abstract— The basic objective of this study is to reach the optimal sizes of micro-grid components, investigating technical and economic performance, taking into consideration the environmental impacts. In the intended case study, the proposed micro grid supplies two small factories; installed in a farm as a case study, with electricity, both on-grid and off-grid modes are investigated. The micro-grid comprises wind turbines, photovoltaic modules, and diesel generator and battery bank. The electrical energy generated from the micro-grid required to cover the estimated load pattern; with a peak of 76 kW, of the applied case study. To evaluate system economy two criteria are used; the net present cost and the cost of generated electricity. The sustainability of supplying the load is an indicator of the system technical performance measured by the percentage of power shortage. The most feasible system components for the selected application are obtained; based on required parameters, using HOMER simulation package. The results showed that Wind/Photovoltaic (W/PV) on-grid system is more economic than Wind/Photovoltaic/Diesel/Battery (W/PV/D/B) off-grid system as the cost of generated electricity in case of on-grid is 0.266 $/kWh while the second is 0.316 $/kWh. Taking into consideration the cost of Carbon Dioxide (CO2) emissions, the off-grid system will be competitive to the on-grid and more economic than diesel generators (DG) system as the calculated cost of energy is found to be (0.266, 0.257 and 0.345$/kWh), for grid connected, off grid, and diesel systems. Some of the previously reviewed studies discussed stand alone Renewable Energy (RE) micro-grid and others investigated grid connected system. But none of the reviewed papers compared between the two cases; on-grid and off-grid "RE micro-grid systems". The current study presents the comparison between the two cases from an economic point of view.

Index Terms—Environmental Emissions; Micro-grid System; Off-grid System; On-grid System; Optimum Energy Systems; Renewable Energy Sources; Smart Grids.

◆

1 INTRODUCTION

As development is rapidly taking place all around the world, in the demand for electricity is enormously increasing and expected to continue in the future. To mitigate climate change, clean energy generation is the answer. Thus it is essential now to rely on renewable energy sources to supply as much as possible energy demand, saving the limited fuel resource and reduce green house gases emissions, [1]. Hence, more attention is directed to smart grid technology. Peng and Shi Yan [2] summarized a number of control methods and techniques that are used in grid connected renewable Energy Systems (RES), to overcome the randomness and unbalance of energy output. Recently, there is a great interest in using micro-grids (MGs) in power systems as they are considered flexible, intelligent, and active power networks [3]. In addition, they are able to improve system reliability, efficiency, and security leading to more promotion of the renewable energy sources integration [4]. MGs can be either connected to the grid or used as Distributed Energy Resources (DERs) to supply the loads off- grid (i.e., islanded mode) [4].

Adopting micro-grid concept enables the integration of several micro generators without disturbing the network operation, synchronizing micro generation with loads [6]. As it is obvious now the importance of micro-grid; either connected with conventional or non-conventional sources, is increasing and Micro-grid can play an essential role in future electricity transmission, provided that it is proper functioning. This means that it is possible to connect or disconnect it to the main grid whenever required. The importance of micro-grid connected to the main grid and the importance of islanding in proper time is analyzed during the fault in the main grid in the environment [7].
One of the benefits of MG is reducing the main grid congestion as well as reducing the losses of the line thereby increasing the line efficiency, [8-9]. Due to environmental concerns the major concern these days is introducing nonconventional sources of energy into the existing systems. Micro-grid with its operation; in grid connected as well in islanded mode, provides higher flexibility in this regard, [10-11].

Balancing of supply-demand is required in case of island operation, which is necessary if the main grid is not large enough or disconnected due to faults in operation, [12]. Two studies of the micro-grid effect on the reduction of cost while improving the reliability of small scale distributed generators using different optimization approaches were presented, [13-14]. The proposed concepts permit high penetration of distribution generation.

