International Journal of Engineering Innovation & Research
Volume 4, Issue 4, ISSN: 2277 – 5668

The Effects of Intermittent Solar Radiation in Off-grid Solar Power System

A Case Study of Two Cities; Irbid and Abu Dhabi 'Worst Month' Method

Taleb H. Al-theanat, Mhd Aymen Lpizra
Electrical Engineering Department
University of Bridgeport, Bridgeport, USA

***Abstract* – Many Photo-Voltaic (PV) Engineers design the PV system based on the annual average solar irradiation values of the installation area. This design is adequate if the weather of the installation area provides a small variation between the maximum and minimum solar irradiation values. This study illustrates the impact of the solar radiation by comparing the design of two off grid PV systems installed in two different locations have same annual average solar irradiation values. The case study selected the city of Irbid in Jordan and Abu Dhabi in UAE. The monthly average Irradiation values in Irbid are very diverse where the minimum, average and maximum values are spaced compared with the values in Abu Dhabi which has no significant variation of solar irradiation from month to month. Comparing the Design of the two different systems will reflect the impact of the sporadic solar irradiation on the rating values for the components of each system, which is affecting PV system cost. The design assumes the same load based and the worst case scenario of the solar irradiation.**

Each system will consist of PV modules, charge controller, power inverter and batteries.

***Keywords* – Photovoltaic System, Off-Grid, Solar Irradiation, PV Module.**

I. INTRODUCTION

These days the world is facing a major energy dilemma. Energy demand is increasing while the traditional energy sources are declining and the energy cost is snowballing. In addition to the environmental concern of using these resources. Fossil fuel is one of these resources that is used the most to produce energy for multiuse. However, it emits greenhouse gases, such as methane, nitrous oxide, and carbon dioxide to the atmosphere and has an adverse impact on the environment and participate in the global warming.

Global warming has many consequences on the future of the planet and the human life. As a result, people looked for solutions to avoid a bleak future. Using solar energy to produce electricity was one of the options that would solve many problems like reducing pollution and stopping the reliance on fossil fuel.

Nowadays, solar power system is being used in many applications such as home, lighting, water pumping.. etc.

The PV system may be interconnected with the grid or standalone with or without energy storage. This paper studies the off-grid PV systems design with energy storage units.

II. SOLAR INFORMATION

Solar radiation is the energy we get from the sun. It is also known as short-wave radiation. Solar radiation comes in many forms, such as visible light, radio waves, heat (infrared), x-rays, and ultraviolet rays, it can be measured in kW or W. Irradiance is the intensity of solar energy or the solar radiation on square meter, it can be measured in kW/m².

Insolation or irradiation is the total amount of solar radiation energy received on a given surface area during a given time. It could be expressed as "hourly irradiation" if recorded during an hour or "daily irradiation" if recorded during a day. It is typically measured per day and expressed as (Wh/m^2 per day). Each location on the earth has its own insolation profile. The insolation values for both locations of the case study are shown in Table 1 and 2 at different tilt angles.

Table 1 : Insolation (Wh/m² per day) for a location of (Lat. 24.467° N, Lon. 54.367° E) at Abu Dhabi city.

