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Comparative economic viability and environmental impact of PV, diesel and grid systems for large underground water pumping application (55 wells) in Jordan

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Abstract

The current work was based on four selected underground water production wells (W25, W29, W34 and W47), out of 55 wells available in total, at Disi water project located south of Jordan to power underground water pumping using a stand-alone solar photovoltaic (PV) system for an operation period of 25 years. The economic viability of large stand-alone solar PV system of 13 MW in total had been analysed through life-cycle cost computation compared with other four possible powering options, i.e. genset-powered, grid-networked systems, PV-grid and PV-genset. Individual cost banks were identified and studied based on previous practical experiences. Results of the life cycle costs per kWh in the order from the best to worst alternative is the PV (US$0.136 /kWh), PV/grid (0.140), grid (US$0.144 /kWh), PV-genset (0.185), and genset (US$0.239 /kWh), respectively. This proved that the PV solar system is more cost effective and suitable to use over other conventional types of energy for such large power system. Also, payback period analysis was carried out and showed that the PV system is a good option to be recommended highly compared with the other options. Following, the environmental aspects of using clean PV energy were discussed. The resulting savings in CO_2 emission reached 30,000 tons per well throughout the study period, which summed up to about 1.5 million tons of CO_2 for all Disi wells. A briefed risk assessment was conducted for the intended project. Risk levels associated to several hazards were identified as well. The work in this paper can be generalized to other cases worldwide under similar conditions.

Keywords: Photovoltaic; Economic viability; Life cycle cost; CO_2 emission; Risk assessment

Background

The major conventional sources for powering underground water pumps are either fossil fuel generators or electricity from a nearby grid. Both methods have considerably expensive running costs and varying implementation costs depending on the location, nature and budget of the water project. The choice of this concept over conventional means of energy regarding cost over a period of time as well as CO_2 emission is gaining more and more popularity around the world, especially where electricity is either unavailable or unreliable. Several papers regarding these issues were found in the open literature and are summarised as follows:

Thomas (1993) stated that the method of the life cycle cost (LCC) is an efficient method to be used to evaluate the financial viability of a PV water pumping solar system. Senol (2012), Abu-Aligah (2011), Mahjoubi et al. (2010), Odeh et al. (2006), Mahmouda and Natherb (2003) and Kolhe et al. (2002) all studied the economical aspects of solar photovoltaic (PV) water pumping compared to diesel genset, by using the method of LCC. The results indicated that the PV solar water pumping, in terms of cost, is better than the diesel pumping systems.

The studies of Purohit (2007), Firatoglu and Yesilata (2004) Short and Oldach (2003) proved that the financial viability of solar PV energy with respect to the other conventional options, electric or diesel genset, for the pumping of water is the principal barrier which slows down its broad adoption. Kordab (2007) studied the

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priority options of photovoltaic systems for water pumping in rural areas in the Economic and Social Commission for Western Asia (ESCWA)—the United Nations, member countries by using cost analysis method to determine the cost of the kilowatt hour produced compared with diesel fuel prices during the life of the PV systems (assumed to be 20 years). The study stated that the PV systems are competent with other options when the total cost of the PV system is less or equal to US$7 /$W_p$.

Alsema and Nieuwlaar (1997) conducted a life cycle assessment LCA which involves the comprehensive assessment of all environmental impacts throughout the life cycle of the PV system. The concept of energy pay back time (EPBT) was also discussed. Eventually, the conclusions revealed that, from an environmental point of view, the use of PV as a replacement for fossil fuel-based electricity generation has significant environmental benefits and there seems to be no significant bottlenecks that cannot be overcome. Goodrich et al. (2011) studied all aspects regarding the PV system components manufacturing costs. His study depended on first-hand data from industry stakeholders, supplemented with public data sources. A sensitivity analysis in the identification of cost drivers was also conducted, along with discussing the direct and indirect costs.

Tamrat (2007) analysed the viability of renewable energy technologies for rural electrification in selected sites in Ethiopia. The results showed that the use of micro-hydro power generation is preferable. But in most areas where the wind speed was below 5 m/s with no stream or river available, PV system would be the best choice. Meanwhile, Elker (2005) and Heliknson et al. (1991) found that photovoltaic power is more cost-competitive when used to power a micro irrigation system as compared to an overhead sprinkler system. The work of Qoaider et al. (2010) was to investigate the economic feasibility of photovoltaic technology to supply the entire energy demands to off-grid irrigated-farming-based communities in the arid regions. Chandraskar and Kandpal (2005) presented a framework for studying the effect of several existing and proposed financial and fiscal incentives on the effective capital cost of a renewable energy system to the user. The results showed that the provision of income tax benefit on the amount of investment made by the user on the purchase and installation of renewable energy system is likely to be more attractive than the provision of low interest loan.

Krauter and Ruther (2003) conducted a CO_2 comprehensive balance within the life-cycle of a photovoltaic energy system. Calculations of the possible effect on CO_2 reduction by PV energy systems were made in Brazil and Germany. Roy (2012) demonstrated that the test results on the application of solar PV DC system provided satisfactory performance on water pumping, and moreover, it is user and environmentally friendly. Together with decreasing PV module costs and increasing efficiency, PV is getting more pervasive than ever.

Mahjoubi et al. (2013) investigated the economic viability of remote PV water pumping systems in the desert of Southern Tunisia, which will have to satisfy an average daily volume of 45 m^3 throughout the year compared with diesel genset by using the method of the LCC. Their study indicated economic viability of PV water pumping systems in the desert of Tunisia. Similar work by Grima (2014) was carried out in Ethiopia to study the economic feasibility of water pumping. The result showed that direct coupled PV pumping system is cost-effective in terms of life cycle cost and technologically feasible for rural water supply by virtue of its very low running cost and high reliability of the component and the system as a whole.

Sahin and Rehman (2012) studied economical feasibility of producing energy using PV solar panels of 9.99-kW total capacity and utilizing it to pump water at five locations in Saudi Arabia. They found that the cost of water pumping to vary between 2 and 3 cents/m^3. Parajuli et al. (2104) presented a financial model to compare three technical scenarios of water pumping using petro-diesel, jatropha-based biodiesel and solar photovoltaic pumps to pump drinking water in one of the remote rural village of Nepal. The financial model is carried out to compare the alternatives on the basis of the economic parameters: net present value, equivalent annualised cost and levelised cost of water pumping. Analysis is carried out considering different influential parameters: water head, discharge, incentives on the investments, which have effects on the cost of pumped water. Likewise, in case of biodiesel-based system, different yield rates of jatropha plants are also considered in estimating the cost of producing biodiesel. It was found that biodiesel-based system is more attractive than that of the diesel-based pump but still remains more expensive than that of solar pump. From the technical perspective (reliability and easiness in operation) and economic evaluation of the technical alternatives, solar pumping system was found to be the most viable solution to pump drinking water in the project area.

All previous studies were addressed to small PV water pumping systems. However, as the authors are aware of, no pre-feasibility assessment has been done before in order to assess large-scale off-grid-connected PV power plant (13 MW) for underground water pumping, which made this research a challenge. The aim of this work is to compare the costs of pumping the underground water of five powering options. These are PV, grid, genset and combinations of PV/grid and PV-genset by using the method of the LCC. The question of which one of the system is most cost effective is the subject of this study.

It is based on field results taking into account maintenance and operation costs, fuel costs, salvage costs, in addition to initial costs. The present value of the life time costs of the different methods of pumping was used for comparison.