R. Nazir et al, [15] optimized the utilization of local renewable energy for on-grid application. The proposed

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micro-grid model integrated two renewable energy plants; a micro hydro and a photovoltaic system to be connected to grid. The authors used HOMER and MATLAB software. Based on the load profiles and the availability of water resources the simulation results showed the largest capacity MHP produced the lowest energy cost, greatest reduction of CO2 emission, and largest RE fraction. The optimization model included individual models for: hybrid system, Loss of Power Supply Probability (LPSP) and Levelized Cost of Energy (LCE). Chan et al studied implementing a micro energy grid to a community and presented estimates of the effect of the urban micro energy grid on the reduction of energy demand and carbon emissions, [16]. The authors developed a number of key performance indicators (KPIs) to be used as a framework on the whole community micro energy grid design. Site-wise strategies were selected to meet the KPIs and minimize the capital cost of the project. An advanced real-time energy management system is proposed to optimize micro-grid performance in a real-time operation.

The proposed strategy of the management system is based on particle swarm optimization algorithm to minimize the energy cost and CO2 and other pollutant emissions while maximizing the power of the available renewable energy resources, [17]. Simulating the system performance, the authors considered three different scenarios according to the proposed problem complexity. The suggested management and control system was experimentally tested to validate the simulation results obtained from the optimization algorithm. Nikkhajoei and Lasseter identified the benefits of the Distribution Energy Sources micro-grids as; acceptable power quality, higher reliability, and high efficiency of energy utilization, which will lead to reduced pollutant generation. Nevertheless, they emphasized the importance of MG protection as the integration of the DERs with micro-grid is critical [18]. Hence, renewable energy generators should be designed to be highly flexible and controllable [19].

2. MICRO-GRID SYSTEM COMPONENTS

The proposed MGS is to feed an electrical load of two small factories installed the National Research Centre (NRC) farm in Noubarya, Egypt. The site is considered as an experimental field for different research activities. In this study the system comprises a small wind turbine and photovoltaic, in addition to battery bank and diesel generator in off-grid case.

Wind and solar statistics are obtained based on observations in the Noubarya area taken between April 2012-April 2015 monthly averages. Meteorological data of Noubarya site: Monthly average solar radiation is about 2.57 (kWh/m2/day) and Monthly average wind speed is 5.5 m/s.

2.2.1 Photovoltaic Panel (PV)

The total peak power of the PV generator required to supply certain load depends on load, solar radiation, ambient temperature, power temperature coefficient, efficiencies of solar charger regulator and inverter in addition to the safety factor taken into account to compensate for losses and temperature effect. This total energy generated and its power obtained as follows, [20- 22]:

$$E = A \times r \times H \times PR \quad (1)$$

Where:

- E: Energy (kWh).
- A: Total solar panel Area (m^2).
- r: solar panel yield or efficiency (%).
- H: Annual average solar radiation on tilted panels (shadings not included).
- PR: Performance ratio, (range between 0.5 and 0.9, default value = 0.75).

Several factors affect the measurement of PV efficiency, including:

- Wave length - PV cells respond differently to differing wave lengths of light, producing varying qualities of electricity.
- Materials - different PV materials behave differently.
- Temperature - cells work better at lower temperatures, with efficiency dropping off at higher temperatures.
- Reflection - any reflected light decreases the efficiency of the cell.
- Resistance - the cells electrical resistance creates losses, affecting the efficiency.

$$P\,(PV) = Fpv \times Cpv \times \left(\frac{G}{K}\right) \quad (2)$$

Where:

- Fpv is the PV de-rating factor;
- Cpv is the rated power of the pv (kW);
- G is the solar radiation incident on the surface of the PV (kWh/m2); and
- K is the peak solar intensity at the earth surface (1 kW/m2).

2.2.2 Wind Turbine (WT)

The power output is determined from the wind turbine characteristic curve according to the instantaneous wind speed. In this case only considers small wind turbine with rated power less than 50 kW. Wind turbine power curve is as follows [20], [21], [22]:

$$P_W = \begin{cases} 0 & V < Vci \\ a \times V^3 - b \times Pr & Vci < V < Vr \;\; and\; 0\; for\; V > Vco \\ Pr & Vr < V < Vco \end{cases} \quad (3)$$

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

$$a=\frac{Pr}{(Vr^3-Vci^3)}$$

(4)

$$b=\frac{Vci^3}{(Vr^3-Vco^3)}$$

(5)

Pr, V, Vci, Vr and Vco, are rated power, instantaneous, cut-in, rated and cut-out wind speeds in (m/s) respectively.

$$P_w = \frac{1}{2} \times \rho \times A \times Vr^3 \times C_p$$

(6)

Where: ρ is air density, A: turbine swept area (m2), and C_p: power factor**.**

2.2.3 Battery bank (BB)

Batteries are used to supply load requirements if renewable generated energy is not enough and to store the energy that exceeds load requirements. The battery capacity for a certain period may be defined as follows [20]:

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

(7)

Where:
- AD: daily autonomy.
- EL: load requirement at certain the time interval.
- η_v and η_{Wh}: efficiency of inverter and battery bank respectively.