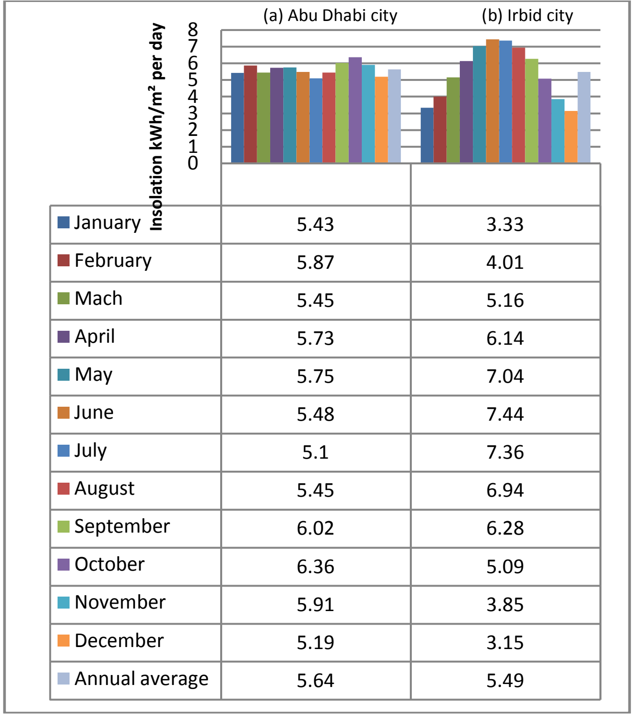
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Tilt 0°	3.97	4.76	5.17	6.20	7.15	7.20	6.42	6.18	5.96	5.34	4.38	3.68
Tilt 9°	4.46	5.19	5.40	6.28	7.03	7.00	6.29	6.19	6.17	5.77	4.91	4.18
Tilt 24°	5.09	5.68	5.57	6.16	6.56	6.40	5.84	5.97	6.26	6.24	5.57	4.82
Tilt 39°	5.43	5.87	5.45	5.73	5.75	5.48	5.10	5.45	6.02	6.36	5.91	5.19
Tilt 90°	4.34	4.19	3.19	2.49	1.94	1.77	1.85	2.17	3.11	4.27	4.60	4.28

Table 2 : Insolation (Wh/m2 per day) for a location of (Lat. 32.5° N, Lon. 35.5° E) at Irbid city.

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Tilt 0°	2.66	3.40	4.67	5.90	7.16	7.74	7.58	6.85	5.76	4.33	3.08	2.46
Tilt 17°	3.33	4.01	5.16	6.14	7.04	7.44	7.36	6.94	6.28	5.09	3.85	3.15

Tilt 32°	3.74	4.33	5.32	6.01	6.55	6.76	6.75	6.63	6.38	5.47	4.31	3.58
Tilt 47°	3.95	4.42	5.20	5.58	5.73	5.74	5.80	5.98	6.13	5.55	4.53	3.82
Tilt 90°	3.36	3.44	3.47	2.97	2.48	2.21	2.33	2.88	3.74	4.16	3.79	3.33

The Chart in figure 1 shows the insolation values in both locations. It is obvious that the monthly average insolation value at Abu Dhabi is not varying from month to month as it does in Irbid. At Abu Dhabi, the maximum insolation value is 6.02 kWh/m² per day and it occurs in September and the minimum is 5.1 kWh/m² per day in July. However at Irbid the maximum value is 7.44 kWh/m² per day in June and the minimum is 3.15 kWh/m² per day in December. So, the variance of the insolation values at Irbid is higher than the values at Abu Dhabi. But at the same time, Irbid and Abu Dhabi have very closed annual average insolation values of 5.49 kWh/m² per day and 5.64 kWh/m² per day, respectively.



January	5.43	3.33
February	5.87	4.01
Mach	5.45	5.16
April	5.73	6.14
May	5.75	7.04
June	5.48	7.44
July	5.1	7.36
August	5.45	6.94
September	6.02	6.28
October	6.36	5.09
November	5.91	3.85
December	5.19	3.15
Annual average	5.64	5.49

Fig.1. Insolation values represented as a chart for the location at : (a) Abu Dhabi city at 39° tilt; and (b) Irbid city at 17° tilt.

It is very essential to mention that the highest and lowest air temperature at Irbid are 42.6°C and -3.2°C, respectively[1]. Also, the highest and lowest air temperature at Abu Dhabi are 48°C and 12.6°C, respectively[2]. The impact of the temperature is presented in the designing process.

III. OFF-GRID SOLAR POWER SYSTEM

In this system, battery bank is used to store energy, and the PV system is standalone and not interconnected to the grid'.

The main components of the system are shown in Figure 2:

- PV modules: convert the solar energy into electrical energy.
- Charge controller: regulates current flow from the PV modules to the battery and protect the battery bank from overcharging .
- Battery bank: stores DC electricity to provide the load with energy in the night or during cloudy days where the sun is not available
- Power inverter: convert DC power to AC power to meet the load requirement, it also protects the battery bank from over-discharging.

