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SCIENCE DIRECT
Renewable and Sustainable Energy Reviews
10 (2006) 128–138
RENEWABLE & SUSTAINABLE ENERGY REVIEWS
www.elsevier.com/locate/rser

Techno-economic feasibility of energy supply of remote villages in Palestine by PV-systems, diesel generators and electric grid

Marwan M. Mahmoud*, Imad H. Ibrik

Energy Research Centre, An-Najah National University, Nablus, P.O. Box 721, West Bank, Palestine

Received 14 September 2004; accepted 15 September 2004

Abstract

As a contribution to the development program of rural areas in Palestine, this paper presents three energy supply alternatives for a remote village represented in PV system, diesel generator and electric grid. Design of these systems and the associated costs of their utilization are illustrated.

A computer-aided dynamic economic evaluation method with five indicators is used to compare the economic-effectiveness of these energy systems. The results show that, utilizing of PV systems for rural electrification in Palestine is economically more feasible than using diesel generators or extension of the high voltage electric grid. The obtained results represents also a helpful reference for energy planers in Palestine and justify the consideration of PV systems more seriously.

Keywords: Techno-economic feasibility of energy systems; Rural electrification dynamic evaluation methods; PV-power generators

Contents

* Corresponding author.
E-mail address: rerc96@yahoo.com (M.M. Mahmoud).

1364-0321/$ - see front matter
doi:10.1016/j.rser.2004.09.001

1. Introduction

Palestine has a large number of remote small villages that lack electricity and the probability of connecting them with the high voltage grid in the near future is very poor due to financial and political situation [1]. The daily average of energy demands in these villages are extremely low and vary in the range of 0.5–3 kW h per household. The main electrical loads in these villages are represented in lighting, TV and refrigerators. Small diesel generators of power range from 3 to 7 kV A are widely used by different villagers to cover the power demands of their houses and to sell the excess generated power at very high price (US \$ 0.8–1.4 per kW h) to their neighbors [2]. Usually the operation of these generators is limited on the night periods. The low voltage networks connecting these systems with the consumers are mostly unprofessionally layed out, which makes these networks dangerous and accompanied with high power losses. In addition, these small generators pollute strongly the environment, and are not reliable due to their frequent faults. The price of diesel fuel in Palestine is relatively high since it amounts to US \$ 0.65/l.

Therefore, utilizing of such generators does not represent a durable effective solution.

Palestine has a high solar energy potential, where the daily average of solar radiation intensity on horizontal surface is 5.4 kW h/m^2, while the total annual sunshine hours amounts to about 3000 [3]. These figures are very encouraging to use PV generators for electrification of remote villages as it has been world wide successfully used.

A non electrified rural village, which represents a considerable number of Palestinian rural villages had been selected for implementing a techno-economic study of using PV systems, diesel generators and electric grid for electrification of such villages.

2. The remote village Atouf–Jordan valley

2.1. Location and living conditions

Depending on a comprehensive assessment on non-electrified villages in the West Bank [1], Atouf was found to be one of the most appropriate villages to be subject to a techno-economic comparison study on electrification by grid connection, diesel generators and solar electric generators [1].

This village is located in the Jordan Valley (West of Jordan River) at the coordinates 32°15′N; 35°30′E. Its inhabitants work mainly in farming and cattle breeding. Their number amount to about 200 living in 25 houses. A school and a small clinic are available in Atouf. Drinking water is obtained from artesian wells in the village area. The economic situation is moderate since the income of an inhabitant does not exceed 12,000 US $ per year.

The daily energy needs in such villages are very low. The households use mainly wood and biomass for cooking and baking bread. Kerosene and gas lamps are still used for lighting [1].

The village has no gas stations and is 10 km far from the nearest high voltage grid (33 kV).

2.2. Solar and wind energy potential

The village area (Jordan valley) is known with high solar energy potential and low wind energy potential. The annual average of wind velocity is about 3 m/s which makes the utilization of wind energy converters surely un feasible. In contrary, utilizing solar energy would be feasible since the daily average of solar radiation on horizontal surface (E_s) was measured to $E_s = 5.4$ kW h/m^2 day [3].