Battery depth of discharge is specified and not to be exceeded. So that:

$$E_{min} = EBN \times (1 - DOD) \quad (8)$$

Where:
- E_{min}:minimum allowable capacity of the battery bank.
- EBN: nominal capacity of battery bank.
- DOD: depth of discharge.

2.2.4 Diesel Generator (DG)

PV and WT are known to be intermittent inaction, so a backup source is needed to insure supply continuity. DG is used for generating electricity in remote area. In case of off-grid system (DG) is used as a backup if the renewable sources are insufficient to supply the load. DG is sometimes used to charge the batteries to increase its state of charge (SOC) to an adequate state. DG rated power should be enough to support the load power whenever needed. Energy output and fuel consumption equations are shown as follows [20], [21]:

$$E_{(kWh)} = P \times h \times d \quad (9)$$

$$C_{(L)} = E \times C_{kwh} \quad (10)$$

Where:
- E: active electric energy in output of the diesel engine in kWh.
- P: active electric power output of the diesel engine in kW.
- H: number of hours per day the genset runs.
- d: number of days the power generator runs.
- C_{kwh}: fuel consumption of per kWh
(normal value is between 0.3 and 0.6 l/kWh).
- C = fuel consumption in liter.

2.2.5 Converter

Bi-directional converter is crucial in case of integrated energy system. Inverter can be modeled as follows [20]:

$$P_{di} = P_{Gout} \times \eta_{di} \quad (11)$$

Where:
- P_{di}: inverter charging power output.
- P_{Gout}: Generator power output.
- η_{di}: Efficiency of inverter in charging.

Efficiency of DC/AC conversion nowadays is more than 90%. Inverter size is investigated in this study; 20 kW.

3. CASE STUDY

NRC farm activities are mainly agricultural; hence the crop residues are used to produce animal fodders. As the farm soil is sandy hence it's recommended to add hydrogel to reduce the amount of water required for irrigation. Based on these applications, two small factories are established one for producing animal fodders and the other for hydrogel production.

Load Pattern

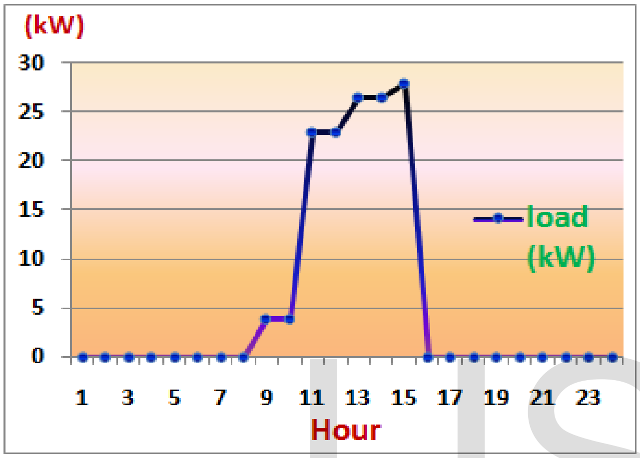
In order to define the micro-grid system configuration, the load pattern of each of the two previously mentioned factories is estimated. Monitoring the process operation in the two factories, the daily load profile of each of this of 28 kW, 16 kW is estimated. These equipments used are shown in table 1.

Defining the load pattern depends on types of equipment, their rated power and time of operations. Estimated daily load patterns for two factories are presented in figure 1 (a, b).