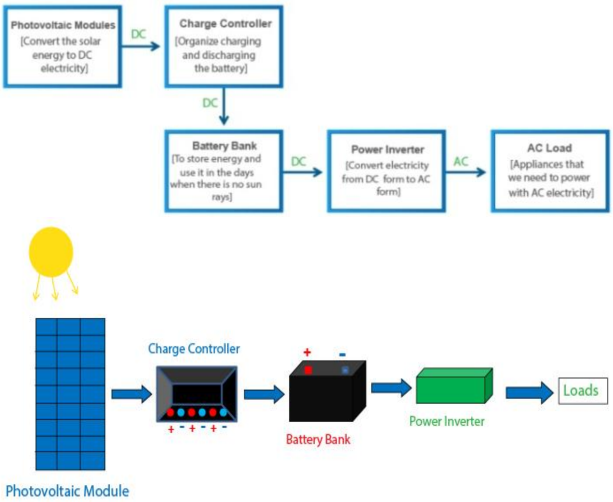


Fig.2. Block diagram of an Off-Grid Solar Power System.

IV. DESIGNING THE SYSTEM AT BOTH LOCATIONS

A. Load Estimation

Table 3 shows the power and energy of each appliance of the assumed load supplied by the PV system at both locations.

Table 3 : Power and energy of the load.

Appliance	**Quantity (Q)**	**Power (W) (P) each**	**Power (W) (P) Total**	**Usage time(hrs)/day (T)**	**Energy (Wh/day) E =Q× P ×T**
Light	4	25	4×25= 100	4	4 ×25×4 = 400
TV	1	100	1×100= 100	3	1×100×3 = 300
Laptop	1	90	1×90= 90	4	1×90×4 = 360
Kettle	1	1000	1×1000=1000	0.2	1×1000×0.2 = 200

Microwave Oven	1	700	1×700=700	0.3	1×700×0.3 = 210
Phone Charger	2	5	2×5= 10	3	2×5×3 = 30
Total	**10**	**-------**	**2000 W** [Max]	**--------**	**1,500 Wh/day**

From Table 3, there is 10 appliances in each location need to be powered by the PV system. To be conservative, it was assumed the diversity factor of the load is unity; all the appliances are turned on together at the same time, then the power will be 2000 W which is the maximum power that the load could consume. The average daily consumption of energy is 1500 Wh. These two values will be used in designing the components of the system.

Typically, the system voltage is selected based on the load level. Because the load is 1.5 kWh per day, so a voltage level of 12 V for the system was selected.

B. Power Inverter Sizing

Assume that a power inverter has 90% efficiency [η = 90%] is available.

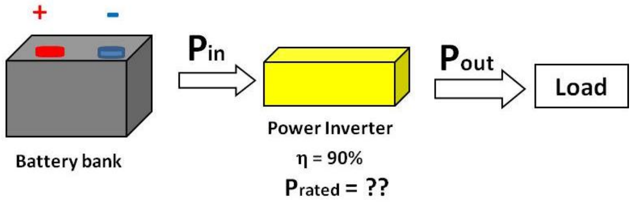


Fig.3. Efficiency of power inverter.

The maximum load could be 2000 W, so, the output power of the inverter should be at least 2000 W. The input power that the inverter should be receive from the battery bank or the PV array is determine by the following,

$$\text{Efficiency } (\eta) = \frac{\text{Output power}(Pout)}{\text{Input power}(Pin)} \times 100$$

$$\text{Therefore, Pin} = \frac{2000\text{W}}{0.90} = 2222.22 \text{ W}$$

So, the power inverter must be able to carry at least 2222W. This could happen if all appliances turned on at the same time. So, the inverter rating will be chosen to be 2500W.

So the selected power inverter has the following specifications:

- Prated = 2500 W
- Vin-rated = 9 - 17 V-DC
- Vout-rated = 230 V-AC +- 5%
- f = 50Hz +- 0.4Hz (since the load is designed for a grid with 50 Hz)
- η = 90%

Because the load in both locations is the same, then, the same power inverter will be used.

C. PV Module Sizing

Assuming 100-W PV modules are available with data shown in table 4, so the number of the required modules should be found for both locations. The modules will be mounted at fixed tilt angle during the year. For the case of Abu Dhabi, from table 1, an annual average insolation of 5.64 kWh/m²/day was chosen which occurs at tilt angle of 39°.

