An overview of electrification rural areas in Palestine by using micro-grid solar energy

Imad H. Ibrik*

Abstract: Palestine has a large number of rural areas which have no electricity services and cannot be connected to local grid in the near future for political and financial obstacles. This paper present the techno-economic impact of electrification of small communities by using micro-grid photovoltaic (PV) systems, and also reduction in CO2 emission in comparison to using diesel generator which causes high rates of environmental pollution will be analyzed. The implemented two micro-grid PV systems for electrification two communities in Palestine will cover the electricity needs of households and street lighting and can replace traditional unsustainable energy sources. Also, micro-grid PV systems have positive impacts on people's health and on the environment besides economic and social benefits.

1. Introduction

Nowadays, it is well established that solar energy is the best option to meet the electricity demand in the near future. Palestine is facing the growth of energy demand, especially in electrical energy, across all sectors, and by necessity, future generation expansion will rely substantially upon increasingly expensive fossil fuels (Ibrik, 2019; Ibrik & Hashaika, 2019). Therefore, Renewable Energy (RE) sources in Palestine are necessary nowadays and in the future to support sustainable development and socioeconomic development.

ABOUT THE AUTHOR

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PUBLIC INTEREST STATEMENT

Renewable energy sources have become the choices of future energy supply, chiefly due to energy security and the sustained emissions emanating from conventional energy sources leading to global warming. In this line, micro-grids-distributed systems of local energy generation are today technologically and operationally ready to provide communities with electricity services, particularly in rural areas in Palestine and other neighboring countries. These micro-grids provide a range of services, from residential lighting alone to entertainment, refrigeration, and productive commercial uses like milling. Depending on the number of customers served, the types of services provided. The objective of this research is to show the social, economic, environmental, and technical impact of...
Palestine purchasing most of its needs of electrical energy from Israeli Electric Corporation because of the absence of fossil fuel resources; on the other hand, there is a large number of rural areas which lack the basic life services, especially electricity, because they are located in places far from conventional supply which causes any connection with grid is very poor, and also these remote small villages are located in area C under Israeli governmental control, which try to force the people of those areas to leave their lands (Country report of Palestine, 2012).

Palestine has a high solar energy potential, where the daily average of solar radiation intensity on the horizontal surface is 5.4 kWh/m², while the total annual sunshine hours amounts about 3,000 (Mahmoud & Ibrik, 2006). People in rural areas in Palestine are still using diesel generators for their electrical energy demand. Normally, the working hours of the diesel generators are limited to small periods of time. And the cost of diesel fuel is high and is increasing in addition to continuous maintenance and air pollution. Therefore, the use of diesel generators is not an effective choice for rural electrification (Juaidi, Montoya, Ibrik, & Manzano-Agugliaro, 2016; Mahmoud & Ibrik, 2006).

The solar photovoltaic (PV) systems have shown their potential in rural electrification projects in Palestine. With continuing price decreases of PV systems, these projects are becoming economically attractive and growing experience is gained with the use of PV in areas such as social and communal services, agriculture, and other productive activities, which can have a significant impact on rural development (Ibrik, 2016, 2018; Imad, 2010).

2. Case study: Remote villages Al-Mkahal and Saeed-In Yabad-Jenin
Khbrat Al-Mkahal is in the southwest of Jenin district, the nearest city is Yabad which is 5 km away, and the location coordinates for Al-Mkahal village are as follows: 32º 25’15, 85º 46’33, 94ºE, Figure 1.

Depending on a comprehensive assessment on non-electrified villages in the West Bank, Al-Mkahal was found to be one of the most appropriate villages to be subject to a socio-techno-economic impact study of electrification by mini off-grid centralized PV system (Ammous, 2016). Figure 2 shows the PV power plant in Al-Mkahal village.
Al-Mkahal village inhabitants work mainly in farming and cattle breeding, and some of the young people are working as construction workers. Their numbers amount to about 70 individuals and 10 families. Drinking water is obtained from artesian wells in the village area. Some people were using candles and gas cylinders for lighting, cooking, and pumping water, and sometimes, they operated old generator for 2 h at maximum due to cost and high fuel consumption, so the cost of energy consumption will be over 50 US$/month for some families, including the cost of transportation.

Al-Saeed village is in the southwest of the province of Jenin. The closest urban center is the city of Y'abad which is 3 km away. The village is located at bottom of the mountain where the settlement was built on top. The location coordinates are 32º 25’ 23”N and 35º 10’ 56”E. Figures 3 and 4 show the location and the PV power plant at Al-Saeed village.