This current work presents a comprehensive study as it addresses, in addition to economic analysis, the issues of environmental impact due to CO_2 emissions and risk assessment. This project is one of the largest underground water pumping using PV system in the region. Moreover, the water is being pumped from different number of wells (55) covering ground surface area of about 750 km^2 (Ellington et al. 2015). Therefore, it can be considered as a leading project in terms of design and energy management. The authors feel that this study may help the decision-makers to select the most suitable power option out of five power alternatives that have not been addressed before for large underground water pumping systems and can be applied for similar cases globally. It should be noted here all the required data for accomplishing this work are taken from a previous paper published by the authors (Ebaid et al. 2013), which is related to the sizing of the PV components.

Disi wellfield
Wellfield location
The area of Disi wellfield is located in the south of Jordan, 340–350 km away from Amman (GAMA Enerji Co. 2999) as shown in Fig. 1. The wellfield area is more than 20–30 km away from the nearest electrical grid with some wells almost 70 km far. Fifty-five water production wells were arranged in 12 main lines forming a plant-shaped distribution, which helped in ensuring better access to each well and covering as much as possible of the aquifer area.

Selection criteria of design wells
The 55 wells where categorized into five main groups depending on its altitudes, and the maximum altitude difference was found to be 132 meters. If a difference of 25 m in altitude would be assumed as significant in categorizing the wells, four groups are formed: A, B, C and D. One well was selected from each of the four groups. Those selected wells were geographically optimized to represent the whole Disi wellfield that will help construct a proper solar map for all Disi area. The selected wells were as follows: W25 of group A, W39 of group B, W34 of group C and W47 of group D.

Wellfield pumping head
For completion of work, some design data, about the pumping system is presented here. This includes the total pumping heads (TPH) of each designed well, at a continuous flow rate of $Q = 80^l/_s$ or $288^{m^3}/_{hour}$ according to the agreed project specifications for the next 25 years. TPH will be taken at the end of each 5 year period and then added to the initial conditions of the first period (the current starting conditions of the project). Withdrawal of thousands of cubic meters per day is an unnaturally rapid change in a groundwater system and results in some

Fig. 1 Disi aquifer location in south of Jordan, Gama Energy Co. (GAMA Enerji Co. 2010)

major perturbations of the water reserves. Initially, water level drops very rapidly in the immediate vicinity of the well. This lowering of the water level is known as drawdown and may amount to many tens of meters. The pumping head of each well is being directly affected by the continuous withdrawal of water that causes drawdown. Figure 2 illustrates the predicted water drawdown from the selected four design wells.

To identify the reason behind the rapidly starting drawdown of wells, the time-drawdown hydro-geological analysis should be comprehended, which includes understanding the development procedures of the cone of depression (Heath 1983) which occurs in an aquifer when groundwater is pumped from a well.

To correctly select a proper pump, the expected pumping heads for the next 25 years were studied through intensive hydro-geological analysis of the aquifer, conducted in the feasibility study phase of the project. The know-how of these data was considered as classified Disi project specifications by the Turkish GAMA Enerji Co. 2010. which is responsible for building and operating the project. To ensure that the selected pump will meet all head or discharge pressure requirements, the TPH has to be calculated (Eq. 1), which is being directly affected by the continuous withdrawal of water that causes drawdown (Ebaid et al. 2013). Based on the above, a submersible pump is selected and supposed to last 25 years according to its specification (Table 1).

$$\text{TPH} = \text{SWL} + \text{DD} + \text{H}_\text{L}(\text{m}) \tag{1}$$

Where THP is the total pumping head (m), SWL is the static water level (m), DD is the drawdown (m) and H_L is the head loss in the well due to pipes and fittings, and

$$H_L = f\left(\frac{L}{D_i}\right)\left(\frac{V^2}{2g}\right) \ (m) \ \text{(Darcy-Weisbach)} \tag{2}$$

where f is the friction factor, L is the total length of pipe (m), D_i is the inner diameter of pipe (m) and V is the velocity of water (m/s).

For the current pumping case, pumping lines connecting the semi axial submersible vertical pump (Flowserve Hamburg Company) and the pressure tank are already selected to be of galvanized steel pipes with internal diameter D_i of 40 cm and internal roughness e_t of 0.15 mm, friction factor f can be obtained using Moody chart, hence head loss H_L can be obtained from Eq. 2 above and graphically shown in Fig. 3.

It can be seen that the head losses are clearly not significant, and it can almost be neglected when estimating the pumping head. Then, the total pumping heads (THP) of design wells for the next 25 years of water pumping can be directly calculated from Eq. 1 and shown in Fig. 4.

It should be noted here that the TPH is lower than the SWL. The reasons are that the head loss is very small as shown in Fig. 3 and the effect of the drawdown of water during pumping which decreases with head increase. In addition to that, the water is not replenished.

Water power, pump power and motor power

Water power P_W is the power required to raise water at a specified flow rate $\dot{Q}$ against a specified head, assuming 100 % pump efficiency η_P and this can be calculated by Eq. 3,

$$P_W = (\rho g)(\dot{Q})(\text{THP}) \ (kW) \tag{3}$$

Pump power P_P can be either the power developed at the motor shaft (motor output) or that absorbed at the pump shaft (pump input), and it depends on the pump efficiency η_P according to Eq. 4,
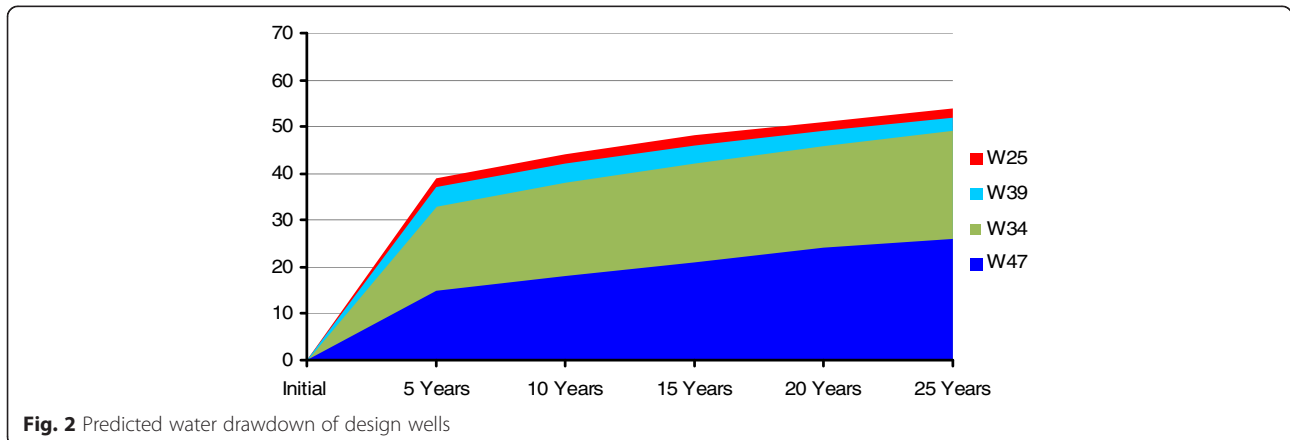
$$P_P = \frac{P_W}{\eta_P} (kW) \tag{4}$$

Fig. 2 Predicted water drawdown of design wells

Table 1 Predicted trend of well pump head variation for continuous 25 years of pumping (Ebaid et al. 2013)

Well number	Current actual SWL (m)	In 5 years (m)	In 10 years (m)	In 15 years (m)	In 20 years (m)	In 25 years (m)
W25	101.6	252.0	260.5	266.4	269.8	272.3
W39	128.5	263.4	271.5	277.1	280.3	282.7
W34	147.4	245.0	252.4	257.6	260.5	262.7
W47	161.4	238.2	242.2	245.0	246.6	247.7

Motor power P_m is that needed by the electrical motor to operate the pump, it differs according to the motor efficiency η_m as shown in Eq. 5 below:

$$P_m = \frac{P_P}{\eta_m}(kW) \tag{5}$$

Using Eqs. 3, 4 and 5, motor power P_m design values are obtained and drawn graphically in Fig. 5. Pump and motor efficiencies were taken as 77.9 and 89 %, respectively, from the specification of the originally selected submersible pump.