However, the minimum amount of insolation at Abu Dhabi during the year will be chosen to size the PV modules which is 5.10 kWh/m² per day and this is at July (worst month) to insure enough power are generated to cover the demand.

So, the insolation (minimum value) for the location at Abu Dhabi = 5.10 kWh/m²/day, and the maximum total energy of the load for one day = 1500 Wh/day. But, because of losses the total energy required will not be 1500Wh/day. The charge controller, batteries and power inverter have efficiencies of 97%, 95% and 90%, respectively, and the allowed voltage drop due to the wiring is 3%, that means the wires have efficiency of 97%. Assuming that the PV array will be away from shading, so, no losses due to shading, therefore :

Total PV modules energy needed =

$$\frac{\text{Required energy per day}}{\eta\,\text{inverter} \times \eta\,\text{controller} \times \eta\,\text{batteries} \times \eta\,\text{wires}}$$

$$= \frac{1500\ \text{Wh/day}}{0.90 \times 0.97 \times 0.95 \times 0.97} = 1864.58 \cong 1865\ \text{Wh/day}$$

Corrected load

The produced power by the PV module is 100 watts at STC (Standard Test Condition: Irradiance = 1000 W/m², Air mass = 1.5, and Temperature = 25°C). As the temperature rises, the output power of the module will decrease. Considering the worst case, the air temperature at Abu Dhabi could reach temperature of 48°C at 1000 W/m² solar irradiance. From the datasheet of the PV module the Power Temperature Coefficient is -0.45%/°C . The module temperature can be calculated as the following :

$$\text{Tmodule} = \frac{\text{Tair} + \text{G}\,(\text{NOCT} - 20°\text{C})}{\frac{800\text{kW}}{\text{m}^2}}$$

$$= \frac{48°\text{C} + 1\text{kW/m}^2\,(46°\text{C} - 20°\text{C})}{0.8\text{kW/m}^2} = 80.5°\text{C}$$

Where:

NOCT: Normal operating cell temperature at solar irradiance of 800 W/m² and ambient temperature of 20°C. From the 100 -W PV module's datasheet NOCT = 46°C.

Tair : The ambient temperature of the PV module/cell.

G : The solar irradiance at the required ambient temperature Tair .

Now the reduction of the PV output power at this temperature will be : 100×0.0045(80.5-25) = 24.975W. So, the PV output power at this temperature will be 100 - 24.975= 75.025W.

Now, number of PV modules needed =

$$\frac{\text{Required energy per day (corrected load)}}{\text{insolation} \times \text{power of the PV module}}$$

$$= \frac{1865}{5.1 \times 75.025} = 4.87 \cong 5 \text{ modules}$$

The five PV modules should be connected in parallel in order to have a total voltage of 12 V as shown in figure 4.

Table 4: Datasheet for a proposed 100-W module.

Characteristics (STC)	**Symbol**	**Unit**	**Values**
Maximum System Voltage	Vdc	V	1000
Open Circuit Voltage (Voc)	Voc	V	22.9
Short Circuit Current (Isc)	Isc	A	6.15
Rated voltage @ maximum power	Vmpp	V	18.56
Rated current @ maximum power	Impp	V	5.39
Rated Maximum Power @ STC	PMAX	W	100
Maximum Series Fuse	[A]	A	15
Module Efficiency (%)	η	-	15.2
Normal Operation Condition Temperature	NOCT	°C	46
Voc Temperature Coefficient	Tvk	%/°C	- 0.348
Power Temperature Coefficient	Tpk	%/°C	- 0.45
ISC Temperature Coefficient	TIk	%/°C	0.031

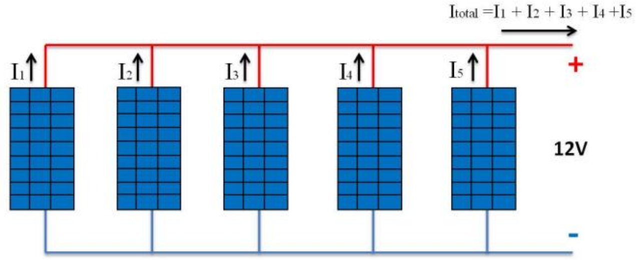


Fig.4. The connection of 5 modules in parallel that will be used at Abu Dhabi..