People were also using candles, batteries, and gas cylinders for lighting, cooking, and pumping water. These sources are costly due to transportation and high dependency on them because there are no other power resources, so the cost of energy consumption was higher than 50 US$/month for some families.
3. Design of PV systems

3.1. Measuring solar radiation (solar energy)

The availability of solar radiation will affect the power output of PV modules, as the generated energy will decrease in rainy and cloudy day (Energy Research Centre—ERC, 2014).

The readings indicate that the annual average solar radiation rate is 5.4 kWh/m²/day for both sites, and the maximum value was 8.19 and 7.56 kWh/m²/day in June for Saeed and Mkahel, respectively, while the minimum solar irradiation was 2.7 and 3.13 kWh/m²/day in December.

According to the result which collected using weather station sensors and mainly irradiation data Figures 5, 6 in the areas, we can easily analyze the performance of the PV system.

3.2. Selection elements of system design

3.2.1. Electrical load

An estimation of family user daily consumption has been realized based on the information in the questionnaire and the beneficiaries needs regarding the electricity.

The estimated daily demand and all the appliances which will/may be used in communities are shown in Table 1.

| Applications             | # Quantity | Power (Watt) | h/day | W.h/day |
|--------------------------|------------|--------------|-------|---------|
| PL lamp                  | 2          | 11           | 4     | 88      |
| TV                       | 1          | 120          | 5     | 600     |
| Radio                    | 1          | 20           | 5     | 100     |
| Mobile charger           | 1          | 10           | 1     | 10      |
| Small refrigerator       | 1          | 200          | 5     | 1,000   |
| Highly efficient         | 1          | 180          | 2     | 360     |
| washing machine          |            |              |       |         |

Total = 2,158
Table 2. Characteristics of installed batteries

| Battery module type   | AGM LEAD ACID RITAR 2 V |
|----------------------|-------------------------|
| No. of battery bank  | 24                      |
| Capacity (100)       | 1,000 Ah                |
| Days of autonomy     | 1.5                     |

Table 3. Economic aspects

|                        | Saeed           | Al-Mkahal       |
|------------------------|-----------------|-----------------|
| Energy output (kWh)    | 19,446.93       | 17,945.1        |
| Monthly bill from PV system (US$/family) | 15              | 15              |
| Monthly energy expenses before PV installation (S/family) | 50S              | 50S              |
| Monthly saving (S/family) | 35              | 35              |
| Yearly total saving ($) | $3,780 ($35 × 12) | $4,200 ($35 × 12) |
| PV installation cost ($)       | 22,000          | 22,000          |
| S.P. B.P (year)           | 5.82            | 5.3             |

Figure 5. Irradiation—Khirbat Al-Mkahal.

Figure 6. Irradiation—Khirbat Saeed.
Using highly efficient appliances in this kind of project, the total loads in the village will be around 21,58 kWh/day. The total PV energy output, savings are illustrated in Table 3 and the simple pay back period (S.P.B.P) for both locations.

3.2.2. Sizing PV generator

In selecting a suitable PV module when designing a PV solar system to cover the average load energy demand of 21,580 Wh/day, PV array size can be determined, using Equation (1).

\[ P_{\text{PV-array}} = \left( \frac{E_L}{\eta_v \times \eta_R} \times \text{PSH} \right) \times S_f \]  

(1)

\( E_L \): Estimated average daily load energy consumption in Wh/day (21,580 Wh/day)

\( \text{PSH} \): Peak Sun Hours (5.4 h) (Juaidi et al., 2016)

\( \eta_v \): Efficiency of inverter (95%)

\( \eta_R \): Efficiency of wire losses (97%)

\( S_f \): Safety factor (1.15)

\[ P_{\text{PV-array}} = 4987 \text{ watt} \]

The PV module of type 135 Wp Canadian solar is installed in this project, so the number of modules in system (Nm) is determined in Equation (2).

\[ Nm = \frac{P_{\text{PV-array}}}{P_{\text{selected module}}} \]  

(2)

\[ Nm = 36.9 \approx 36 \text{ module} \]

3.2.3. System voltage selection

Selecting the operating DC voltage of standalone PV system is based on system requirements, so the selected system voltage is 48 Vdc.

According to system voltage, the number of modules in series (Nms) is calculated according to Equation (3).

\[ Nm = \frac{P_{\text{PV-array}}}{P_{\text{selected module}}} = \frac{48}{17.6} = 2.72 \approx 3 \text{ module in series} \]  

(3)

The PV array is composed of 36 PV modules on galvanized steel metallic support and distributed by three sub-array of 4 string, and each string has 3 modules (3 modules * 4 string * 3 sub-array = 36 modules), and the array capacity is 4.86 KWp of 135 Wp PV module and also with approximate area of 38.88 m².

