Off-grid photovoltaic systems as a solution for the ambient pollution avoidance and Iraq's rural areas electrification

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Abstract. The growing demand for local pollution free renewable energy sources in the world considered the solar energy as a one of the important renewable energy technologies and becomes dominant to the renewable energy source being exploited. The paper presents a unique approach to study and analysis off-grid photovoltaic (PV) system in order to provide the required energy for a one fold household in Diyala State, Iraq as well as the CO_2 emissions and life cycle (LCC) and economical aspect was considered. The results of the study by depending on site metrological data shows that the unit of electrical cost of (1 kWh) about ($0.51) and this value is not expensive compared to the current unit cost of electricity and becomes effect and encouraged the use the PV system to electrify the rare sites. The average of CO_2 emissions get avoidance about 1840 kg/year compared with conventional fuels used in Iraq to generate electricity.

1 Introduction

The global challenge to get green energy from reliable and cost-effective services remains one of the major challenges facing the world in this century. The application of green energy solutions significantly impact on the air qualities as well. More than 85% of mercury emissions originate from coal combustion for power generation and industrial processes [1]. The last investigations have shown that concentrations of most air pollutants in Baghdad City have shown a downward trend in recent years, but they are generally in many instances worse than natural ambient air; thus, all pollutants (except CO) fluctuated between high and below limits certified by Iraqi and international standards [2]. Although grid extension still remains the preferred mode of rural electrification [3], an extension of the central electricity grid to geographically remote and sparsely populated rural areas can either be financially unviable or practically infeasible. The efforts in using renewable energies have been often focused on single technologies. Reliance on a single technology generally results in an over-sizing of the system, thereby increasing the initial costs. Recently, the PV energy systems received more interest because of like these systems can overcome the intermittent nature of renewable energy sources, the over-sizing issue and enhance reliability of supply. In the developed countries, often advanced fuel systems such as hydrogen are considered. Examples of such studies include the following Khan and Iqbal [3] who investigated the feasibility of a hybrid system with hydrogen as an energy carrier in Newfoundland, Canada; Barsoum and Vacent [5]; Karakoulidis et al. [6], Giatrakos et al. [7] and Türkay and Telli [8].

Givler and Lilienthal [9] conducted a case study of Sri Lanka, where they identified when a PV/diesel hybrid becomes cost effective compared to a stand-alone small solar home systems (50 W PV with battery).

Solar energy is one of the important renewable energy technologies and photovoltaic system installation has played a big role in renewable energy because PV systems are pollution free, economical, highly reliable for long-time operation and secure energy source. The major obstruction of PV technology is its high capital costs compared to conventional energy sources. In isolated regions and because of the scarcity of means, it is necessary to optimize the solar off grid PV system in order to minimize the costs and to make the PV systems competitive with the other forms of renewable energies [10]. Figure 1 shows the off grid PV system for household [11].

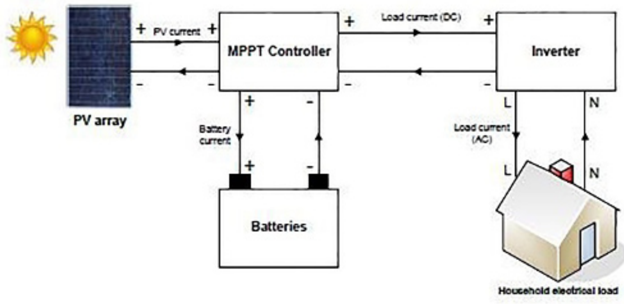

Figure 1. Off-grid PV system.

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Iraq is located in very high world's solar radiation and has an excellent solar availability. The annual average total solar radiation over Iraq ranges from about 2490 kWh/m²/year on the eastern territories to more than 2880 kWh/m²/year in the western territories (deserts). About 90% of the Iraqi territory have an average total radiation greater than 2680 kWh/m²/year [4]. The aim of this study is to provide a renewable energy system from the available resources, PV at a given site that can meet the electricity demand. The selected off-grid remote home in rural village Budjah, a small village in the Muqdadiyah district in the Iraqi state of Diyala. The site details are listed in Table 1. The area around the village is partially hilly with flat plains constituting the rest.