In the case of ***Irbid city***, the annual average insolation of 5.49 kWh/m²/day was chosen which occurs at tilt angle of 17°. The minimum value of insolation is 3.15 kWh/m²/day which occurs in December. The same losses factors and efficiency values that used at Abu Dhabi's system will be used here, therefore :

$$\text{Total PV modules energy needed} = \frac{1500\,\frac{\text{Wh}}{\text{day}}}{0.90 \times 0.97 \times 0.95 \times 0.97}$$

$$= 1864.58 \cong 1865\ \text{Wh/day}$$

The air temperature at Irbid could reach 42.6°C at 1000 W/m² solar irradiance. Therefore, the module temperature can be calculated as the following :

$$\text{Tmodule} = \frac{\text{Tair} + \text{G}\,(\text{NOCT} - 20°\text{C})}{\frac{800\text{kW}}{\text{m}^2}}$$

$$= \frac{42.6°\text{C} + 1\text{kW/m}^2\,(46°\text{C} - 20°\text{C})}{0.8\text{kW/m}^2} = 75.1°\text{C}$$

Now, the reduction of the PV output power at this temperature will be : 100×0.0045(70.5-25) = 22.545W. So, the PV output power at this temperature will be 100 - 20.475= 77.455W

Now, Number of PV modules needed =

$$\frac{\text{Required energy per day (corrected load)}}{\text{insolation} \times \text{power of the PV module}}$$

$$= \frac{1865}{3.15 \times 77.455} = 7.64 \cong 8\ \text{modules}$$

They will be also connected in parallel as shown in figure 5.

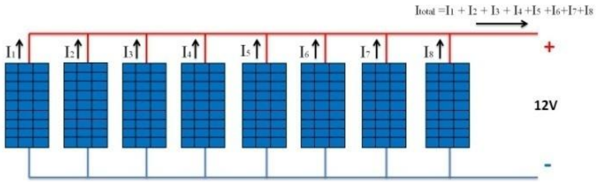


Fig.5. The connection of 8 modules in parallel that will be used at Irbid.

D. Battery Bank Sizing

12-V batteries with 100 Ah capacity are available at the market, it is necessary to know how many battery is required to cover the load for maximum 3 day in case there is no sun and for night usage. Assuming that the temperature of battery bank is kept at 25°C, therefore, the temperature correction factor will be 100%.

Now,

- The corrected load energy seen by the battery bank (Etotal) $= \frac{\text{Required energy per day}}{\eta\text{inverter} \times \eta\text{wires}} = \frac{1500\,\text{Wh}}{0.9 \times 0.97} = 1718.213$ Wh per day.
- Days of autonomy [storage], n = 3 days.
- 12v-batteries with 100 Ah capacity are available.

Assuming that the efficiency of the battery is 95% and its depth of discharge (DOD) is 80%, and the ambient temperature will be kept constant at 25°C, so, there is no losses. Now, the capacity of the battery bank can be calculated as the following :

$$\text{Battery bank capacity} = \frac{ET \times n}{\eta \times DOD \times Vr}$$

Where:

ET : The corrected load energy seen by the battery bank (Wh).

n: Days of autonomy.

η: efficiency of the battery.

DOD: Depth of discharge.

Vr: The rated voltage of the battery.

Because the previous parameters are the same in both locations, then, they will have the same number of batteries and the same connection.

Then,

$$\text{Battery bank capacity} = \frac{1718.213\ Wh \times 3\ days}{0.95 \times 0.8 \times 12\ V}$$

$$= 565.2\ Amps.Hrs\ [Ah]$$

$$\text{Number of batteries} = \frac{Battery\ \ bank\ \ capacity}{Battery\ \ size} = \frac{565.2}{100}$$

$$= 5.652 \cong 6\ batteries$$

They should be connected in parallel as shown in fig. 6.

