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Modelling, Simulation, and Optimization of a Hybrid PV Solar System

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Abstract:

This paper presents a case study on the Islamic University of Gaza (IUG) photovoltaic (PV) solar system, being located in Gaza Strip. The IUG system is a hybrid off-grid system which includes a PV array, DC to AC inverter, charge controller, battery bank and backup diesel generator. The main target is to optimize the IUG system using HOMER Pro. (Hybrid Optimization of Multiple Electric Renewables) developed by NREL (National Renewable Energy Laboratory). The meteorological data of IUG location was taken from National Aeronautics and Space Administration (NASA). The average daily energy consumption of the electrical loads connected to the system is 574.3 kWh/d. The optimization yields the appropriate size of each component of the system and the lowest net present cost of the optimal configuration. The desired benefits of this paper are to present a comparison between the installed system and the optimal configuration from electrical and economic aspects and to determine in quantities how renewable energy sources contribute to reducing emissions caused by non-renewable energy sources. The results from the electrical point of view mainly showed that the DC-AC inverter was oversized. However, looking from an economic point of view, there was $ 166384.36 saving in the net present cost of the optimal configuration over the installed one.

Keywords: Photovoltaic; Hybrid; HOMER Pro; Optimization.

Introduction:

Gaza Strip suffers from frequent electricity outage for long periods of time because of the Israel occupation. Therefore the need for alternative sources of energy becomes highly urgent. Among these sources, a backup diesel generator formed a good choice. Recently the use of PV solar systems began to be widely spread because of their merits as they are environmentally friendly and do not need fuel to operate where PV solar systems depend on sunlight to generate electricity. (Kumar, Pukale, Kumabhar, & Patil, 2016). PV solar systems include three basic configurations. They are: Stand-alone system, grid tie system and grid interactive system. Stand-alone systems are often used in remote or rural areas where the local electrical utility grid is unavailable. (Morshed, Ankon, Chowdhury, & Rahman, 2015). Stand-alone systems become more reliable if they are integrated with another source of energy, often a backup diesel generator. Where backup diesel generators are considered as continuous power sources (Sandeep & Vakula, 2016).

System description

The IUG PV solar system is a 141.75 kWp. The system consists of a PV array, a charge controller, a DC-AC inverter, a battery bank and a backup diesel generator. Since there is another source of energy other than the solar energy which is the backup diesel generator, the IUG system is treated as a hybrid system. Hybrid PV solar systems are considered as reliable energy systems. A brief description of each system component is as follow:

Charge controller

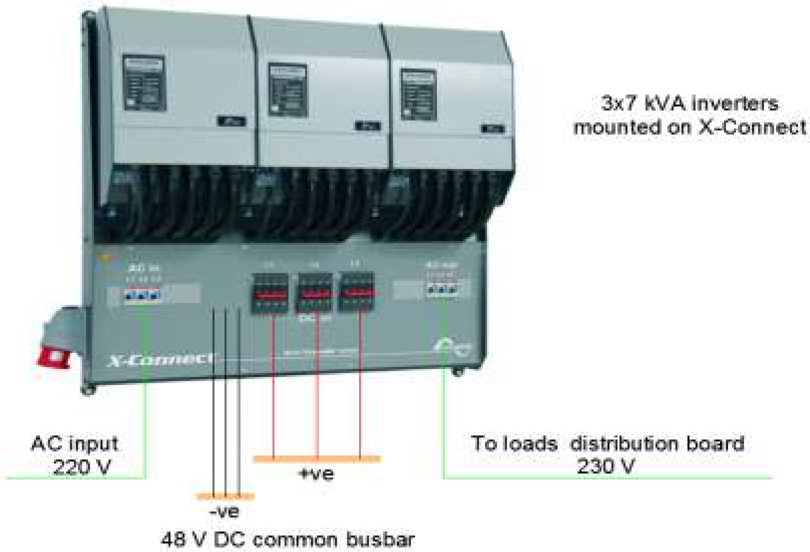
The charge controller is of STUDER type, its model is VT-80 with a maximum input solar power of 5 kW (Studer, http://www.studer-innotec.com/media/document/0/vt-complet-en-3.pdf, 1950). The allowable solar functional circuit voltage of the controller ranges from above the battery system voltage which is 48 V to 145 V. Moreover, the maximum solar open circuit voltage is 150 V. The VT-80 controller utilizes a maximum power point tracking (MPPT) algorithm, thus the controller has electrical conversion efficiency up to 99%. As the system coupling is DC-coupling, the controller regulates the output voltage of the PV array to the rated voltage of the battery bank. The total power of the charge controllers is 150 kW. The connection diagram of the charge controller in the system is as shown in Figure 1.