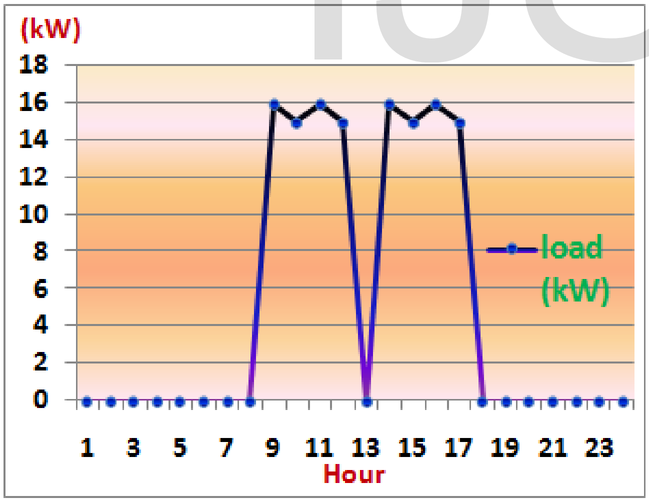
TABLE 1

EQUIPMENTS USED IN TWO SMALL FACTORIES LOAD AND ITS POWER REQUIRED

	Equipment	Power (HP)
1st Factory (Fodder)	Mixing Feed Unit	5.5
	Feed Piston	25
	Horizontal Cooling Fan	5
	Softener	2
2nd Factory (Hydrogel)	Motor	20
	Electrical Heaters	1.5



a) Fodder Factory

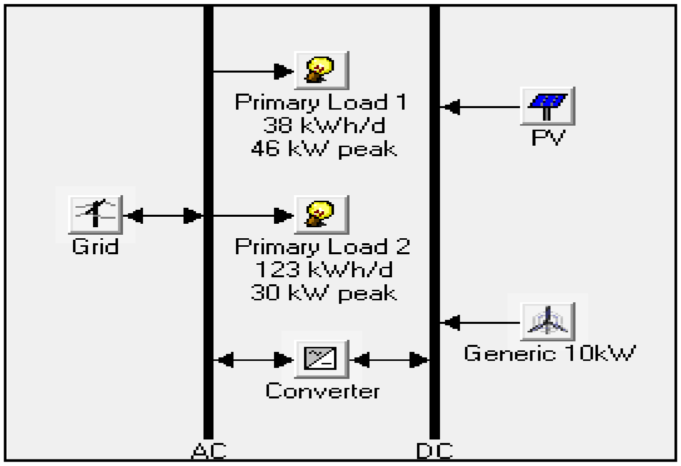


b) Hydrogel Factory

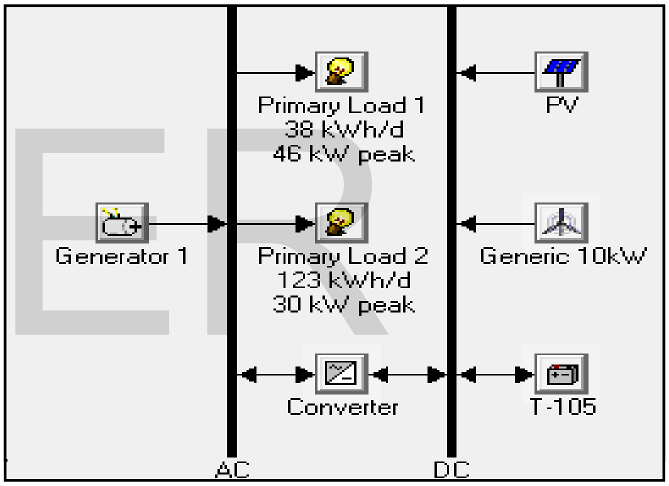
Fig1: Daily Load Profile

4. SIMULATION OF MICRO-GRID SYSTEM

A schematic (WT-PV) on-grid system supplying load pattern is shown in figure. 2. a. while figure 2.b. presents the (WT-PV/B/DG) off-grid system



a) On-grid system



b) On-grid system

Fig.2: WT-PV systems serving an AC load implemented in HOMER

It is clear from figure 2.a that in case of grid connected, the system comprises PV modules, 10 kW WT Generic type and bidirectional converter. The two loads are also illustrated in the figure defined as primary load 1 and primary load 2 with their power configuration. In figure 2.b the PV, WT are supported by a generator and a battery bank as this system is off-grid.