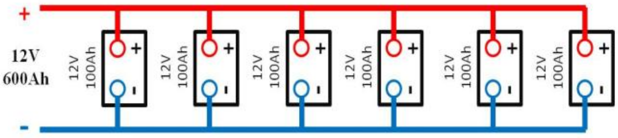


Fig.6. The connection of 6 batteries in parallel that will be used in both systems.

D. Charge Controller Sizing

Designing the charge controller requires to know the number of strings for the PV modules and their short circuit current and open circuit voltage. Because designing the charge controller depends on the number of PV modules, so, each system will have a different charge controller. In the case of Abu Dhabi, from figure 5, it is obvious that the number of strings is 5, by looking at the datasheet of the module that is shown in table 4, the short circuit current is 6.15 A and the open circuit voltage 22.9 V for each module at temperature of 25°C. The current will increase due to increasing of temperature and voltage will decrease due to decreasing of temperature, therefore;

Abu Dhabi [Max. ambient temperature = 48°C , Min. ambient temperature = 12.5°C, as calculated before Max. module temperature = 80.5 °C and Min. module temperature = 12.5°C].

The increment in current = ISC Temperature Coefficient × ISC × (Tmax - 25) = 0.031%/°C × 6.15A × (80.5 - 25) = 0.1058A

So, the short circuit current due to high temperature = 6.15 + 0.1058A = 6.2558A

The increment in voltage due to low temperature = Voc Temperature Coefficient × Voc × (25 - Tmin) = 0.348% /°C × 22.9V × (25 - 12.5) = 0.99615 V

So, the open circuit voltage due to low temperature = 22.9V + 0.99615 V = 23.89615V

Now the rated current and voltage of the charge controller can be found as following:

The rated current of the charge contr. = #of strings × Ishort-circuit = 5 × 6.2558A = 31.279 A

The voltage of the charge controller that should be carried = Voc = 23.89615V.

Therefore, the charge controller that will be used in the system at Abu Dhabi should handle at least 31.279 A and 23.89615V. Because a charge controller with the previous values is not available in the market, therefore, a 30Vmax, 35A charge controller will be chosen.

Now, At ***Irbid***, the system will have 8 PV modules with data sheet shown in table 4. From figure 6, number of strings is 8. The temperature effect should be taken in consideration, therefore;

Max ambient temp = 42.6°C , min ambient temp = -3.2°C , as calculated before max. module temp. = 75.1 °C and min module temp = -3.2°C.

The increment in current = ISC Temperature Coefficient × ISC × (Tmax - 25) = 0.031%/°C × 6.15A × (75.1 - 25) = 0.0955A

So, the short circuit current due to high temperature = 6.15 + 0.0955A = 6.2455A.

The increment in voltage due to low temperature = Voc Temperature Coefficient × Voc × (25 - Tmin) = 0.348%/°C × 22.9V × (25 - (-3.2)) = 2.2473 V

So, the open circuit voltage due to low temperature = 22.9V + 2.2473 V = 25.147V.

The charge controller will have the following specifications:

The rated current of the charge controller = # of strings × Ishort-circuit = 8 × 6.2455A = 49.964 A

The voltage of the charge controller that should be carried = Voc = 25.147 V.

So, the charge controller should handle at least 49.964 A and 25.147V. A 30Vmax, 50A charge controller will be chosen.

V. THE RESULTS

The overall losses of power from the PV array to the load is shown in figure 7. Where the energy needed from the PV array is 1865 Wh in order to receive at the load side 1500 Wh.

Fig.7. Overall losses in the system.

Table 5 shows the required components for each system. From the table, it is obvious that the number of PV modules in the system of Irbid city greater than in Abu Dhabi city. In addition, the charge controller of Irbid's system has a rated current greater than the one of Abu Dhabi's system. Therefore, the cost of the Irbid's system will be more than Abu Dhabi's system, Although both locations have almost the same annual average insolation values.

Table 5 : Main components of each system.

	PV Modules	**Power Inverter**	**Batteries**	**Charge Controller**
Irbid	Quantity : 8 P = 100-W each	Quantity : 1 P = 2500W	Quantity : 7 C = 100 Ah each	Quantity : 1 **Irated** = 50 A **Vnominal** = 12V **Vmax** = 30V or greater
Abu Dhabi	Quantity : 5 P = 100-W each	Quantity : 1 P = 2500W	Quantity : 7 C = 100 Ah each	Quantity : 1 **Irated** = 35 A **Vnominal** = 12V **Vmax** = 30V or greater

And here is the block diagram of the system at each city.