Methods
Economic analysis
The investment costs of PV systems are still relatively high (Zwaan 2003), although this cost is decreasing rapidly as a result of technology improvements and economies of scale. High investment costs, or total system costs, represent the most important barrier to PV deployment today. Total system costs are composed of the sum of module costs including mounting structures, inverters, batteries, cabling and power management devices.

While the costs of different technology module types vary on a per watt basis. These differences are less significant at the system level, which also takes into account the efficiency and land-use needs of the technology. Total system costs are sensitive to economies of scale and can vary substantially depending on the type

of application according to the International Energy Agency (IEA) (International Energy Agency (IEA) 2009).

In the following sections, a complete economic analysis will be conducted for each proposed energy alternative and the final values will be compared to determine the most cost-effective alternative. The method to be used in this study is the life cycle cost LCC method. Life cycle cost analysis (LCCA) key elements can be broken down into the following three variables: the costs of ownership, the operation costs and the salvage value. The period of time over which these costs are incurred and the discount rate that is applied to future costs are to be equated with present-day costs.

Project alternatives
Prior to beginning an LCCA, project alternatives need to be established. These alternatives were selected to be distinctly different and viable solutions for pumping water from Disi wells. The chosen alternative is usually the most reasonable and cost-effective solution for pumping purposes, but as the comparison includes renewable-versus-conventional energy sources, the selection would more likely be biased for the PV system as environmental and sustainability factors will be included. In this work, five powering scenarios for the submersible pumps are to be discussed in terms of cost effectiveness and installation viability, those five scenarios are as follows:
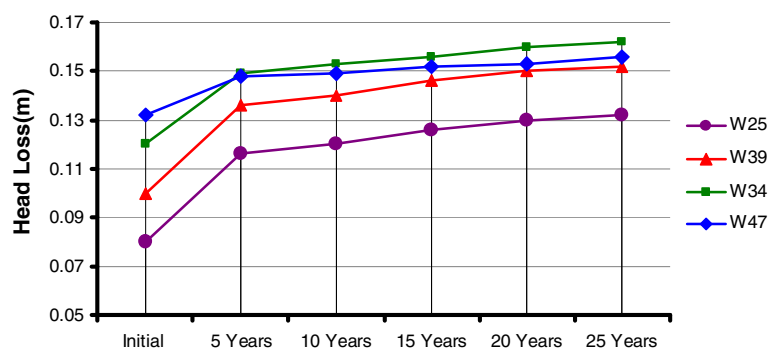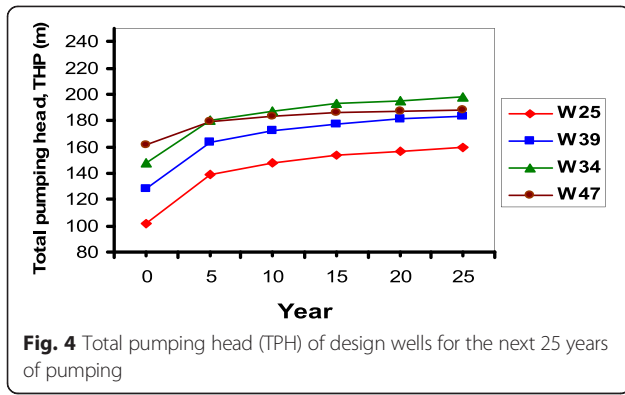

Fig. 3 Calculated head loss of design wells for next 25 years of pumping

Fig. 4 Total pumping head (TPH) of design wells for the next 25 years of pumping

1. Twenty-four-hour PV system, using batteries for night-time operation.
2. Twenty-four-hour electrical grid system. The electrical grid is very far and it would need a huge infrastructure to be available, however, this option will still be considered.
3. Twenty-four-hour diesel genset system which usually requires the use of two generators to back-up each other.
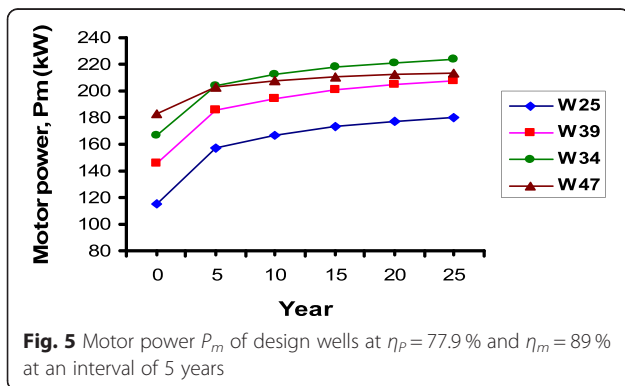
Two more scenarios will be considered, combining the daytime operation of the PV system with night-time operation for each of the other two conventional systems:

1. Twelve-hour PV, 12-h diesel genset system.
2. Twelve-hour PV, 12-h electrical grid system.

Initial system costs (PV, genset and electrical grid)
Costs that will be incurred prior to the running of the system are initial investment costs. All initial costs are to be added to the total LCCA at their full value. However, some parameters that will be used in the LCC should be stated here. These are the following:

1. Real interest rate (i_r): according to Eq. 6, Fisher (International Monetary fund 2010) stated that the

Fig. 5 Motor power P_m of design wells at $\eta_P = 77.9\,\%$ and $\eta_m = 89\,\%$ at an interval of 5 years

real interest rate is approximately the nominal interest rate i minus the expected inflation rate i_f:

$$1 + i_r \cong (1 + i) - \left(1 + i_f\right) \qquad (6)$$

In this work, an optimistic estimation of 1 % real interest rate can be adequate and close the low values in the past few years of the Jordanian economy (Fisher 1977).

2. Present worth value (PW): the present worth value of an annuity A (periodic cash flows) can be calculated according to Eq. 7:

$$PW \ \text{of} \ \text{Annuity} = \frac{P}{A}(A, i, n) = \left[\frac{1 - \frac{1}{(1+i)^n}}{i}\right] \qquad (7)$$

where P is the present value, A is the present value of an annuity and n is the total life (years).

The present value of any money to be received in the future can be computed by Eq. 8:

$$PW \ \text{of} \ \text{Future} = \frac{P}{F}(F, i, n) = \frac{1}{(1+i)^n} \qquad (8)$$

where F is the future value.

The frequency of compounding affects the present value of cash flows. Hence, stated interest rate can deviate significantly from the true interest rate. However, to simplify the calculations of this study, the compounding would be assumed to happen annually in all cases.