Table 1. Details of the selected site.

Particulars	Details
Village	Budjah
District	Muqdadiyah
State	Diyala
Country	Iraq
Latitude	33°58'N
Longitude	44°56'E
Max. Temp. (during summer)	47 °C
Min. Temp. (during winter)	6 °C

2 Household Daily Load Profile

The residential unit is simple and not require heavies of quantities of electrical power used for lighting and small electrical appliances. The Load profile was proposed considering the general hourly based load usage. At midnight hours, the power consumption for the residential unit comes down where only basic electrical appliances are consuming power. The load demand rises up during morning hours when everybody gets-up. Throughout the noon hours the load demand levels are minimum as most of the family members are outside. Again, during the evening hours when all the family members are present, the power consumption rises as everyone switches on various entertainment appliances.

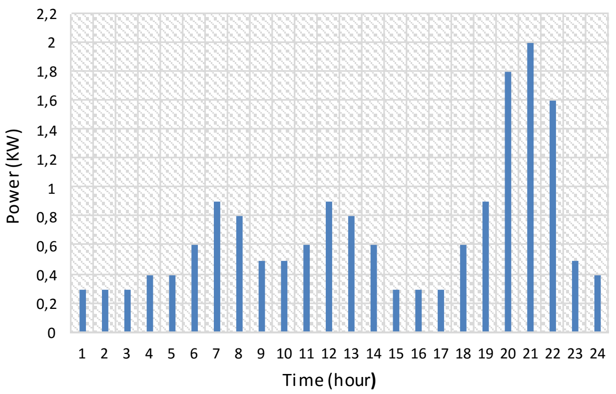

Figure 2. Household load profile.

According to the load profile shown in Figure 2 the average of hourly power consumption is 0.54 kW, minimum of hourly power consumption is 0.3 kW and the maximum of hourly power consumption = 2 kW, the load requirement considered should be maximum hourly load consumption. The average energy consumption of electrical appliances is assumed 13.16 kWh/day i.e. 395 kWh/month. Thus the proposed solar off-grid PV system should be overestimated about 14 kWh/day.

3 Site Meteorological Data

Iraq is among the countries with remarkable potential in solar energy. The off-grid PV system of the interest area that located in the remote village in the Muqdadiyah district at Diyala state. The site meteorological data showed in Table 1 and the solar resource for that site as shown in Figure 3.

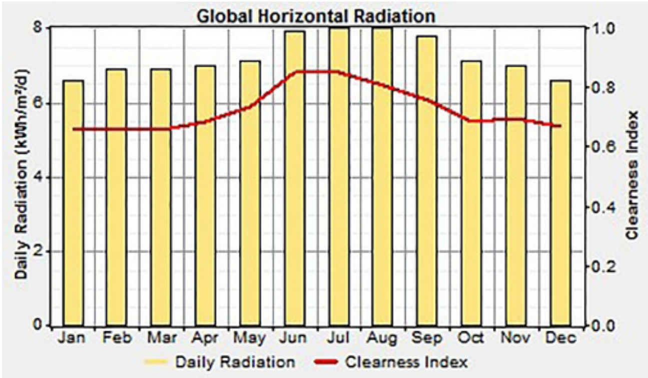

Figure 3. Solar energy profile at the selected site

4 Design and Modeling of the PV System

The main components of the off-grid PV system are namely PV array, battery, controller, inverter and load. The solar PV system is simulated such that the PV module charge the battery through the controller and battery also provides the power to the load when the solar radiation is insufficient. DC/AC inverter provides AC electricity to the required residential AC loads.

4.1 Solar Energy Input Data

The calculation from Figure 3 clarify the annual average of the solar radiation 7.2 kWh/m²/day and the average clearness index was found to be 0.71 The highest solar radiation was estimated at 7.9 kWh/m²/day in June while the lowest was 6.6 kWh/m²/day in December. The (G_{av}) selected in this project to be 7.1 kWh/m²/day.