5. MICRO-GRID OPTIMIZATION

Micro-power system optimization objective is minimizing both net present cost and cost of produced energy, under the conditions of specified values of permissible capacity shortage and defined renewable fraction. This requires deciding different component sizes, site meteorological data, and the system mode of operation (Off/On) grid.

The objective of optimizing micro-power system is to minimize the net present cost, minimizing the cost of produced energy simultaneously. The optimization model may be formulated as [20]:

Objective function:

$$\text{Min } z = \sum \text{Net Present Costs (NPC)} \tag{12}$$

$$\text{NPC} = \{\text{CC} + \sum_{i=1}^{N} \frac{(\text{RC} + \text{O\&M C} + \text{FC} - \text{SV})}{(1+i)^{N}}\} \tag{13}$$

Where, CC: Capital cost, RC: Replacement cost, O&MC: Operating & Maintenance cost, FC: Fuel cost, SV: Salvage cost, i: interest rate, and N: Number of years (project life time).

Subject to the following Constraints:
(defined by user according to the application)

- Maximum Allowable Shortage/year.
- Minimum Renewable Fraction.
- Wind and solar percentage of renewable fraction (wind-solar).
- Annual Real Interest Rate.

Decision Variables are:

- Photovoltaic (module power, number of modules), Solar Radiation on site.
- Wind Turbine (turbine power, number of turbines), Wind Speed at the Site.
- Battery Bank (battery Ah, number of batteries)
- Diesel Generator (power in kW).
- Converter (rated power).
- Mode of application (Off/ or grid connected).

In this study; the assumptions are:

- Max. Allowable Shortage = 15% (which is acceptable for the current case study).
- Min. Renewable Fraction = 70%.
  (Increase renewable fraction as possible provided that it is economically feasible).
- Percent of renewable fraction for each renewable source (Solar: 70 % & Wind: 30%) = 100%.
- Annual Real Interest Rate = 6%.
  (According to the declared international rate on Egyptian banks).
- In case of off-grid, grid extension cost and grid electricity price are used to be compared with the cost of energy generated from renewable energy system. For on-grid system the current grid power price and sellback rate are taken to be 0.05$/kWh [23]. In off-grid system, the price of diesel fueling the backup generator is 0.15 $/L. The project life time 25 year based on PV panel life time which is the longest life of all components.

a. System Configuration

Simulation model input data:

- Wind Turbine (WT): Generic DC (10 kW).
- Photovoltaic (PV) panel: SiP24-Atersa
  (each panel 0.180 W).
- Battery (B): "Trojan T-105" (6V, 225Ah).
- Diesel generator (DG): 20 kW
- Converter: ACME 20 kW.

a.

b. Micro-grid Control Approach

If the hourly simulated required demand is higher than the supplied energy and the battery had reached the minimum charge level (DOD), the diesel generator is switched on. Different configurations of WT/PV for on-grid system and WT/PV/DG/B for off-grid system are considered. Different wind turbine and photovoltaic models are used. The full experiments were conducted for both on/off grid cases.

6. RESULTS

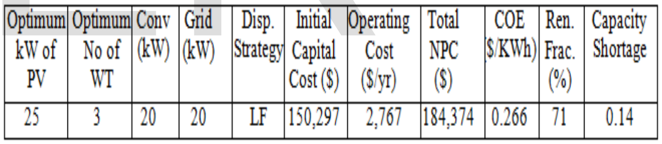
6.1 Optimum Configuration for Micro-Grid System

The optimization results of the simulated systems are shown in table 2 and 3. Table 2 represents on-grid system results while table 3 represents off-grid system. Optimum cost-effective summary for both cases are shown in Appendix.

Case 1: On-Grid System

TABLE 2

OPTIMIZATION RESULTS FOR NUBARYYAH SITE (ON-GRID)



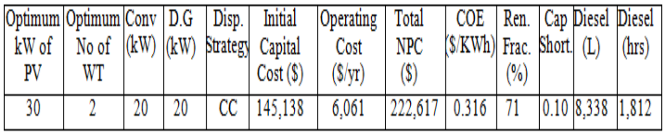
Optimum kW of PV	Optimum No of WT	Conv (kW)	Grid (kW)	Disp. Strategy	Initial Capital Cost ($)	Operating Cost ($/yr)	Total NPC ($)	COE ($/KWh)	Ren. Frac. (%)	Capacity Shortage
25	3	20	20	LF	150,297	2,767	184,374	0.266	71	0.14

LF: Load Following dispatch strategy, Renewable power sources charge the battery but the generators do not.