Figure 1. Charge controller connection diagram.

DC to AC Inverter

The DC to AC inverter used in the system is a STUDER type inverter, its model is XTH 8000-48 (Studer, http://www.studer-innotec.com/media/document/0/datasheet_xtender_series_en.pdf, 1950). This inverter converts 48 V DC to 230 V AC with a continuous power of 7 kVA. The inverter can be connected to an AC power source which might be either the electrical utility grid or a backup diesel generator. This inverter has a charging function which allows battery charging from the backup diesel generator. Studer Innotec Company provides each block of three inverters with an X-connect panel which contains DC circuit breakers and other components that make the installation process easier. The three inverters mounted on the X-Connect panel can be configured either as three-phase system voltage to provide power to three-phase appliances or as one-phase system voltage to increase the output power. In the IUG system, the three inverters mounted on the X-connect panel connected in parallel and acting as one-phase system voltage. Moreover, the total number of inverters is 18 inverters i.e. six X-connect panels. Accordingly, the total power of the inverters is 126 kVA. Figure 2 shows the connection diagram of three inverters mounted on the X-Connect panel.

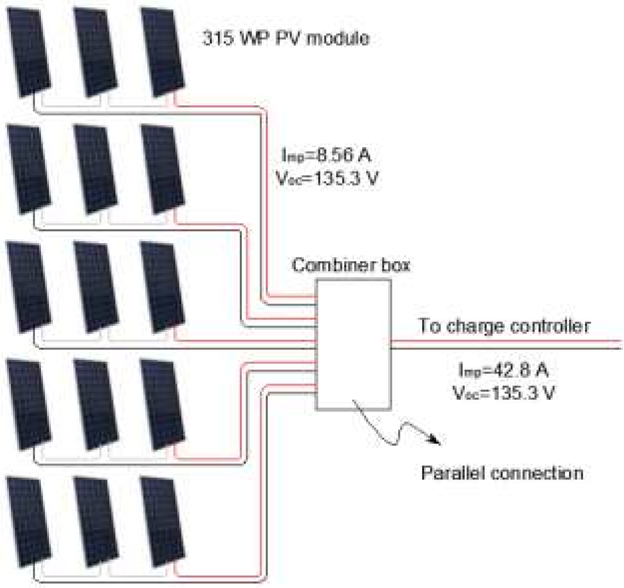
Figure 2. Three inverters connection diagram.



PV array

The type of PV modules used in the system is SUNTECH of model STP315-24/Vem (Wuxi Suntech, 2001). This module has a rated power of 315 Wp at standard test conditions (STC). The open circuit voltage (Voc) of the module is 45.1 V. The array is divided into 30 sub-arrays. As shown in Figure 3, each sub-array contains five strings of modules connected in parallel. As well, each string consists of three modules connected in series. The output of a sub-array is the input of a charge controller. It is important to note that for a PV string consisting of a number of modules connected in series, the Voc of the string is equal to the Voc of one module multiplied by the number of modules in the string. Furthermore, for the PV sub-array which consists of a number of strings connected in parallel, the Voc of the sub-array is equal to the Voc of one string. Based on the previous facts, the Voc of a string and the Voc of a sub-array in the IUG system are equal and have a value of 135.3 V. The open circuit voltage is an important parameter in a PV array configuration. As a rule of thumb, the Voc of a string of modules connected in series should be less than the maximum solar open circuit voltage of the charge controller which the string would be connected to it. Parallel strings can be added provided that the strings power does not exceed the maximum input solar power of the charge controller (Solanki, 2013).

Figure 3. Sub-array configuration.