4.2 Average Daily Load Demand

The average daily household load demand (EL) was 13.16 kWh/day, 0.54 kW/h showed in Figure 2, and the daily total demand was but the modeled solar off-grid PV system should be overestimated to the value 14 kWh/day, 0.58 kW/h.

4.3 PV Array size required

The size of the PV array, that required to use in this project, can be calculated as the following equation [12]:

$$PV_{size} = \frac{EL}{G_{av} * \mu_{pv} * TCF * \mu_{out}} \tag{1}$$

where,

G_{av} Is the average of solar energy input/day.
TCF Temperature correction factor

μ_{pv} PV module efficiency
μ_{out} Battery efficiency (μ_b) * inverter efficiency (μ_{in}).

Assuming the cell temperature reach to 58^{0}C in the area field, the temperature correction facture (TCF) will be 0.9 and assume the PV module efficiency $\mu_{pv} = 11\%$

$$\mu_{out} = \text{battery efficiency} * \text{inverter efficiency}$$
$$0.8*0.9 = 0.72$$

by using equation (1) calculated area required for PV modules is 23.4 m^2

$$PV\,Peak\,power = PV_{size} * PSI * \mu_{pv} = 3042\ W_p \quad (2)$$

The selected model is (Generic, a-Si:H, triple junction) with the following specification at standard test conditions STC:

- Peak Power: 140 W_p
- Peak power current: 3.87 A
- Peak power voltage: 36.2 V
- Short-circuit current (Isc) 5.10 A
- Open-circuit voltage (Voc) 46.2 V

The array with 22 modules is required to supply the energy for the residential house. The configuration of series and parallel of the resulted PV array can be adjusted according to the required DC bus voltage and current, respectively. If the DC bus voltage is chosen to be 48 V, then 2 modules will be connected in series and 11 strings will be connected in parallel.

4.4 Model of the Battery

The battery model used in the PV system based on a lead-acid battery PSpice model [14]. The battery model has to work in two operation modes: charge and discharge. The battery is in charge mode when current into the battery is positive, and discharge mode when the current is negative. The battery storage capacity was calculated by using the following relation [13, 14, 15]:

$$\text{Storage capacity} = \frac{Nc * EL}{DoD * \mu_{out}} \quad (3)$$

DoD Battery Maximum permissible depth discharging.
Nc Largest number of continuous cloudy days of selected site.

The largest number of continuous cloudy days *Nc* in the selected site is about 3 days. Thus, for the maximum depth of discharge for the battery *DoD* of 0.8, and battery efficiency 80%, the storage capacity using equation (3) the storage capacity becomes 35156 Wh. Since the selected DC bus voltage is 24 V, then the required ampere-hours of the battery = 65625/24 ≈ 2800 Ah. If a single battery of 24 V with a capacity of 350 Ah is considered, then 2 batteries are required to connect in series and 4 batteries connected in parallel to give 8 batteries for the overall system.

4.5 Inverter Model Required

The required inverter must be able to the maximum expected power of AC load requirements it can be chosen as 15% higher than the rated of the power of the total AC load. Therefore the rated inverter power becomes 1500 W. The specifications of the selected inverter will be 1500 W, 20 V_{DC}, 220 V_{AC}, and 50 Hz.

4.6 Battery Charge Controller Model

The number of battery charge controller required for the off-grid PV system has to able to carrying short circuit current of PV array it can be calculated as the following [17]:

$$\text{Total maximum power of PV} = P\max * Npv \quad (4)$$
$$\text{Controller Maximum power} = Vo * Ic \quad (5)$$

Number of controller required =

$$\frac{Total\ maximum\ power\ of\ PV}{Controller\ Max\ Power} \quad (6)$$

where:
Ic Maximum current the controller which can handle from the PV system to the battery bank.
Npv Total number of PV modules required to meet the residential load.
Vo Battery voltage.

5 Analysis the life Cycle Cost

This part computes the estimated values of the life cycle cost (LCC) for off-grid PV system. The LCC of an item consists of the total costs of owning and operating an item over its lifetime, expressed in today's money [16-19]. The costs of an off-grid PV system include acquisition costs, operating costs, maintenance costs, and replacement costs.