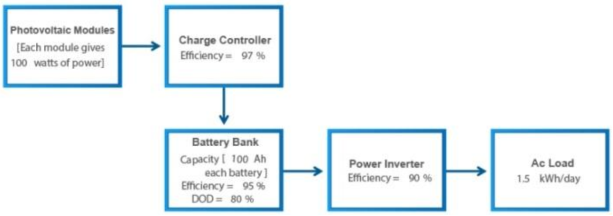


Fig.8. Overall system diagram.

VI. CONCLUSION

This study has presented the effects of intermittent solar radiation in off-grid solar power system design, where worst month method has been employed. However, After designing the two systems in both cities, the results showed that the cost of the system at Abu Dhabi is cheaper than the system at Irbid, and the components of Irbid's system have higher rated values than Abu Dhabi's system. These differences occurred due to the variation of solar irradiation from month to month at the location of Irbid not like in Abu Dhabi. So, it is very important to study the monthly average insolation values at the required location, and take in consideration the variation of these values in order to make the right decision and the right location before investing money in an off-grid solar power system.

REFERENCES

[1] Jordan Meteorological Department, http://www.jometeo.gov.jo.

[2] National Center of Meteorology & Seismology, United Arab Emirates**,** http://www.ncms.ae.

[3] Nominal Operating Cell Temperature. (n.d.). Retrieved April 16, 2015, from http://www.pveducation.org/pvcdrom/modules/nomin al-operating-cell-temperature.

[4] Philadelphia Solar Modules. (n.d.). Retrieved May 18, 2015, from http://philadelphia-solar.com/wpcontent/uploads/sites/12/2014/11/ M36s1.pdf.

[5] Photovoltaic Tutorial. (n.d.). Retrieved May 19, 2015, from http://www.thesolarplanner.com/steps_page8.html.

[6] NASA Surface meteorology and Solar Energy - Location. (n.d.). Retrieved June 1, 2015, from https://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?&num=216121&lat=30.329&hgt=100&submit=Submit&veg=17&sitelev=&email=skip@larc.nasa.gov&p=grid_id&step=2&lon=35.44

[7] Mingzhi Zhao; Zhizhang Liu, "Design and Application of Off-Grid Solar PV System in Inner Mongolia of China," *Power and Energy Engineering Conference, 2009. APPEEC 2009. Asia-Pacific* , vol., no., pp.1,4, 27-31 March 2009.

[8] Khatami, M.; Mortazavi, H.; Mashhadi, M.R.; Oloomi, M., "Designing an off-grid PV system: For a residential consumer in Mashhad-Iran," *AFRICON, 2013* , vol., no., pp.1,5, 9-12 Sept. 2013.

[9] *Stand-alone Photovoltaic Systems: A Handbook of Recommended Design Practices*. Albuquerque, NM: Sandia National Laboratories, 1988. Print.

AUTHOR'S PROFILE

Taleb H. Al-theanat

was born in 1990 in Irbid city, Jordan. He received his Bachelor’s degree in Science of Electrical Engineering from Jordan University of Science and Technology, in 2013. He is currently perusing his master's degree in Electrical Engineering from University of Bridgeport, USA. His current research interests: Solar Electric Power Systems, Wind Power Systems Electric Power Systems and Smart Grid. He can be reached at altheanattaleb@giee.org.

Mhd Aymen Lpizra

received Ph.D in Electric Power and Control in 1998 from Wichita State University and M.Sc. in Measurement and Control in 1994 from Idaho State University. He has worked as Adjunct Professor at University of Bridgeport since 2007 and worked at Eversource (Electric Utility) in Massachusetts as Lead Performance and Reliability Engineer since 2015. He worked at United Illumination Co. (Electric Utility) in Connecticut as a Lead Planning Engineer. His research interests are in Power Generation Stability, Power Distribution, Distribution Generators, High Voltage, and Switching Power Supply Design. can be reached at mlpizra@bridgeport.edu.