The mentioned rule is verified in the array of the IUG system whereas the Voc of the sting (135.3 V) is less than the maximum solar open circuit voltage of the charge controller (150 V) also the sub-array power (4.725 kW) is less than the maximum input solar power of the charge controller (5 kW).

Battery bank

BEA type batteries are used in the system. The model of the battery is 22 PVV 4180 with a capacity of 3210 Ah @ C10h and nominal voltage of 2 V. This model is designed with a valve regulated lead acid (VRLA) technology (BAE Batterien GmbH, 2010). The positive electrode of the battery is tubular lead calcium while the battery Electrolyte is gel. In order to obtain the DC system voltage which is 48 V, 24 batteries were connected in series to form a battery string. Moreover, six battery strings were used in the system with a total number of 144 batteries. The reason of selecting the 48 V DC system voltage, in this case, is the higher efficiency of the inverters compared with the inverters efficiency when the DC system voltages are 12 or 24 V.

Simulation using HOMER software

Solar radiation and temperature data

HOMER software downloads solar radiation and temperature data of a predetermined location form NASA database (Nurunnabi & Roy, 2015). IUG is located on 31°51' N latitude, 34°44' E longitude. Figure 4 shows the monthly average solar global horizontal irradiation (GHI) data of IUG location.

Figure 4. Monthly average solar GHI data for IUG location.

The lowest value of daily radiation is 2.87 kWh/m^2/day while the highest value is 8.07 kWh/m^2/day. The lowest and highest values of daily radiation are intercepted in December and June months respectively. The annual average solar GHI equals 5.57 kWh/m^2/day.

The blue colour curve with black dots in Figure 4 represents the clearness index which is a fraction of the radiation on the horizontal surface of the earth to the extra-terrestrial radiation (Reddy & Raturi, 2010). The value of the clearness index depends on atmospheric conditions such as water vapour content and clouds distribution. The clearness index is a dimensionless value between 0 and 1. Higher values of clearness index occur in clear sky.

The monthly average temperature data of IUG location is shown in Figure 5. The annual average temperature of IUG location is 19.82 °C. Ambient temperature directly affects the open circuit voltage of a PV module. At a fixed solar radiation level, increasing temperature leads to decreasing the Voc, consequently it reducing the power output.

Figure 5. Monthly average temperature data for the IUG location.

Electrical load

The electrical loads fed from the PV solar system include around 70% of the building lighting that often operate from 8:00 AM to 5:00 PM, main internet servers devices (about 10 KVA) operating for 24 hours a day and air conditioning units of the main internet servers room (about 18 KVA) also operating for 24 hours controlled by a thermostat to keep the temperature within an acceptable set point. The electrical loads are connected directly to the inverters output so the inverters electrical parameters represent the actual electrical loads.

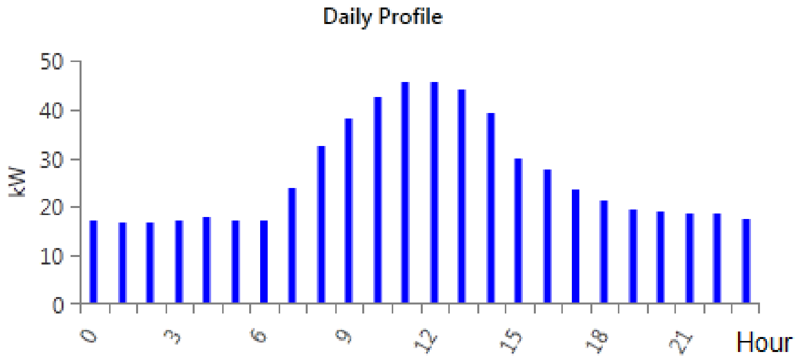
IUG system supervisor can monitor the system via the remote control and programming centre (RCC-02). The RCC-02 has a feature developed by Studer Innotec Company which is recording electrical values of the system such as output current, voltage and power. The recorded data is stored on SD card minute by minute. Studer Innotec

Company offers a free analysis tool (Xtender Data Analysis Tool) which allows displaying the electrical values graphically (Studer, http://www.studer-innotec.com/media/document/0/xtender-data-analysis-tool-1.6.30.zip, 1950). As an example of using Xtender Tool, system parameters such as the total AC input power (P-ACin), the total AC output power (P-ACout) and the total solar power (P-Solar) for the 15th of July, 2017 are shown in Figure 6.