Table 2. Cost data of the PV system components.

Item	Cost
PV	$5/$W_p$
Battery	$1.5 /Ah
Charger	$5.878/A
Inverter	$0.8 / W
Installation	10% of PV cost
M&O/ year	2% of PV cost

The LCC of the PV system includes the sum of all the present worths (PWs) of the costs of the PV modules, batteries, battery charger, inverter, the cost of the installation and the operation and the maintenance (O&M) cost of the system. The details of the used cost data for all items are shown in Table 2 [15, 20].

The lifetime *N* of all the PV system items is considered to be 20 years, except that of the battery which is considered to be 5 years. Therefore, there are an extra 3 groups of batteries (each of 8 batteries) should be purchased, after 5 years, 10 years, and 15 years. The inflation rate *i* of 3% has been assumed and a discount or interest rate *d* of 9%. The PWs of all the items are calculated as follows [16, 17]:

- PV array coast C_{pv} = 5*22*140 =$15400
- Initial coast of batters C_b = 1.5 *2800 = $4200

The PW of the first extra group of batteries (purchased after N = 5 years) C_{b1pw} is calculated, to be $3164.5, from:

$$C_{b1pw} = C_b \left(\frac{1+i}{i+d}\right)^N \quad (7)$$

The PW of the second extra group of batteries (purchased after N = 10 years) C_{b2PW} and the third extra group (purchased after N = 15 years) C_{b3PW} are calculated, using an equation (7) and the values are $2384.3 and $1796.4 respectively. Table 3 shows that the LCC cost of controller, inverter and installation.

Table 3. LCC cost with installation of PV system components.

Details	Value
Controller cost	$293.9
Inverter cost	$1200
Installation cost	$1540

The PW of the maintenance cost C_{MPW} is $3583.4, and was calculated using the maintenance cost per year (*M/yr*) and the lifetime of the system (*N* = 20 years), from [18]:

$$C_{mpw} = \frac{M}{yr}\left(\frac{1+i}{1+d}\right)\left[\frac{1-\left(\frac{1+i}{1+d}\right)^{N}}{1-\left(\frac{1+i}{1+d}\right)}\right] \quad (8)$$

The life cycle of the PV system can be calculated as follows:

$$LCC = C_{PV} + C_b + C_{b1PW} + C_{b2PW} + C_{b3PW} + C_{controller} + C_{inv} + C_{inst} + C_{MPW} \quad (9)$$

so the life cycle cost of PV system is $32194.

The annualized LCC (ALCC) of the PV system in terms of the present day dollars can be calculated, to be $2614.8/year, using equation (10) [16, 17]:

$$ALCC = LCC\left[\frac{1-\left(\frac{1+i}{1+d}\right)}{1-\left(\frac{1+i}{1+d}\right)^{N}}\right] \quad (10)$$

Finally, the electrical unit cost (cost of 1 kWh) was calculated, to be $0.51/kWh with the following equation:

$$\text{Unit electrical cost} = A\frac{ALCC}{356EL} \quad (11)$$

Therefore, in remote sites that are so far from the electric grid, the PV suppliers are encouraged to sell the electricity of their PV systems at a price not lower than $0.51 /kWh to earn a profit. It is to be noted that although this price is low compared to the current unit cost of electricity in Iraq and this price will drop if the future initial cost of the PV modules drops also. Meanwhile if the future unit cost of electricity in Iraq increases due to the rapid increase in the conventional fuel prices, the PV power generation will be promising in the future typical home electrification due to its expected future lower unit electricity cost compared to the conventional utility grid.

6 CO_2 emissions avoidance

Iraq relies on dams and natural gas for electricity generation and has 9 major stations spread over its territory, the generation of 1 kW/h of electricity by using natural gas produce 0.465 kg of CO_2 while to generate the same value by using PV produce 0.105 kg of CO_2 [21], the natural gas is classified as a second largest producer for CO_2 after the coals that used in power stations. According to present study the generating of 14 kWh/day by using natural gas produce 6.1 kg/day and at the same time it produce 1.3 kg/day by using a PV system get avoidance in CO_2 emissions about 1840 kg/year compared with conventional fuels used in Iraq to generate electricity.