During main summer months, high solar intensities exceeding 8 kW h/m^2 day has been measured. The lowest average intensity has been registered during January with a value of 3.2 kW h/m^2 day. The village launches about 3000 sun shine hours per year. The annual average of ambient temperature amounts to 22 °C while it exceeds 37 °C during the months June–August [3].

Most houses of the village have solar water heaters on their roofs which is enough to cover the total daily hot water needs from April to October. The above briefed illustration had encouraged us to candidate this remote village to be a model for a solar electrification in Palestine.

3. The PV-power supply system

3.1. The electrical load of the village

The distance between the village and the nearest tower of the 33 kV lines is 10 km. The electrical load in the village is mainly concentrated on the night period since the population work during the day in the agricultural fields and cattle pasture.

The main electrical loads necessary for improving living conditions in the village are: household appliances (lighting, TV, refrigerator, radio, washing machine and fan); street lighting (sodium lamps); school appliances (lighting, educational TV and lab equipment); clinic appliances (lighting, refrigerator and lab devices). These are specified in Table 1.

3.2. Sizing of the PV-generator

The most appropriate PV power system to cover such a load is illustrated in Fig. 1.

The peak power of the PV generator (P_{pv}) is obtained as follows [1]:

$$P_{pv} = \frac{E_L}{\eta_V \eta_R \mathrm{PSH}} S_f \tag{1}$$

where E_L (daily energy consumption) = 95.7 kW h, the peak sun hours PSH = 5.4 [4]; the efficiencies of the system components ($\eta_R = 0.92$, $\eta_V = 0.9$) and the safety factor for compensation of resistive losses and PV-cell temperature losses $S_f = 1.15$. Substituting these values in Eq. (1), we obtain the peak power of the PV generator:

$$P_{pv} = 24.614\ \mathrm{kW_p}$$

To install this power, a mono-crystalline PV module type SM 55 [222] of a gross area of $A_{pv} = 0.4267\ \mathrm{m}^2$, rated at 12 VDC and a peak power of $P_{mpp} = 53\ \mathrm{W_p}$ is selected. The number of the necessary PV modules (N_{pv}) is obtained as:

$$P_{pv} = \frac{P_{pv}}{P_{mpp}} = 464\ \text{PV modules} \tag{2}$$

Each 16 modules will be connected in series to build 29 parallel strings. Considering the open circuit voltage ($V_{oc} = 21.7$ V) and the short circuit current ($I_{sc} = 3.15$ A) of SM 55

Table 1
The electrical loads in the village Atouf

	Energy consumption (W h/day)
Households	87,500
Street lighting	4000
School	2200
Clinic	2000
Total daily energy consumption	95.7 kW h/day

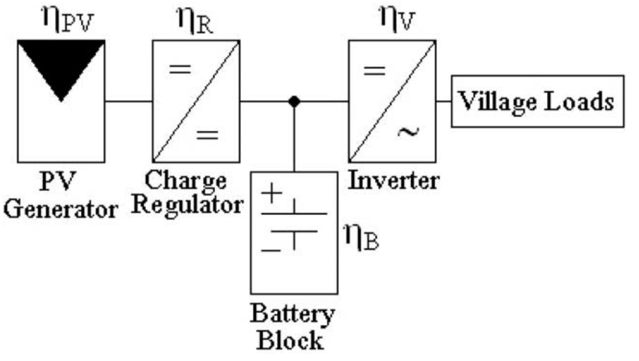

Fig. 1. PV power system of the remote village (Atouf).

at standard conditions [4], we obtain an open circuit voltage and short circuit current for this PV array of:

$$V_{oc} = 21.7\ \mathrm{V} \times 16 = 347.2\ \mathrm{V}$$

$$I_{sc} = 3.15 \times 29 = 91.35\ \mathrm{A}$$

Accordingly, the maximum power point of this array will be in the *I–V* curve at the coordinates of $V = 278.4$ V and $I = 88.16$ A.