So, the modules of the system were installed in series, and as a result,

\[ V_{\text{o.c.array}} = 22 \times 3 = 66 \text{ V} \]

\[ I_{\text{o.c.array}} = 8.19 \times 4 = 32.76 \text{ A} \]

3.2.4. Sizing of battery bank

The battery is the most important part in a stand-alone PV system, so we consider that the battery will cover the needs of beneficiaries at night and cloudy day which required a highly efficient battery.

The capacity of the battery (C_A-H) is measured in Ampere-hours, as in Equation (4).
\[ C_{A-H} = N_c \times E_L / V_B \times DOD \times \eta_v \times \eta_{lb} \]  \hspace{1cm} (4)  

\( N_c \): Numbers of days of autonomy (1.5–3 days)  
\( V_B \): Operating voltage for system (48 V)  
\( DOD \): Maximum depth of discharge (0.6–0.75)  

\[ C_{A-H} = 1,045 \text{ A.h} \]  
\[ C_{WH} = C_{A-H} \times V_B. \] \hspace{1cm} (5)  
\[ C_{WH} = 1,000 \text{ Ah} \times 48 \text{ V} = 48 \text{ kWh} \]

The specification of selected batteries is illustrated in Table 2.

3.2.5. Sizing of charge controller  
The basic function of charge controller is to extract as energy as possible from PV array in order to maintain a high state of charge of the battery and avoid its complete discharge, so it controls the cycle of charge and discharge avoiding overcharge and deep discharge.

When we selected the charge controller, we consider that the unit has the following characteristics:

- Highly efficient charge controller with low self-consumption  
- Maximum power point tracker (MPPT) to get the maximum power of PV array  
- Possibility to maintain the batteries at floating voltage to compensate the losses in case of full charge  
- Advanced algorithm of charge and discharge control

The size of the charge controller will be selected according to Equation (6).

\[ P = V_B \times I \] \hspace{1cm} (6)  

\[ 4,860 = 48 \times I \times 1.15 \]

\[ I = 88 \text{ A} \times S_{f2} \]

\[ I = 110 \text{ A} \]

\( S_{f2} \): Safety factor (1.25); in special conditions, the panel produces more power then its rated (about 25–30%). For example, sunlight reflects from snow and water.

So, we used MPPT-150 A and peak efficiency of 97.5%.

3.2.6. Sizing of inverter  
When we select the inverter which will be used in the project, we consider the system voltage, output voltage 230 V/50 Hz, low self-consumption with efficiency, maximum charge current >15 A and the input of inverter has to be matched with the battery bank voltage as in electric grid as follows (Energy Research Centre—ERC, 2014):

\[ \text{Rating inverter} = \text{PV rating} = 135 \text{ Wp} \times 36 = 4,860 \text{ W} \]
The input energy of inverter = PV rating × PSH × \( \eta_R \)

\[ = 4,860 \times 5.4 \times 0.97 = 25,456 \text{ Wh} \]

The output energy of inverter = input energy of inverter × \( \eta_V \)

\[ = 25,456 \times 0.95 = 22,974 \text{ Wh} \]

We selected inverter with a highly efficient sinusoidal bidirectional generator with self-consumption less than 10 W, the working voltage is 48 Vdc, and the output voltage is 220 V/50 Hz, with capacity 5 kW (Savalia, Yadav, Davda, & Kanojia, 2016).

3.3. Total energy generated by PV power plant

The system was monitored using the data logger, and the data were collected and stored each hour, so we can obtain total produced energy on monthly and annual basis, using Equation (7).

\[ E_t = \sum (E_{m1} + E_{m2} \ldots \ldots E_{m12}) \]  

where \( m_1 = \text{January}, \ldots, m_{12} = \text{December} \)

\( E_m \): Actual energy production by plant in month (kWh)

\( E_t \): Annual energy production by plant (kWh)

For the estimated energy generated by PV plant, in order to inspect the performance of PV power plant in reference to global and technical factor, we have to calculate the estimation energy that may produce using this PV plant, using Equation (8).

\[ E_e = H \times A \times \eta \]  

\( E_e \): Estimated energy generated by PV plant (kWh)

\( H \): Irradiation (kWh/m\(^2\))

\( A \): Net plant area (m\(^2\))

\( \eta \): Efficiency of photovoltaic module in operating condition

Figures 7 and 8 shows the actual vs. estimation energy output and the load consumption in both villages.