PV component initial costs
For the PV system, the cost of each major component in terms of user specified variables is to be determined based on the design specifications of the PV components as summarized below:

- PV panels: poly-crystalline modules, MaxPower CS6X-300W$_P$ solar panel type from Canadian Solar Inc.
- Inverter: 250-kW inverter Sunny Central 250U manufactured by SMA Inc.
- Batteries: 8 V Rolls Series 5000 battery with a 20-h rated capacity of 820 Ah from the American manufacturer Surrette
- Charge controllers: FLEXmax 80, the voltage-adjustable 80 A$_{DC}$

The calculations for sizing the PV system, inverters, batteries and charge controllers and PV areas are all presented in a previous paper related to this work (Ebaid et al. 2013). It should be mentioned here that the listed number of the PV panels is calculated based on the

actual DC power produced after identifying the power losses (temperature loss factor, battery loss factor, cable loss factor, and mismatch loss factor). Another important issue is the life-time efficiency of the PV panels, which will be reduced down to 80 % of the total peak power reaching the panel's rated life of 25 years.

Also, for the total number of batteries required, the calculations are based on the factors that affect their performance (discharge rate and depth of discharge, days of autonomy, aging, temperature, and the round trip efficiency specified by the manufacturer, 80 %). Dust accumulation problem on PV surfaces was accounted for as a 5 % power loss factor (Ebaid et al. 2013). The land availability would not be a problem for the case of this study at Disi area as this desert areas will be most probably offered for free by the government to the project. So, land costs would conveniently be discarded. Based on that, the major components, which include type and rating, quantities, the unit price cost and the total cost, are all listed in Table 2 below.

Genset initial costs

A 250-kW generator would be very suitable for the power requirements. From prior experience with the Jordanian market of generators, Caterpillar gensets (Worldwide Power Products 2012) have good reliability with continuously available service and spare parts, so a Caterpillar C9 250 kW generator was selected with an estimated price (shipping and customs included) of US$100,000. Since two generators will be needed to

backup each other, the total initial cost of this alternative would be US$200,000.

Electrical grid through Disi desert initial costs

Costs for establishing a grid network in Disi desert would certainly be very expensive, especially as the distance from the nearest electrical grid increases. According to confidential data from the National Electric Power Company NEPCO Ltd. and the Electrical Distribution Company EDCO Ltd. 2011 (International Monetary fund 2009), Disi project will require establishment of one main station, 55 transforming substations from 33 to 0.415 kV (500 kVA) on each well and about 150 km of transmission lines.

The estimated cost per kilometre of transmission lines (including the columns, cables, insulators etc.) equals about US$21,429, with an additional cost of US$14,286 per kilometre to cover other miscellaneous costs such as road opening, labour and transportation. With 150 km total distance that the grid lines should cover (considering the 1.5 km spacing between the 55 wells, distance to the main substation and additional distance for line detours due to the hard terrain of Disi), the total estimated transmission line cost for the 55 wells would equal US$5,375,143. Figure 6 below shows the suggested trails that lead to each design well from the main station location (indicated by the black arrow).

The total estimated cost of the 55 transforming substation is US$785,714. For the main station, cost is approximated at US$2,857,143. Total estimated cost

Table 2 Initial PV component costs (Ebaid et al. 2013)

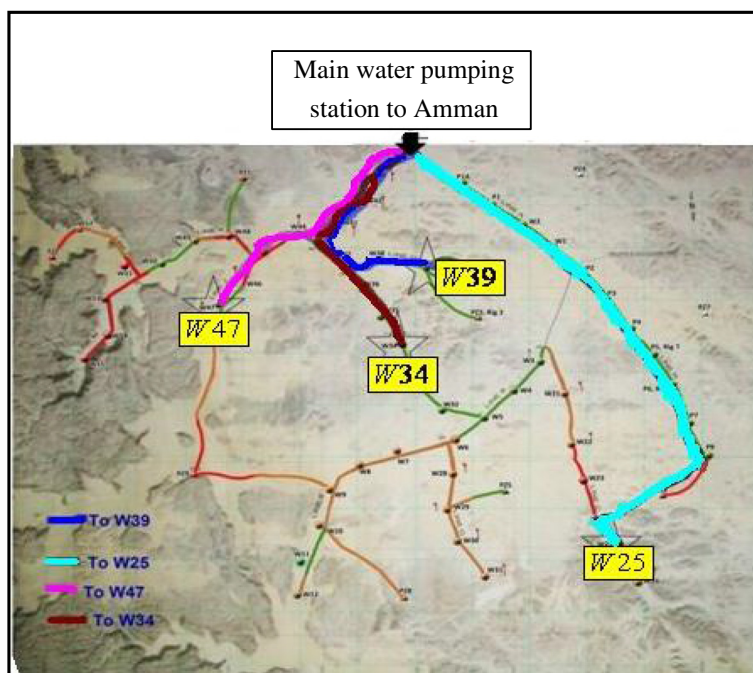| Well number	PV component costs for the PV alternative (prices in USD)					
	PV panels (300 W$_P$) + structure			Inverters (250 kW, SMA Inc.)		
	Quantity	Unit price	Total	Quantity	Unit price	Total
W25	2969	500	1,484,500	1	54810	54810
W39	3503	500	1,751,500	1	54810	54810
W34	3847	500	1,923,500	1	54810	54810
W47	3827	500	1,913,500	1	54810	54810
Well number	Batteries (8 V, 820 Ah)			Charge controllers (FlexMax 80, 24 V, 80 A$_{DC}$)		
	Quantity	Unit price	Total	Quantity	Unit price	Total
W25	1186	1000	1,186,100	395	571	225,545
W39	1399	1000	1,399,100	466	571	266,086
W34	1537	1000	1,537,100	512	571	292,352
W47	1529	1000	1,529,529	510	571	291,210
Gross total PV component costs (prices in USD) (PV panels + structure, inverters, batteries and charge controllers)						
W25	2,950,855					
W39	3,471,496					
W34	3,807,762					
W47	3,789,049					

Fig. 6 Electrical Distribution Company (EDCO) (International Monetary fund 2009) intended trails for electrical grid to each design well

for the grid with a 10 % other cost factor equals approximately US$9, 900,000. Dividing the cost upon the 55 production wells, each well would have an initial cost of US$180,000.

Operation costs

The second step in the completion of the LCCA is to define all future operation costs of each alternative. The operation costs are annual costs of manpower, overhead and fuel involved in the operation of the facility. It excludes maintenance, transport and repair costs. All operation costs are to be discounted to their present value prior to addition to the LCCA total.

PV system operation costs

Most PV system operational costs are related to overheads and labours. It includes on-site guards and labourers for cleaning the modules and regular component checks, especially for the batteries. This cost according to Goodrich et al. (2011) could be three times the usual overheads of electrical systems. Also, Goodrich et al. (2011) stated that the life cycle labour and overhead costs can be estimated to equal US$0.49/$W_p$ for ground-mounted panels. In this work, life-cycle cost of only US$0.2 /$W_p$ is to be considered to compensate for additional manpower and skill needed. Considering the total number of 300 W_p of PV panels used at each design well, a total operational cost for the PV alternative, during the 25 years of operation, would equal US$204,286 for W25; US$234,286 for W39; US$252,857 for W34 and US$241,429 for W47, respectively.