Figure 6. System power for the 15th of July, 2017.

The total AC output power (p-ACout) represents the consumed power by the electrical loads. Actually, it is the load power. The stored electrical values of the total AC output power are imported to HOMER to create the load profile. Hence, the load profile is identical to the actual load of the system. Consequently, HOMER calculated the average daily energy consumption and the peak power of the electrical loads connected to the system. They were 574.3 kWh per day and 58.77 kW respectively. The daily profile is shown in Figure 7.

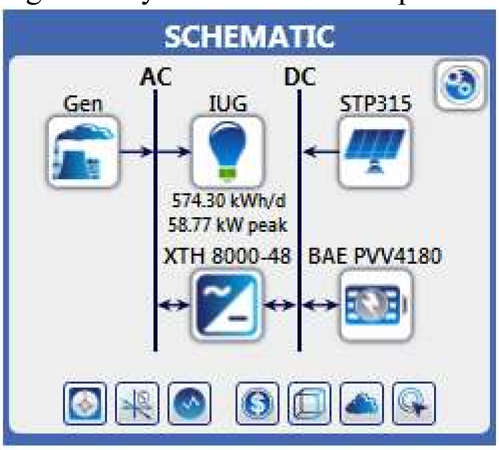
Figure 7. Daily profile.



System modeling

System components were modelled in HOMER software. The required data for modelling were obtained from the components datasheets while the components costs were obtained from the final payment made by IUG to install the system. Furthermore, the power factor was calculated from the system recorded data, it was often equal to one. So, the apparent power of the inverter in kVA was deemed equal to the active power in kW. Figure 8 shows the system model developed in HOMER. In Figure 8, “Gen” refers to the backup diesel generator, “IUG” refers to the electrical loads, “STP315” refers to the PV array including the charge controllers, “XTH 8000-48” refers to the inverters and “BAE PVV4180” refers to the battery used in the system.

Figure 8. System model developed in HOMER.



The charge controller does not appear in Figure 8 because HOMER included the charge controller with PV array. The remaining required data to complete the system model using HOMER software are listed in Table 1.

Table 1. Required input data of the system model.

Battery input data	Value
Round trip efficiency (%)	90
Minimum state of charge (%)	50
Float life (years)	20
Capital cost ($/battery)	1174.4
Replacement cost ($/battery)	1009
Initial state of charge (%)	100
PV module input data	**Value**
Lifetime (years)	25
Derating factor (%)	80
Converter capital cost ($/kW)	389.3
Converter replacement cost ($/kW)	170
Converter lifetime (years)	15
PV module capital cost ($/kW)	1324.4
PV module replacement cost ($/kW)	825.4
Ground reflectance (%)	20
Panel slope (degree)	30
Panel azimuth (degree West of South)	0
Converter input data	**Value**
Capital cost ($/kW)	1243.3

Replacement cost ($/kW)	1000
Lifetime (years)	15
Design constraints	**Value**
Annual capacity shortage (%)	0
Project lifetime (years)	25

The operation and maintenance costs of each component are assumed to be 1% of the component capital cost similar to (Prasetyaningsari, Setiawan, & Setiawan, 2013) work. The inverters are connected to the main backup diesel generator which supplies all electrical loads in IUG including those which are connected to the inverters output. Therefore, only the fuel price parameter of the backup diesel generator was used to model the backup diesel generator and was set to the average fuel price in the fuel stations which is 1.47 $ per liter.

System simulation

The currently installed system was simulated. The architecture of the simulated system is presented in Table 2. Where the rated power of the PV array "STP315" is 142 kW, the charge controllers rated power "STP315-MPPT" is 150 kW, the required rated power of the backup diesel generator "Gen" is 59 kW, the number of battery used in the system "BAEPVV4180" is 144 battery and the inverters rated power "XTH 8000-48" is 126 kW.

Table 2. Currently installed system architecture.