According to the result, the total energy generated for the period (2015–2017) is 15.12 and 14.5 MWh in Saeed and Mkahel, respectively.
The maximum generated energy was 626.2 kWh in June 2017 and the minimum was 201.8 kWh in December 2017 for Saeed Area, whereas in Mkahel, the maximum generated energy was 605.07 kWh in July 2016 and the minimum was 271.5 kWh in February 2015.

4. Technical impact of rural electrification in Al-Mkahal and Saeed villages

4.1. Performance ratio (PR) of PV systems
This impact factor is also called quality factor because it measures the actual energy ratio to estimated energy and shows the loss effect on yield due to geographical and seasonal factors which affect the PR value to fall to 40–90%, and for well-designed system, PR ratio range is 70–90%.
The annual average PR in Saeed is 71%, and the maximum value of PR is 93% in August 2015 and the minimum value of PR is 43% in February 2017, as shown in Figure 9.

The annual average PR in Mkahel is 77%, and the maximum value of PR is 90% in July 2016 and the minimum value of PR is 54% in April 2016, as shown in Figure 10.

4.2. Capacity utilization factor (CUF)
This factor measures the actual energy to output if the system operated at nominal power during the specific period, using Equation (11).

\[
CUF = \frac{Et}{(H + P)} \times 100\% \tag{11}
\]

\( P \): Installed capacity of the plant (Wp)
\( H \): Number of hours in one year/month/day

The annual average CUF in Saeed is 23%, and the maximum value of CUF is 31% in August 2015 and the minimum value of CUF is 13% in December 2017, as shown in Figure 11.

The annual average CUF in Mkahel is 23% as Kkirbat Saeed, and the maximum value of CUF is 32% in October 2017 and the minimum value of CUF is 15% in May 2015, as shown in Figure 12.
CUF value refers to the period of time during a year when the PV system is generating energy at its full power energy, so for Saeed and Mkahel area, it is about 84 days in a year.

4.3. Performance of battery charging and discharging
In both sites, the monitoring system checks each day using the sensor and installed data logger the following parameters:

- Battery temperature
- Ambient temperature
- Charging and discharging state of the battery

These parameters help the analyzer to ensure that the system works without any problem and to solve any issues that may affect the operation of the system in future; Figures 13 and 14 are a sample from both sites.
5. Economic and social impact of rural electrification in Al-Mkahal and Saeed village

Economics is the basis of most engineering decisions so this section presents an economic analysis of the proposed stand-alone PV system estimated by using the life cycle cost (LCC) method. The LCC of an item consists of the total costs of operating and owning it over its lifetime. The costs of these system items include buying cost expressed in today’s price, operating cost, and maintenance and replacement cost.

Economic and social impacts of rural electrification at the household level are multidimensional: both tangible and intangible. The impacts and benefits are either direct or indirect. Rural areas in Palestine consume above 65% of supplied electricity in the household level. The direct impacts are mostly economic, family’s income was enhanced, and the efficiency of their product was increased. The other impacts are related to the social and cultural aspects of life, areas such as education, health, women’s status, modernization, etc. (Ishaq, Ibrahim, & Abubakar, 2013).

6. Environmental impact of rural electrification in Al-Mkahal and Saeed villages

Recently, environmental benefits may be one of the important reasons for using PV systems in rural areas. The annual reduction of CO\textsubscript{2} for Al-Saeed and Al-Mkahal villages is shown in Table 4.

| #  | System       | CO\textsubscript{2} emission reduction (kg.CO\textsubscript{2}) |
|----|--------------|-------------------------------------------------------------|
| 1  | Khirbat Saeed| 13,612.851                                                  |
| 2  | Khirbat Emkahel| 12,561.57                                                    |

7. Conclusions

The design and analysis of results of the implemented systems and technological configuration of electrification of Saeed and Al-Mkahal villages with micro-grid system generation have performed very well. The electricity dispenser and training on load management key for no blackouts, battery in good health, and minimum start-ups of the generator set. From this pilot project, it is clear that utilization of PV-hybrid system is more economically feasible for electrification of remote villages with geographic, climate, and load conditions similar to these communities in Palestine. The PV system does not pollute the environment as it uses diesel generator.

Acknowledgments

The research leading to these results was made possible by funding from the Spanish Cooperation and supervision by ERC at An-Najah National University. Therefore, we would like to express our gratitude to all the above partners for their support.

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Availability of data and material

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

Citation information

Cite this article as: An overview of electrification rural areas in Palestine by using micro-grid solar energy, Imad H. Ibrik, Cogent Engineering (2019), 6: 1638574.

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