Genset operation costs

The main source of cost for the genset alternative is diesel fuel. Manpower and overhead costs for this alternative are relatively small and assumed to be included in the final contingency factor. As the prices of fuel worldwide are growing up, its expenses are gaining more and more concern regarding operational costs of systems as fuel is directly affected by inflation rates.

Fuel consumption of a diesel genset is related to the load factor of its engine, which is the ratio of required power output to the maximum rated power output of the genset. As the power demand increases, fuel consumption increases accordingly. Special charts for fuel consumption versus the load factor are usually available in the specification sheets of equipment. For the selected Caterpillar C9 250 kW genset, the approximated General Fuel Consumption Chart, (Worldwide Power Products 2012) can be used as a reference at the load factors indicated in Table 3.

Table 3 Fuel consumption versus load factor for diesel gensets GAMA Enerji Co (2010)

Genset size (kW)	Diesel consumption (L/h)			
	One-fourth load	One-half load	Three-fourths load	Full load
200	18	29	42	55
230	20	33	47	63
250	22	36	51	68
300	26	43	61	81

Relating the diesel consumption values to the power demand of wells, bearing in mind that only one generator will be running at a time, Table 4 shows the genset load factors that will be resulted at each design well and the estimated amount of diesel consumed over the whole study period.

The life cycle fuel consumption was calculated by summing the consumptions of all phases of the study period (25 years). As per the phase fuel consumption, it was computed by multiplying the litres/year, at the beginning of each phase, by the length of that phase (5 years). In each year of the study period, the diesel prices are being affected by inflation rates. Therefore, the pricing of fuel costs should be made on present worth bases using the real interest rate $i_r = 1$ % in the time value of money, International Monetary fund, and report no. 09/159 (International Monetary fund 2009). Then, to calculate the present worth (PW), each fuel consumption period should be considered separately and its fuel costs are to be reduced to present worth, similar to the following sample of calculations for well (W25) at the current diesel cost is US$0.73/litre.

$$
\begin{aligned}
\text{Total diesel cost} &= \text{Diesel cost} \times [(315,360 + 315,360) \\
&\quad \times (P/A)(A,1\%,5) + (446,760) \\
&\quad \times (P/A)(A,1\%,20) \times (P/A)(F,1\%,5)] \\
&= 0.73 \times [(315,360 + 315,360) \times 4.853 \\
&\quad + (446,760 \times 18.046 \times 0.9515)] \\
&= \text{US}\$7,834,430 \quad \text{for 25 years of operation} \\
&\quad \text{at W25}
\end{aligned}
$$

Similarly, for the rest of design wells, costs of diesel for the whole 25 year operation period are US$8,855,714 for W39 and US$9,357,143 for both W34 and W47.

Electrical grid operation costs

The electrical grid system operation costs will mainly result from the electricity tariff (electricity price) in cent/kWh, with an additional overhead and manpower cost of 2 % per year of the initial grid cost. Considering the initial cost indicated in section "Electrical grid through Disi desert initial costs", overheads and manpower cost about US$3,571 /year for each well, totalling US$80,000 per well for the whole study period. The water pumping tariff equals 60 cent/kWh according to the retail tariff of electricity according the National Electric Power Company of Jordan (NEPCO) (National Electric Power Company of Jordan NEPCO 2011). Addition of taxes and the soon-expected rise in electricity prices would approximately turn this value to 64 cent/kWh. According to the historical data of electricity prices in Jordan at certain periods, the rise of electricity tariffs has been fluctuating up and down due to the rate of inflation of those periods. In this study, the electricity tariff is assumed to be affected only by an inflation rate of 5 % per year, Blignaut et al. (Blignaut et al. 2005).

Yearly values can be computed through fitting the motor power data using Easy Fit 5.5 Professional software into a probability distribution, and then generate yearly data according to the parameters of the fitted distribution. Results of generated motor power data along with the corresponding kWh electrical consumption and the total yearly prices are all shown in Figs. 7 and 8. The computed total study period costs in Fig. 8 are brought back to present worth and will be directly used in the final LCCA of this alternative.

Table 4 Estimated diesel fuel consumption for each design well in each pumping phase

| Well number	Real load factor (%)					
	Design load factor (ratio)					
	Fuel consumption (L/year)—24-h genset scenario					
	0–5 Years	5–10 Years	10–15 Years	15–20 Years	20–25 Years	Life cycle diesel consumption (L)
W25	0.46 %	0.63 %	0.67 %	0.69 %	0.71 %	10,512,000.0
	One half	Three fourths	Three fourths	Three fourths	Three fourths	
	315,360	446,760	446,760	446,760	446,760	
W39	0.58 %	0.74 %	0.78 %	0.80 %	0.82 %	12,658,200.0
	Three fourths	Three fourths	Three fourths	Full	Full	
	446,760	446,760	446,760	595,680	595,680	
W34	0.71 %	0.86 %	0.89 %	0.91 %	0.93 %	14,147,400.0
	Three fourths	Full	Full	Full	Full	
	446,760	595,680	595,680	595,680	595,680	
W47	0.73 %	0.81 %	0.83 %	0.84 %	0.85 %	14,147,400.0
	¾	Full	Full	Full	Full	
	446,760	595,680	595,680	595,680	595,680	
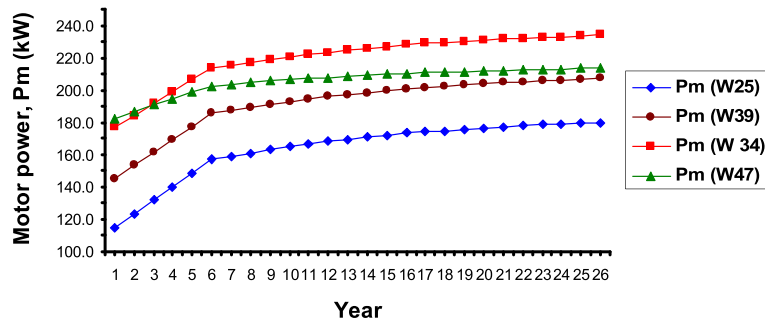
Fig. 7 Yearly motor power P_m of design wells

Maintenance and repair costs

For simplicity, maintenance costs and repair costs have been combined in the LCCA; however, it should be understood that there is a distinction between those two costs. Maintenance costs are scheduled costs associated with the upkeep of the facility, while repair costs are un-anticipated expenditures that are required to prolong the life of equipment system without replacing them.

PV component maintenance and repair costs

Maintenance and repair costs for a PV system can usu-ally be estimated as 10–15 % of the operational costs for the whole life of the PV system, Hansen et al. (2005). For this work, it will be conservatively taken as 12 %, which would be equal to US$24,514, US$28,114, US$30,343 and US$28,971 for wells W25, W39, W34 and W47, respectively.

Genset maintenance and repair costs

Based on Caterpillar (CAT) genset specifications and the on-site experience of preventive maintenance fre-quency for CAT generators (being currently used at the well construction phase); lubrication and fuel system service is needed every 200 working hours using stand-ard grade of engine oil (though, it is usually better to be replaced every 150 working hours under severe

running conditions). The recommended oil by the manufacturer is CAT DEO SAE 15 W40. Coolant and air filters' replacement is due every 1,000 working hours and battery replacement every 10,000 working hours. Table 5 lists the estimated amounts and costs of preventive-maintenance materials and the total costs required throughout the study period by assuming 1 % real interest rate. The estimated genset maintenance cost was multiplied by 30 % to compensate for spare parts that would be necessary for repairs and over-hauls, along with manpower and overheads related to maintenance work. Hence, the total approximated cost would equal US$590,948 per well for the whole study period.