Architecture				
STP315 (kW)	STP315-MPPT (kW)	Gen (kW)	BAE PVV4180	XTH 8000-48 (kW)
142	150	59.0	144	126

The actual rated power of the PV array is 141.75 kW but that rated power was rounded in HOMER to be 142 kW. HOMER calculated the suitable backup diesel generator rating to be 59 kW. The backup diesel generator with that rated power is capable to provide the load with its peak power which was 58.77 kW. The backup diesel generator provides the load with the required energy when the solar energy is unavailable and the battery bank is empty.

System optimization

The system model was optimized according to the search space represented in Table 3. In the search space, different sizes and quantities are assigned to the system components in compliance with the study of (Papaioannou, Papadimitriou, Dimeas, Zountouridou, Kiokes, & Hatziargyriou, 2014). The chosen sizes for both the inverters and the charge controllers are multiples of 21 kVA and 10 kW respectively. The number of batteries strings is changed by adding one string each time, begins with one string. The changing step of the PV array rated values is 4.725 kW which equals the sub-array rated power connected to one charge controller. The backup diesel generator rated power kept on the same value.

Table 3. Optimization search space.

XTH 8000-48 Capacity (kW) Optimizer	Gen Capacity (kW)	STP315 DC Capacity (kW)	STP315 Size (kW) Optimizer	BAE PVV4180 Strings (#) Optimizer
21	59	100	118.125	1
42		110	122.85	2
63		120	127.575	3
84		130	132.3	4
105		140	137.025	5
126		150	141.75	6

HOMER simulated all combinations of the search space values to determine the most efficient system configuration similar to the work performed by (Singh, Baredar, & Gupta, 2015). In HOMER, the results are shown in a list of feasible configurations sorted by net present cost. The architecture of the optimal configuration is presented in Table 4.

Table 4. Optimal configuration architecture.

Architecture									
					STP315 (kW)	STP315-MPPT (kW)	Gen (kW)	BAE PVV4180	XTH 8000-48 (kW)
					142	100	59.0	144	63.0

After optimization, the PV array rated power still the same. The reason behind that is the need of more PV array area in the situation of low solar radiation levels, for example in winter seasons. The inverters rated power in the optimal configuration is half of its value in the installed system. This was expected where the peak value of the load was 58.77 kW. The rated power of the charge controllers in the optimal configuration is 100 kW. After contacting Studer Innotec Company, they did not mind connecting 142 kW of PV array to 100 kW of charge controllers.

Simulation results

The electrical parameters comparison of both the installed system and the optimal configuration is presented in Table 5. Knowing that the annual energy required for the load calculated using HOMER is 209620 kWh.

Table 5. Electrical parameters comparison between installed system and optimal configuration.

Component	Installed system	Optimized configuration
PV array energy production (kWh/yr)	232698	230292
Backup generator production (kWh/yr)	16593	16973
Excess electricity (kWh/yr)	23171	21205
Battery bank autonomy (hr)	25	25
Battery bank energy in (kWh/yr)	90236	89796
Battery bank energy out (kWh/yr)	81779	81383

Note that, the backup diesel generator production in the case of the optimal configuration is more than its production in the case of the installed system. This can be interpreted by observing the battery bank energy out, because of the battery bank energy out in the optimal configuration is less than its value in the installed system. Therefore, the backup diesel generator produces more energy in order to compensate the difference of the battery bank energy out in both systems.

The cost of energy generated from the installed system is 0.22 $/kWh while from the optimal configuration, the cost is 0.189 $/kWh. It is worth to mention here, that the energy generated from the installed system costs slightly more than the energy provided from the electrical utility which costs 0.17 $/kWh. This shows the cost-effectiveness of hybrid PV solar system even though the large capital cost on the system. So, hybrid PV solar system, in the long run, is a cost-effectiveness system. The economic comparison between the installed system and the optimal configuration is presented in Table 6.

Table 6. Economic comparison between installed system and optimal configuration.