3.3. Sizing the battery block

The storage capacity of battery block for such systems is considerably large. Therefore, special lead–acid battery cells (block type) of long life time (>10 years), high cycling stability-rate (>1000 times) and capability of standing very deep discharge should be selected. Such battery types are available but at much higher price than regulars batteries. The ampere hour capacity (C_{Ah}) and watt hour capacity (C_{wh}) of the battery block, necessary to cover the load demands for a period of 1.5 days without sun, is obtained as follows [2,4]:

$$C_{Ah} = \frac{1.5 \times E_L}{V_B \times \mathrm{DOD} \times \eta_B \times \eta_V} \tag{3}$$

$$C_{wh} = C_{Ah} V_B \tag{4}$$

where V_B and η_B are voltage and efficiency of battery block, while DOD is the permissible depth of discharge rate of a cell. Assuming realistic values of $\eta_B = 0.85$, DOD = 0.75 and $V_B = 220$ V, we obtain:

$$C_{Ah} = \frac{1.5 \times 95700}{220 \times 0.75 \times 0.85 \times 0.9} = 1137.2\ \mathrm{A\,h}$$

$$C_{wh} = 1137.2 \times 220 = 250.2\ \mathrm{kW\,h}.$$

Table 2
The associated costs of the PV-power system

No.	Component, material or work	Quantity	Unite price NIS	Total price NIS[a]	Life time/ years
1	PV-module (SM 55)	24592 W_p	18	442,656	25
2	Support structure	29	225	6525	25
3	Battery cells	110	1534	168,740	10
4	Charge regulator	1	54,000	54,000	25
5	Inverter	1	72,000	72,000	25
6	Circuit breakers and switches			787.5	10
7	Installation material		2250	2250	25
8	Civil works			9000	
9	Installation cost			9000	
	Total system cost			764,958.5	

[a] 1 US $=4.5 NIS.

To install this capacity, 110 battery cells (each cell rated at 2 V/1100 A h) have to be connected in series to build a battery block of an output rated at 220 VDC/ 1100 A h [4].

3.4. The charge regulator and inverter

The charge regulator (CR) is necessary to protect the battery block against deep discharge and over charge. Input/output ratings of CR are fixed by the output of the PV array and V_B [5]. In this case the appropriate rated power of CR is 25 kW. In this power range it is recommended that the CR should have a maximum power control unit.

The input of inverter have to be matched with the battery block voltage while its output should fulfill the specifications of the electric grid of the village specified as [5]:

$$3 \times 380\ \text{V},\ 50\ \text{Hz (sinusoidal voltage) and } 20\ \text{kV A}.$$

3.5. The coast of PV system

The associated costs of the components, materials and errection of the PV system are listed in Table 2.

4. The diesel electric generator

Diesel generators are widely used in Palestine to provide remote villages with electric power. Usually, these generators require high running cost, frequent maintenance and they pollute the environment [2].

The ratings of the diesel generator are determined by the load. The total load of the village is 16.7 kW. Hence, we select a 20 kV A generator type (catterpiller) with three-phase output AC voltage (3×380 V), 50 Hz with a power factor of 0.85.

Table 3
The associated cost of the diesel generator system

No.	Component or item	Unit	Life time year/h	Unite price NIS
1	Diesel generator	1	13 years	32,000
2	Diesel	Litre	8 L/h	2.9
3	Engine oil	Litre	5 L/150 h	6
4	Diesel filter	1	750 h	20
5	Air filter	1	3000 h	150
6	Overhaul	1	26,280 h	6300
7	Salvage value			–

The associated costs of this generator are listed in Table 3.

5. Electric grid extension

Transmission lines are designed to transport large amounts of electric power, usually expressed in watts or kilowatts, over long distances [6].The voltage at which these lines operate may range from few thousand volts to a value of 750 kV. In general, the larger the amount of power to be carried, and the greater the distance to be traversed, the higher the voltage at which the transmission line is designed to operate.