Electrical grid maintenance and repair costs

The electrical grid requires on-site maintenance, repair, testing and troubleshooting frequently. Due to large variability in the grid maintenance demands, it can be suitably combined with the addition and replacement costs that will be discussed in Section 2.5.3.

Equipment replacement and addition costs

Replacement and addition costs are anticipated expendi-tures to major system components that are required to maintain the operation of a facility.
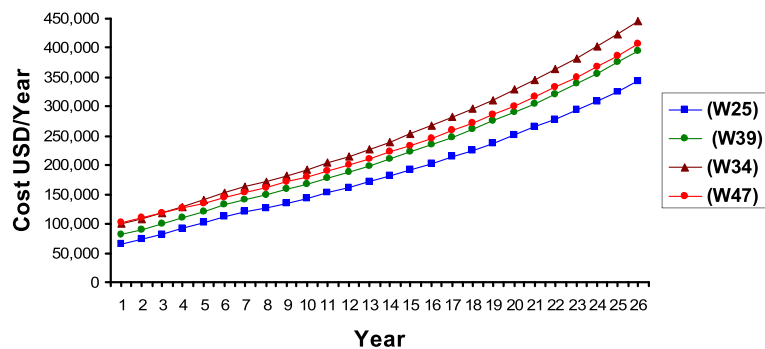

Fig. 8 Yearly present worth electricity cost for each design well

Table 5 Estimated quantities and costs of preventive maintenance material for genset

Item	No. of changes/year	Quantity/change	Price/item (US$)	Cost/year (US$)	Cost/study period (US$) (25 years)
Engine oil	43	35 L/change	7	10,535	263,375
Oil and fuel Filters	43	1 set/change	114	4,902	122,550
Coolant	8	80 L/change	3	1,920	48,000
Air Filters	8	1 piece/change	71	568	14,200
Batteries	1	2 piece/change	129	258	6,450
	Total cost (US$) = Maintenance cost + Spare parts costs				(454,575) + (454,575 × 30%) = US$590,948

Source of prices: data collected verbally from several suppliers of CAT servicing material

PV component replacement and addition costs

Major PV system components that could be considered for the replacement and addition costs include inverters, PV panels and batteries. Life of inverters is usually taken as 10–15 years, Hansen et al. (2005), which requires the system inverter to be replaced one time at the 15th year. The photovoltaic panels will not require replacement during the system lifetime since their expected life is 25 years. However, due to increased power requirements with time which is directly proportional to the water requirements of the well, and decreased panel efficiency (aging power of PV panels at a degradation rate 0.8 %/year should be taken into account), additional PV panels will be needed at each phase of the study period, as indicated in Table 6. Calculations and results related to this work are presented in (Ebaid et al. 2013).

Taking well (W25) as a sample to calculate the additional PV panels' cost, including the 1 % real interest rate (see section "Operation costs") would result in the following:

$$
\text{PV Cost}_{\text{Add}} = \text{Cost}_{\text{PV}} \left[\begin{array}{l} (\text{PV})_{5\,\text{years}} \left(\dfrac{P}{F}\right)(F, 1\%, 5) \\ \quad + (\text{PV})_{10\,\text{years}} \left(\dfrac{P}{F}\right)(F, 1\%, 10) + \\ (\text{PV})_{15\,\text{years}} \left(\dfrac{P}{F}\right)(F, 1\%, 15) \\ \quad + (\text{PV})_{20\,\text{years}} \left(\dfrac{P}{F}\right)(F, 1\%, 20) \end{array} \right]
$$

$$
= 500 \left[(182 \times 0.9515) + (127 \times 0.9053) \right.
$$
$$
\left. + (73 \times 0.8613) + (53 \times 0.8195) \right]
$$
$$
= \text{US}\$196,500
$$

Table 6 Total number of PV panels required by each of the design wells at each pumping phase (Ebaid et al. 2013)

Well number	W25	W39	W34	W47
Initial (0–5 years)	2969	3503	3847	3827
Added (5–10 years)	182	173	158	85
Added (10–15 years)	127	120	111	60
Added (15–20 years)	73	69	62	34
Added (20–25 years)	53	51	47	24
Total	3403	3916	4226	4031

Regarding system batteries, additional quantities will also be needed as the power requirements increase. Battery age is usually determined by the number of the charge-discharge cycles or otherwise by years. Total number of added and replaced batteries needed during the project is divided into three categories (Ebaid et al. 2013).

1. *Backup batteries* which will also have to be replaced in the 15th year (note that it will not be so frequently charged and discharged, and its life could be extended).
2. *Night-time operation batteries*, which will need to be replaced periodically, depending on a life of 15 years. So replacement will occur at the 15th year.
3. *Supplementary batteries*, to be added at the 5th, 10th, 15th and 20th year.

The calculations of the number of replacement and addition batteries for each category listed in Table 7 can be found in Ebaid et al. (2013).

Table 8 lists the total present worth costs of additional PV components that will be required at each pumping phase of the 25 year operation period.

Genset replacement and addition costs

Although generators lifespan or maximum working hours depend on how well the engine is being maintained and the surrounding weather conditions, it is strongly recommended the genset be replaced after 10 years of continuous duty in harsh weather conditions, such as that of Disi, to ensure the reliability of the genset parts, Arif et al. (2010). Accordingly, for this alternative, the two gensets would probably need to be replaced by a brand new one every 10 years, which will result in an additional cost of US$181,429 at the 10th year and US$164,286 at the 20th year, totalling US$354,714, all in present worth considering a real interest rate of 1 %.

Electrical grid replacement and addition costs

There are usually several upgrades for the electrical grid components along with other failure replacement occasions. Therefore, the replacement and addition

Table 7 Batteries to be added and replaced at each design well and the corresponding years (Ebaid et al. 2013)

Well	W25			W39			W34			W47		
Year	Night	Backup	Supp.	Night	Backup	Supp.	Night	Backup	Supp.	Night	Backup	Supp.
Fifth	–	–	73	–	–	69	–	–	63	–	–	34
Tenth	–	–	51	–	–	48	–	–	45	–	–	24
15th	539	539	29	700	700	27	769	769	25	745	745	14
20th	–	–	21	–	–	20	–	–	19	–	–	9

costs (combined with repair and maintenance costs of Section "Electrical grid maintenance and repair costs" for the electrical grid alternative in this study can be assumed to equal 2.5 % per year of the initial grid cost), according to the National Electric Power Company NEPCO Ltd., (International Monetary fund 2009). This equals US$4500 /year per well or about US$100,000 /year per well considering a 1 % real interest rate.

Residual value (salvage value)

Residual value is the net worth of a system at the end of the LCCA operation period. This is the only cost category in an LCCA where a negative value, one that reduces cost, is acceptable.