Installed system

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Autosize Genset	$ 0.00	$ 0.00	$ 0.00	$ 229,584.30	$ 0.00	$ 229,584.30
BAE PVV 4180	$ 169,113.60	$ 145,296.00	$ 42,120.00	$ 0.00	$38,917.46-	$ 317,612.14
STP315 Dedicated Converter	$ 58,395.00	$ 25,500.00	$ 15,000.00	$ 0.00	$8,500.00-	$ 90,395.00
STUDER XTH 8000-48	$ 156,655.80	$ 126,000.00	$ 39,060.00	$ 0.00	$42,000.00-	$ 279,715.80
SUNTECH STP315 - 24/Vem	$ 190,285.20	$ 0.00	$ 47,486.25	$ 0.00	$ 0.00	$ 237,771.45
System	$ 574,449.60	$ 296,796.00	$ 143,666.25	$ 229,584.30	$89,417.46-	$ 1,155,078.69

Optimal configuration

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Autosize Genset	$ 0.00	$ 0.00	$ 0.00	$ 234,408.02	$ 0.00	$ 234,408.02
BAE PVV 4180	$ 169,113.60	$ 145,296.00	$ 42,120.00	$ 0.00	$40,135.98-	$ 316,393.62
STP315 Dedicated Converter	$ 38,930.00	$ 17,000.00	$ 10,000.00	$ 0.00	$5,666.67-	$ 60,263.33
STUDER XTH 8000-48	$ 78,327.90	$ 63,000.00	$ 19,530.00	$ 0.00	$21,000.00-	$ 139,857.90
SUNTECH STP315 - 24/Vem	$ 190,285.20	$ 0.00	$ 47,486.25	$ 0.00	$ 0.00	$ 237,771.45
System	$ 476,656.70	$ 225,296.00	$ 119,136.25	$ 234,408.02	$66,802.65-	$ 988,694.33

From Table 6, the capital cost of the optimal configuration is reduced by an amount of $ 97792.9 compared to its value in the installed system on the contrary to the fuel cost which was increased by $ 4823.72. The overall saving in the net present cost of the optimal configuration over the installed one along the project lifetime is $ 166384.36.

As a matter of fact, Renewable energy systems specifically PV solar systems are environmentally friendly. They contribute to reducing emissions that harm the environment (Roy, Basu, & Paul, 2014). HOMER software was used to simulate the quantities of emissions exported from the installed system and from a system powered by only a backup diesel generator. The results are presented in Table 7 where the installed system emits 16353 kg per year of Carbon Dioxide (CO_2) emissions while a system powered by only a backup diesel generator emits 186088 kg per year of CO_2 emissions. The percentage of CO_2 emissions reduction using the installed system instead of a system powered by only a backup diesel generator is 8.8%.

Table 7. Comparison of emission quantities.

Installed system			Backup diesel generator powered system		
Quantity	Value	Units	Quantity	Value	Units
Carbon Dioxide	16,353	kg/yr	Carbon Dioxide	186,088	kg/yr
Carbon Monoxide	103	kg/yr	Carbon Monoxide	1,173	kg/yr
Unburned Hydrocarbons	4.50	kg/yr	Unburned Hydrocarbons	51.2	kg/yr
Particulate Matter	0.625	kg/yr	Particulate Matter	7.11	kg/yr
Sulfur Dioxide	40.0	kg/yr	Sulfur Dioxide	456	kg/yr
Nitrogen Oxides	96.8	kg/yr	Nitrogen Oxides	1,102	kg/yr

Conclusion

The IUG hybrid PV solar system was modelled, simulated and optimized. In the optimal configuration, the PV array rated power is 141.75 kW, which is the same as that of the installed system. Furthermore, the inverters rated power in the optimal configuration is 63 kW which represent half of the inverters rated power in the installed system. Moreover, the optimal charge controllers rated power is 100 kW compared to 150 kW in the installed system. Also, the optimal required batteries number is 144 batteries, which is the same as that of the installed system. Finally, the backup diesel generator rated power is 59 kW, also the same as that of the installed system. A comparison of the electrical parameters of both the installed system and the optimal configuration was carried out. The comparison showed that, in the optimized system configuration, the backup diesel generator operates for longer periods of time to compensate the battery bank energy shortage. From the economic point of view, the optimization results showed that a cost of about $ 166380 could be provisioned. Similar studies to this study on other types of PV solar systems can be conducted and then a comparison of the different systems can be made. The comparison results will be helpful in selecting the proper PV solar system to install. Adapting the installed system to achieve the optimal configuration was left as future work.

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