The transmission line voltage (V_t) is selected according the following equation [6]:

$$V_t = 5.5\sqrt{0.62L + \frac{S}{150}}\ (\mathrm{kV}) \tag{5}$$

where L the length of the transmission line in km and S is the three phase apparent power of the load. Applying Eq. (5) on the mentioned remote village where $L = 10$ km and $S =$ 21 kV A we obtain:

$$V_t = 5.5\sqrt{0.62 \times 10 + \frac{21}{150}} = 13.85\ \mathrm{kV}$$

As usual, the next available higher standard transmission line voltage value, which is 33 kV (rms value), will be selected.

5.1. Transmission line system cost

The 22 kV transmission line system (TLS) consists mainly of towers, trusses, conductors, insulators, earthing electrodes, isolator switch distribution transformer, distribution board and other installation accessories. Illustration of the TLS design in detail will be renunciated because it is well known and in order to limit the size of this paper. Detailed TLS design is found in [6]. The local costs of main system components in detail with the total cost of accessories and works are illustrated in Table 4.

The needed maintenance cost for the TLS and distribution transformer during the life time of the system, which is assumed to be 25 years, amounts to 2% of the total TLS cost [6].

Table 4
The local costs of the 22 kV transmission line system for the remote village Atouf

No.	Component material, or work	Quantity	Unit price NIS	Total price NIS
1	Tower 12 m length	30	4255.2	127,657
2	Truss 12 m length	82	2650	217,300
3	Conductor ACSR 50 mm^2	33,000 m	5	165,000
4	Conductor ACSR 35 mm^2	11,000	2.5	275,000
5	Strength insulators for towers	180	230	41,400
6	Pin insulators for trusses	246	180	44,280
7	Intermediate cross arms	100	400	40,000
8	Earthing electrodes 18 $mm^2 \times 1.5$ m	202	35	7070
9	Isolator switch	1	10,530	10,530
10	Transformer 30 kV A (22/0.4 kV)	1	10,000	10,000
11	Distribution board	1	14,000	14,000
12	Mechanical parts, installation material, obstacles for tower climb and various accessories			34,790
13	Total installation cost of TLS			265,620
	Total TLS cost			1,005,147

This means that the yearly maintenance cost (C_m) is:

$$C_m = \frac{0.02 \times 1005147}{25} = 804.5 \text{ NIS/Year.}$$

6. Economical evaluation of energy supply systems

6.1. Static and dynamic procedures

This economic study is based on a guide to financial evaluation of investment projects in energy supply by Finck and Oelert [7]. The study has been translated into a computer program in which uncertain assumptions can be altered and through simulation their effects can be measured. The outcome of a project is established through a set of economic indicators. These indicators for PV, diesel and grid extension will then be compared with each other.

In order to establish the absolute or relative acceptability of an investment, we can use tow different procedures, the static method and the dynamic method. They differ from each other in the sense that the dynamic method takes into account the different times at which payments on an investment are receivable. This means in our cases that payments are discounted if they come after a project is commissioned.

Therefore, by using dynamic procedures, receipts and payments are given higher value the earlier they fall and lower value later.

Because of this time component in evaluating investment linked payments, the dynamic method produce undoubtedly better results than the static method [7].

6.2. Dynamic method

This method consists mainly of the following economic indicators:

(a) Net present value.
(b) Internal rate of return.
(c) Annuity.
(d) Cost annuity (cost annuity per production unite).
(e) Dynamic pay-back period.

6.2.1. Net present value (NPV)

The NPV of an investment project at time $t=0$ is the sum of the present values of all cash inflows and outflows linked to the investment:

$$\mathrm{NPV} = -I_0 + \sum_{t=0}^{T}(R_t - I_t)q^{-t} + L_T q^{-T} \tag{6}$$

$$q^{-t} = \left(1 + \frac{i}{100}\right)^{-t} \tag{7}$$

where I_0 is the investment cost at the beginning ($t=0$), T is the life time of project in years, R_t is the return in time period t, I_t is the investment in time period t, q^{-t} is discounting factor, i is the discount rate and L_T is the salvage value.

A project is profitable when NPV > 0 and the greater the NPV the more profitable. Negative NPV indicates that minimum interest rate will not be met [7].