PV component residual value

PV panels The PV system components are expected to return a salvage value through selling it at the end of the project to various types of recycling industries. According to experts, PV panel recycling is currently not viable because waste volumes generated are too small and significant volumes of end-of-life panels will only begin to appear in 2025 or 2030. Based on PV cycle's reported

experiences in the 2010 collection and recycling activities, a price of 175 euros (almost was agreed on per ton of end-of-life silicon PV panels (Bio Intelligence Service et al. 2011). It should be noted that salvage logistics' costs can vary based on the collection and transport system chosen and the distance between the collection point and the recycling centre of PV panels. Referring to the mechanical data of the Canadian Solar MaxPower CS6X-300P panels, the weight of one panel is almost 27 kg. And based on a price of US$286/ton for the end-life PV panels, while considering a real interest rate of 1 %; the salvage value of end-of-life PV panels for each design well can be obtained through using Eq. 9:

$$PV\ Cost_{salvage} = \frac{No.\ Panels\ \times\ Weight\,(kg)/panel}{1000} \times Price\ US\$/ton \times P/F(F, n, i)$$

(9)

Batteries Regarding the end-of-life (scrap) lead-acid batteries and based on the market, its usual price range is US$0.4–1.5 /kg. This price depends on the condition of those batteries, if it is wet (contains acid) or dry,

Table 8 Addition and replacement cost of PV components for each design well at each pumping phase

Well number		W25		W39		W34		W47	
Period	Component	Quantity.	Cost (US$)	Quantity	Cost (US$)	Quantity	Cost (US$)	Quantity	Cost (US$)
Added and replaced fifth year	PV panels	182	87,143	173	82,857	158	75,714	85	40,000
	Batteries	73	68,571	69	65,714	63	60,000	34	32,857
	Inverters	–		–		–		–	
Added and replaced tenth year	PV Panels	127	57,143	120	54,286	111	50,000	60	27,143
	Batteries	51	45,714	48	42,857	45	41,429	24	21,429
	Inverters	–		–		–		–	
Added and replaced 15th year	PV Panels	73	31,429	69	30,000	62	27,143	34	14,286
	Batteries	1107	952,857	1427	1,228,571	1563	1,345,714	1504	1,295,714
	Inverters	1	97,143	1	97,143	1	97,143	1	97,143
Added and replaced 20th year	PV Panels	53	25,714	51	21,429	47	18,571	24	10,000
	Batteries	21	17,143	20	17,143	19	15,714	9	7,143
	Inverters	–	87,143	–	82,857	–	–	–	–
Total present worth (US$) at $i_r = 1$ %		1,382,857		1,640,000		1,731,429		1,545,714	

damaged or with a good container, and even sometimes the ampere-hour rating would be included in the pricing www.recycle.net. For this study, an average price of US$1.1 /kg for the wet-scrap lead-acid batteries will be selected after reviewing the local market prices. Therefore, Eq. 10 can be used to estimate the scrap battery salvage value and results depend on the total number of batteries to be used (as batteries will be replaced at the 15th year.

Referring to battery weight of 193 kg and using a real interest rate of 1 % to bring costs back to present worth.

$$\text{Battery Cost}_{\text{salvage}} = \sum \frac{\text{No. of Batteries} \times \text{Weight (kg)}}{(\text{Battery} \times \text{Price US\$/kg}) \times P/F(F, n, i)}$$
(10)

Other salvage values would be related to mounting materials for the PV system components, protection equipment, copper wires… etc. Its estimated costs can be assumed to equal 3 % of the total salvage value of panels and batteries. Table 9 lists all the salvage values for PV system components

Genset residual value
The price of an end-of-life generator totally depends on its condition. But in all cases, it will not exceed 10–20 % of the initial cost referring to the local market trends. Therefore, in this study, the residual value of the genset is to be taken as 15 % of the initial costs. That result in an estimated total present worth salvage value of US$814,29 (as six generators will be bought throughout the study period, two will be sold at the 10th year, another two at the 20th year and the last two at the 25th year) using a real interest rate of 1 %.

Electrical grid residual value
The residual value of the electrical grid system can be discarded since it will not happen in practical life to dismantle the grid components and sell it to profit back money.

Final life cycle cost analysis (LCCA)
Once all pertinent costs have been established and discounted to their present value, the costs can be

Table 9 Estimated salvage values for PV system components

Well number	W25	W39	W34	W47
PV panels (US$)	22,857	27,143	30,000	30,000
Batteries (US$)	317,143	374,286	411,429	398,571
Other material (US$)	10,000	12,857	12,857	12,857
Total present worth (US$)	350,000	414,286	454,286	441,429

summed up to generate the total life cycle cost of the project alternative $\text{LCC}_{\text{Alternative}}$ according to Eq. 11

$$\text{LCC}_{\text{Alternative}} = \text{Cost}_{\text{Initial}} + \text{Cost}_{\text{Operation}}$$
$$+ \text{Cost}_{\text{Maintenance}} + \text{Cost}_{\text{Add Replace}}$$
$$-\text{Cost}_{\text{Residual}} \text{ (US\$)}$$
(11)

It should be noted here Eq. 11 does not include the cost of CO_2 emission reduction and the cost of selling of PV power during the project period because the evaluation methods and rules applied must be uniform. In our case, LCCA can provide quantitative results, thereby enabling comparison of each technology on an equal footing. The alternative cost per kWh (cost_{kWh}) is to be calculated through dividing the $\text{LCC}_{\text{Alternative}}$ by the total useful energy E_{Useful} in kWh over the study period, as indicated by Eq. 12:

$$\text{Cost}_{\text{kWh}} = \left(\frac{\text{LCC}_{\text{alternative}}}{E_{\text{Useful}}}\right) (\text{CF}) \quad \text{(US\$/kWh)} \quad (12)$$

where CF is the contingency factor to compensate for additional miscellaneous costs. In this study, CF = 5 % is assumed. To estimate E_{Useful} of each design well, the integration of motor power P_m over the operation period is performed. And since the operation period was divided into five phases, the total useful energy can be calculated through Eq. 13

$$E_{\text{useful}} = \int_0^{25} f(P_m)\, dP_m \qquad (13)$$

The yearly power demand data are shown in Fig. 7 depends on what the total useful power demanded at each design well E_{Useful} can be estimated to be equal 37.32×10^6, 43.7×10^6, 50.1×10^6 and 46.9×10^6 kWh for wells W25, W39, W34 and W47, respectively, during the whole operation period of 25 years.

Results
PV component final LCCA
The total life cycle cost for the PV system alternative can be estimated through returning all costs in the PV cash flow diagram of Fig. 9 to present worth and applying Eqs. 11 and 12 for each design well to yield the results listed in Table 10. It should be noted here that including the cost of CO_2 reduction in the final PV LCCA will lower the $\text{Cost}_{\text{PV,kWh}}$ even further and eventually gives a great advantage of using renewable energy over conventional types of energy alternatives.