7 Conclusion

The electrification of rural and remote places worldwide is very important especially in the developing countries as Iraq. Solar photovoltaic technology considered one of the promising renewable energy resources due to their high reliability and safety. At the same time, it represents a vital and economic alternative to the conventional energy generators. This study presents a complete design and the life cycle cost analysis for household in rural site of Diyala State, Iraq is carried out using off-grid PV system. The results of the study shows that electrifying a remote household using PV systems is beneficial and suitable for long-term investments at a price $0.51/kWh it is to be noted that this price is lower compared to the current unit cost of electricity in Iraq, especially if the initial prices of the PV systems are decreased and their efficiencies in the future will increased. The average of CO_2 emissions get avoidance is about 1840 kg/year for the 3042W peak power of the photovoltaic system, compared with conventional fuels used in Iraq to generate electricity.

References

1. K. Styszko, K. Szramowiat, M. Kistler, A. Kasper-Giebl, L. Samek, L. Furman, J. Pacyna, J. Gołaś, C. R. Chim. **18** (2015)
2. A. Rabee, Environ. Monit. Assess. **187**, 1 (2015)
3. S.C. Bhattacharyya, Energ. Sust. Dev. **16**, 3 (2012)
4. M. Khan, M. Iqbal, Renew. Energ. **30,** 6 (2005)
5. N. Barsoum, N. Vacent, *Balancing cost, operating and performance in integrated hydrogen hybrid energy system* in proceedings of the first Asia International conference on modelling and simulation (2007)
6. K. Karakoulidis, K. Mavridis, D.V. Bandekas, P. Adoniadis, C. Potolias, N. Vordos, Renew. Energ. **36** (2011)
7. G. Glatrakos, T.D. Tsoutsos, P.G. Mouchtaropoulos, G. Stavrakakis, Renew. Energ. **34** (2009)
8. B.E. Turkey, A.Y. Telli, Renew. Energ. **36** (2011)
9. T. Givler, T. Lilienthal, Technical Report NREL/TP-710-36774, available from http://www.osti.gov/bridge (2005)
10. J. Abdulateefa, K. Sopiana, W. Kaderb, B. Baisb, R. Sirwana, B. Bakhtyara, O. Saadatiana , Int. J. Sust. Green Energ. **4**, 3-1 (2014)

11. PVDI Solar Energy International, *Photovoltaic Design and Installation Manual*, New Society Publishers (2007)
12. T.M.I. Alamsyah, K. Sopian, A. Shahrir, *Techno-economics Analysis of a Photovoltaic System to Provide Electricity for a Household in Malaysia, Proceedings of the International Symposium on Renewable Energy* (Kuala Lumpur, Malaysia, Environment Protection & Energy Solution for Sustainable Development, 2003)
13. M.M. Mahmoud, I.H. Ibrik, Renew. Sust. Energ. Rev. **10** (2006)
14. M.R. Rivera, *Small wind / photovoltaic hybrid renewable energy system optimization. Master's thesis, electrical engineering* (University of Puerto Rico, 2008).
15. PVDI 2007: Solar Energy International, (Photovoltaic Design and Installation Manual), New Society Publishers.
16. Estimating PV system size and cost. Seco fact sheet No. 24 www.InfinitePower.org.
17. The German Solar Energy Society. 2005. *Planning control apparatus and method and power generating system using them*. Patent US5, 654,883.
18. R. Messenger, J. Ventre, *Photovoltaic Systems Engineering*, CRC Press LLC: Boca Raton, Florida, USA, 2000.
19. A.N. Celik, Renew. Energy. **32** (2007)
20. C.W. Ajan, S.S. Ahmed, H.B. Ahmed, F. Taha, A.A.B.M. Zin, Sol. Energ. **74** (2003)
21. A.N. Celik, Renew. Sust. Energ. Rev. **10** (2006)
22. J. L. R. Proops, P.W. Gay, S. Speck, T. Schröder, Energ. Pol. **24,** 3 (1996)