Case 2: On-Grid System

TABLE 3

OPTIMIZATION RESULTS FOR NUBARYYAH SITE (OFF-GRID)



Optimum kW of PV	Optimum No of WT	Conv (kW)	D.G (kW)	Disp. Strategy	Initial Capital Cost ($)	Operating Cost ($/yr)	Total NPC ($)	COE ($/KWh)	Ren. Frac. (%)	Cap Short.	Diesel (L)	Diesel (hrs)
30	2	20	20	CC	145,138	6,061	222,617	0.316	71	0.10	8,338	1,812

CC: Cyclic charging dispatch strategy, whenever the generators operate, they produce more power than required to serve the load with surplus electricity going to charge the battery bank.

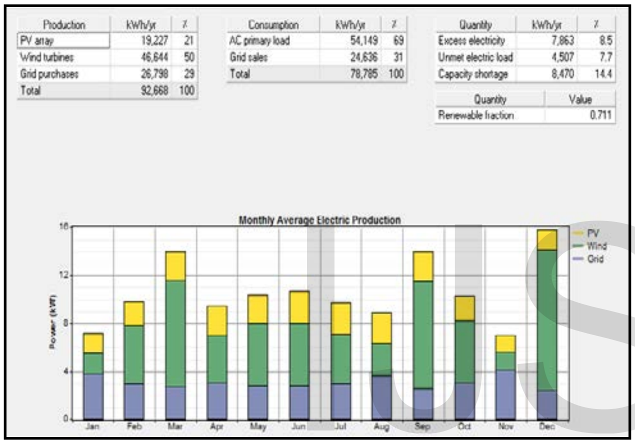
From tables (2 &3), it is indicated that:

- NPC for on/off grid optimum systems are $184,374 and $222,617 respectively.
- COE for on/off grid optimum systems are 0.266, 0.316$/kWh respectively.

Simulating diesel energy system the NPC is found to be $258,531 and COE is 0.345$/kWh, hence on-grid system configuration is the most economic decision (Least NPC & COE) for this case study.

6.2 Energy Performance

Figure 3 (a- b) shows the system energy summary of the optimum configuration in on/off grid cases.



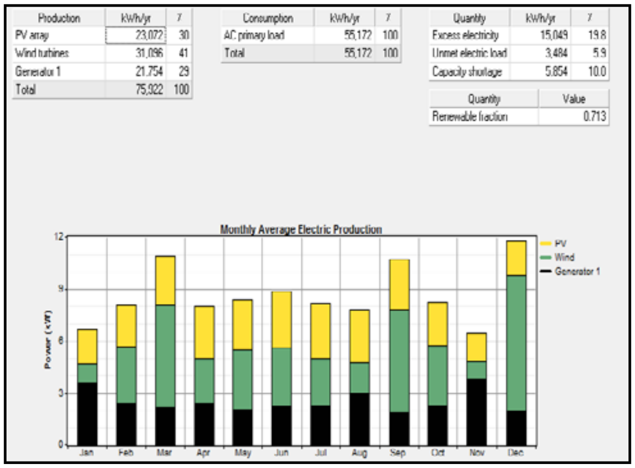
Production	kWh/yr	%
PV array	19,227	21
Wind turbines	46,644	50
Grid purchases	26,798	29
Total	92,668	100

Consumption	kWh/yr	%
AC primary load	54,149	69
Grid sales	24,636	31
Total	78,785	100

Quantity	kWh/yr	%
Excess electricity	7,863	8.5
Unmet electric load	4,507	7.7
Capacity shortage	8,470	14.4

Quantity	Value
Renewable fraction	0.711

a) On-grid system



Production	kWh/yr	%
PV array	23,072	30
Wind turbines	31,096	41
Generator 1	21,754	29
Total	75,922	100