6.2.2. Internal rate of return (IRR)

IRR computes for what interest the NPV will be zero, so it expresses the achievable interest tied-up in the investment.

$$0 = -I_0 + \sum_{t=1}^{T} R_t\left(1 + \frac{\mathrm{IRR}}{100}\right)^{-t} + L_T\left(1 + \frac{\mathrm{IRR}}{100}\right)^{-T} \tag{8}$$

$\mathrm{IRR} = i$ (other wise it would be better to put the money in the bank).

6.2.3. Annuity (A)

The annuity converts all net cash flows connected with an investment project into a series of annual payments of equal amount [7]:

$$A = \mathrm{NPV} \times \mathrm{RF}(i, T) \tag{9}$$

$$\mathrm{RF} = \frac{q^t(q-1)}{q^t - 1} \tag{10}$$

where RF is the capital recovery factor. $A=0$: interest on the capital invested is obtained at least at level of cut-off interest rate. The energy alternative with the highest A is the most favourable one.

6.2.4. Cost annuity (A_k)

A_k is a shortened form of annuity method without inclusion of income in the calculation, it can only be used for evaluating the relative favorability of investment projects on the basis of costs per annum or per unit production [7,8].

$$A_\mathrm{k} = \left[\left(\sum_{t=1}^{T} k_0 q^{-t}\right)\mathrm{RF}(i,T)\right] + (I_t - L_T)\mathrm{RF}(i,T) + L_T i \qquad (11)$$

$$\mathrm{kW\ h - cost} = \frac{A_\mathrm{k}}{\text{Total yearly kW h produced}} \qquad (12)$$

where k_0 is the operating costs per time period. Project with lowest A_k or cost per production unit (kW h) should be selected.

6.2.5. Dynamic pay back period (DPB)

The purpose of calculating DPB is to determine the time point at which the capital invested in a project will be recovered by annual returns, within its service time. The DPB is longer than the static pay-back period because not only capital needs to be recovered but also the calculatory interest maximum acceptable DPB must be shorter than the service life time of the project [7,8].

$$\mathrm{DPB} = \frac{I_0}{\left[\left(\sum_{t=0}^{T}(R_t - I_t)\right)/T\right]} \qquad (13)$$

6.3. Evaluation results and conclusions

To apply the above five dynamic economic methods on the three energy supply systems of the remote village, a computer program, which considers all algorithms (Eqs. (6–13)) had been written. The different variables (costs, salvage values and life time of the system components) necessary for running the program have been taken from Tables 2–4. A realistic interest value amounting to $i = 8\%$ had been considered. Table 5 illustrates the obtained evaluation results for the five dynamic methods if the production unit (kW h) of each system is sold to the consumer at its production cost.

Table 5
Evaluation results of the dynamic economic methods applied on the three energy supply systems

Dynamic method (indicator)	PV-system	Diesel generator system	Transmission line system
Net present value (NIS)	30,595.6	1003.1	3415.7
Internal rate of return (%)	8	8	8
Annuity (NIS)	2866.2	93.96	320
Cost annuity (NIS)	79,511.9	316,160.4	495,213.3
Cost of kW h production (NIS)	2.28	2.76	3.06
Dynamic pay-back period (year)	10.4	11.95	10.71

Based on the above results the following conclusions can be made:

1. The cost annuity and the production cost of energy unit (kW h) of PV-system are less than the costs related to the other tow systems.
2. The net present value (NPV) of the PV system is much higher than the NPV of diesel and transmission line systems.
3. The dynamic pay-back period DPB of the PV-system is less than the DPB of diesel and transmission line systems.
4. The internal rate of return (IRR) for the three systems is equal to the interest rate because the production unit (kW h) of each system is assumed to be sold at its production cost. Of course, if the kW h will be sold at 2.28 NIS then the IRR of the diesel and transmission line systems will be less than 8% and their NPV will be negative.

Therefore, utilizing of PV-system is more economic feasible for electrification of remote villages of geographic, climate and load conditions similar to Atouf village in Palestine. In addition the PV-system do not pollute the environment as the case of using diesel generator.

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