Consumption	kWh/yr	%
AC primary load	55,172	100
Total	55,172	100

Quantity	kWh/yr	%
Excess electricity	15,049	19.8
Unmet electric load	3,484	5.9
Capacity shortage	5,854	10.0

Quantity	Value
Renewable fraction	0.713

b) On-grid system

Fig. 3: The energy performance of the on/off grid optimum system

From figure 3, it is observed that comparing energy production PV contribution in case of on-grid system was 21% and 30% in case of off-grid system. Similarly, WT contribution in the first case was 50% and 41% in the second case. It can also be seen that excess energy is 8.5% in case of on-grid system while 19.8% in case of off-grid system.

6.3 Break-Even Analysis

Break even analysis is applied to define the distance between the site and the electricity grid for which the cost of installing renewable energy micro-grid is equal to the cost of extending electricity. Figure 4 presents the result of the break even analysis.

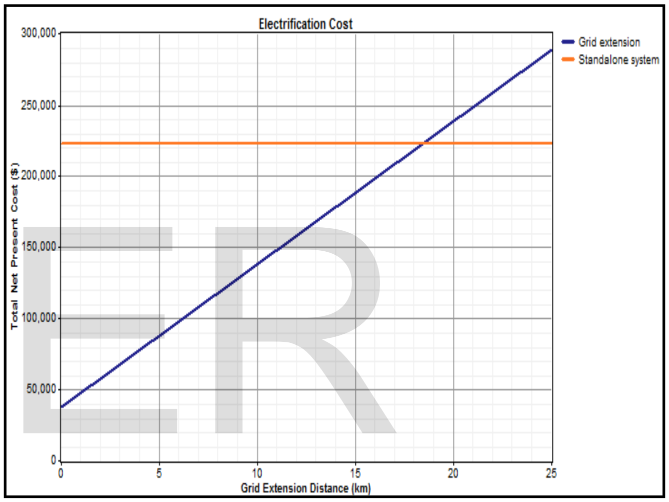


Fig. 4: Breakeven analysis between off-grid renewable energy system and grid extension

Comparing cost of energy of off-grid system with the cost of extending the grid, it could be seen that the break-even is 18.4 km. This means that if the proposed site for installing the micro-grid is greater than 18.4 km, then it is more economic to install the micro-grid.

6.4 Environmental Issues in Micro-grid Planning

Reduction of pollutant emissions are expected using micro-grids instead of conventional energy systems. The estimated off-grid system emissions are presented in Table 4. These data is used to evaluate the cost of CO2 emissions.

TABLE 4

EMISSIONS PRODUCED FROM THE OPTIMUM OFF-GRID SYSTEM

Pollutant	Emissions (kg/yr)
Carbon dioxide	21,956
Carbon monoxide	54.2
Unburned hydrocarbons	6
Particular matter	4.09
Sulfur dioxide	44.1
Nitrogen oxides	484

In previous simulation results, the emission penalties; according to updated Egyptian climate-change plan, have not been considered. The price of one ton of carbon dioxide is in the range \$60-\$80 per ton of carbon [24].

CO2 emissions and avoided cost (external cost):

From simulation results, diesel generator energy output is 21654 (kWh/yr), resulting in 21956 kg/yr of CO2 emission which means that CO2 emissions per kWh generated is about 1.0158. Renewable generators (PV&WT) generated is 54,168 kWh/yr electricity. Multiplying CO2 cost/kWh, by the renewable generated energy and CO2 price results in the cost of avoided CO2 emissions in 0.0581\$/kWh. Deducting the calculated CO2 cost/kWh from the COE resulted from the simulation of off-grid system, the modified COE is found to be 0.257\$/kWh which is almost equal to on-grid case.

7. CONCLUSIONS

Simulation of RE micro-grid system emphasized that the increase of RE fraction decreases the NPC and COE. Results obtained a number of feasible alternatives of RE micro-grids for several levels of renewable penetration. The optimization results showed that::

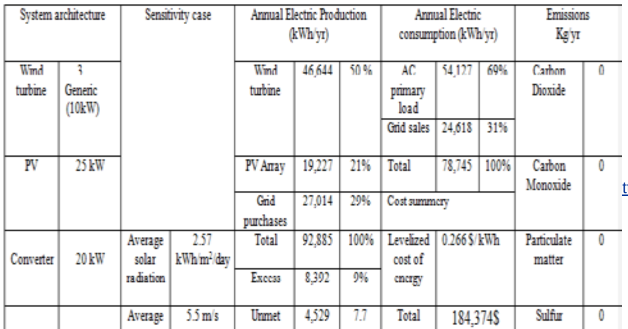
- NPC & COE of on-grid system are \$184,374, 0.266\$/kWh respectively.
- NPC & COE of off-grid system are \$226,617, 0.316\$/kWh respectively.
- NPC & COE of diesel only system are \$258,531, 0.345\$/kWh respectively.
- On-grid configuration system is the best option for this case study.
- Calculating the cost of avoided CO2 emissions, the modified cost of energy (COE) in case of off-grid is found to be 0.257 \$/kWh, hence the off-grid system will be competitive to the on-grid and more economic than diesel generators.

APPENDIX

TABLE 5

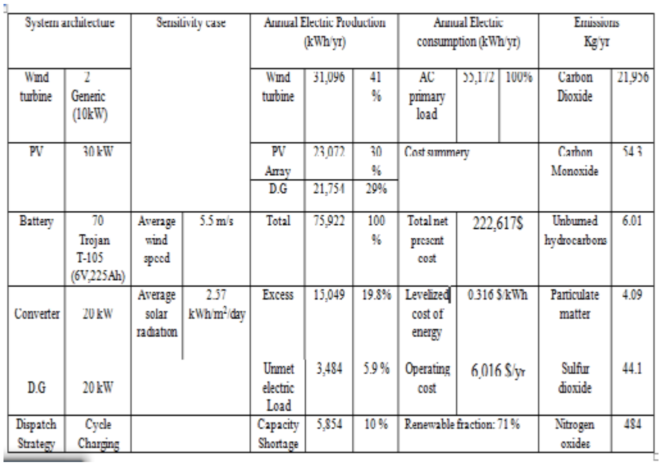
OPTIMUM COST-EFFECTIVE REPORT FOR THE SYSTEMS INSTALLED IN BOTH CASES

A) On-grid system



System architecture		Sensitivity case		Annual Electric Production (kWh/yr)			Annual Electric consumption (kWh/yr)			Emissions Kg/yr	
Wind turbine	3 Generic (10kW)			Wind turbine	46,644	50 %	AC primary load	54,127	69%	Carbon Dioxide	0
							Grid sales	24,618	31%		
PV	25 kW			PV Array	19,227	21%	Total	78,745	100%	Carbon Monoxide	0
				Grid purchases	27,014	29%	Cost summery				
Converter	20 kW	Average solar radiation	2.57 kWh/m^2/day	Total	92,885	100%	Levelized cost of energy	0.266 $/kWh		Particulate matter	0
				Excess	8,392	9%					
		Average	5.5 m/s	Unmet	4,529	7.7	Total	184,374$		Sulfur	0

B) ON-GRID SYSTEM



System architecture		Sensitivity case		Annual Electric Production (kWh/yr)			Annual Electric consumption (kWh/yr)			Emissions Kg/yr	
Wind turbine	2 Generic (10kW)			Wind turbine	31,096	41 %	AC primary load	55,172	100%	Carbon Dioxide	21,956
PV	30 kW			PV Array	23,072	30 %	Cost summery			Carbon Monoxide	54.3
				D.G	21,754	29%					
Battery	70 Trojan T-105 (6V,225Ah)	Average wind speed	5.5 m/s	Total	75,922	100 %	Total net present cost	222,617$		Unburned hydrocarbons	6.01
Converter	20 kW	Average solar radiation	2.57 kWh/m^2/day	Excess	15,049	19.8%	Levelized cost of energy	0.316 $/kWh		Particulate matter	4.09
D.G	20 kW			Unmet electric Load	3,484	5.9 %	Operating cost	6,016 $/yr		Sulfur dioxide	44.1
Dispatch Strategy	Cycle Charging			Capacity Shortage	5,854	10 %	Renewable fraction: 71 %			Nitrogen oxides	484

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