Genset final LCCA
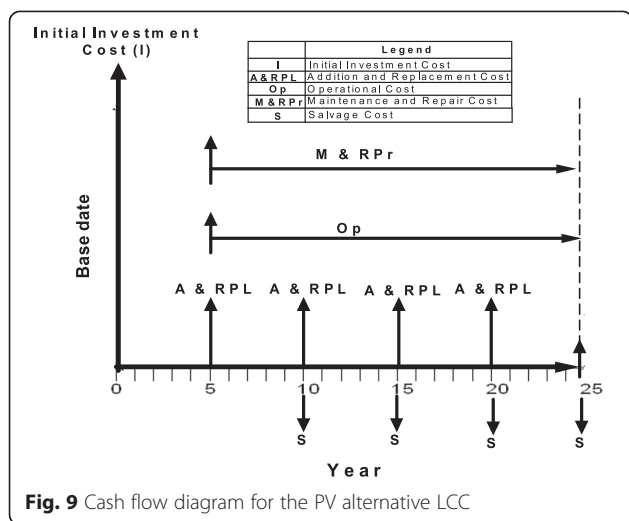Two Caterpillar 250-kW generators are to be used. According to Eq. 11, the LCCs for a 24-diesel genset

Fig. 9 Cash flow diagram for the PV alternative LCC

alternative at each design well are listed in Table 11, and Fig. 10 shows the cash flow diagram of genset LCCA.
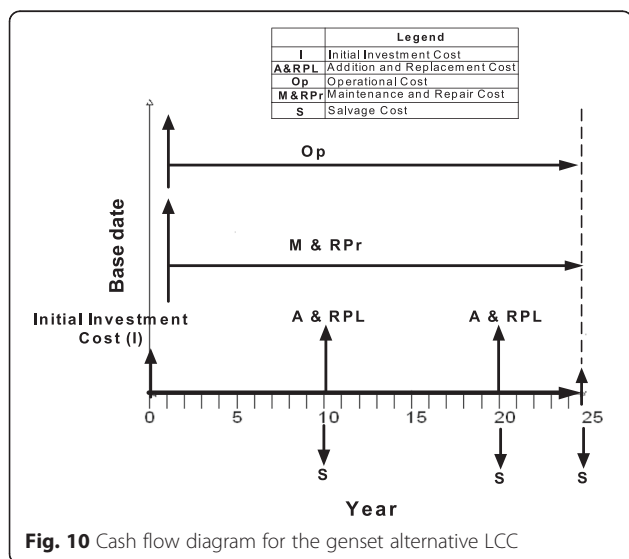
Electrical grid through Disi desert final LCCA
The grid system alternative to supply Disi wells with electrical power varies considerably in LCC between design wells. This is due to varying initial costs according to the distance from the well to the nearest grid available. At the same time, operational costs depend on the amount of electrical power required by the well pump. Table 12 lists down the LCC values for each design well according to the electrical grid alternative, and Fig. 11 shows its cash flow diagram.

PV-grid and PV-genset combinations final LCCA
To investigate the effect of combining pairs of alternatives PV-genset and PV-electrical grid to create more

Fig. 10 Cash flow diagram for the genset alternative LCC

Table 10 Final PV LCCA and cost per kWh values of each design well in present worth (PW) (US$)

Costs (US$)	W25	W39	W34	W47
$Cost_{Initial}$	3,007,143	3,528,571	3,864,286	3,844,286
$Cost_{Operation}$	204,286	234,286	252,857	241,429
$Cost_{Maintenance}$	24,524	28,114	30,343	28,971
$Cost_{Add\&Replace}$	1,382,857	1,640,000	1,731,429	1,545,714
$Cost_{Residual}$	350,000	414,286	454,286	441,429
LCC_{PV} (US$)	4,968,810	5,845,257	6,333,201	6,101,829
$Cost_{PV,kWh}$(US$/KWh)	0.139	0.140	0.126	0.137

options for decision-makers, the following additional two options could be implemented:

- 12-h PV day operation, 12-h diesel genset night operation system.
- 12-h PV day operation, 12-h electrical grid night operation system.

From the first look, the PV-genset option seems to be more appealing than the PV grid option, since the construction of a grid system would necessarily weaken the chance for a feasible use of a PV array. On the other hand, the commonly used PV-genset option for off-grid systems would significantly decrease the initial costs of a night-operating PV system but would result in higher operational and fuel costs. Combining the individual cost banks, after splitting it into halves, since the options are for 50–50 operation, would result in the costs listed in Table 13. It can be noticed that combining a PV array system with a grid network would result in lower costs than that of a PV-genset network. That would be returned to the expensive diesel costs and high fuel consumption by the generator.

Sensitivity analysis
Sensitivity analysis is a technique for determining which input values, if different, would make a crucial difference to the outcome of the analysis.

Table 11 Final genset LCC and cost per kWh values of each design well in present worth (US$)

Costs (US$)	W25	W39	W34	W47
$Cost_{Initial}$	200,000	200,000	200,000	200,000
$Cost_{Operation}$	6,934,286	8,855,714	8,855,714	9,357,143
$Cost_{Maintenance}$	632,857	632,857	632,857	632,857
$Cost_{Add\&Replace}$	345,714	345,714	345,714	345,714
$Cost_{Residual}$	81,429	81,429	81,429	81,429
LCC_{Genset} (US$)	8,194,286	10,115,714	10,115,714	10,454,286
$Cost_{GEnset,kWh}$ (US$/KWh)	0.231	0.243	0.243	0.238

Table 12 Final grid LCC and cost per kWh values of each design well in present worth (US$)

Costs (US$)	W25	W39	W34	W47
Cost$_{Initial}$	180,000	180,000	180,000	180,000
Cost$_{Operation}$	4,942,857	5,742,857	6,531,428	6,071,428
Cost$_{Maintenance}$	100,000	100,000	100,000	100,000
Cost$_{Add\&Replace}$				
Cost$_{Residual}$	0	0	0	0
LCC$_{Grid}$ (US$)	5,222,857	6,022,857	6,811,429	6,351,429
Cost$_{Grid,kWh}$ (US$/KWh)	0.147	0.145	0.143	0.142

Table 13 Well-averaged final LCC and cost per kWh for combined alternatives

Costs (US$)	12-h PV, 12-h genset	12-h PV, 12-h grid
Cost$_{Initial}$	1,880,536	1,870,000
Cost$_{Operation}$	4,429,643	3,027,143
Cost$_{Maintenance}$	330,357	38,571
Cost$_{Add\&Replace}$	960,357	812,857
Cost$_{Residual}$	247,857	207,143
LCC	7,848,750	5,955,714
Cost$_{kWh}$ (US$/KWh)	0.185	0.140

Sensitivity analysis of PV system

(Table 10, shows that addition and replacement cost, operation cost, and residual cost constitute the input critical parameters of the LCC whereas the maintenance cost has much smaller effect on LCC). In this case, it may be advisable to spend additional time and money on determining the degree of uncertainty associated with the annual costs of add and replacement and operation cost. There is usually somewhat less uncertainty with the initial investment cost because it occurs at or close to the base date.

Sensitivity analysis of genset system

Table 11, shows that the input critical parameters to the LCC are operation cost, addition and replacement cost, and maintenance cost whereas residual cost has much smaller effect on LCC. Explanation of these costs are similar to the costs of PV system case.

Sensitivity analysis of grid system

From Table 11, the critical inputs which affect the LCC outcomes are only the operation cost. Other costs have minor effect on the LLC analysis.

Final averaged LCCA summary for power alternatives

Summarizing the final results of the average life cycle cost analysis of each alternative in ascending order, Table 14 combines those results to simplify comparison. It clearly shows that the PV system alternative has the least cost for all design wells (which applies for all wells in the Disi wellfield) and is the most feasible.

Payback period

Payback period (PBP) can be defined as follows:

$$PBP = \frac{Initial\ investment}{Annual\ saving} \quad (14)$$

Payback period for the PV system

The initial investment is based on the average PV component costs of the four wells and equal to US$3,504,791 (see Table 4), and the annual saving is based on the average motor pump P_m of the four selected well and equal 190.018 kW (see Fig. 5).

$$PV\ energy\ generated\ yearly = 190.018 \times 24 \times 365$$
$$= 1,664,558\,kWh$$

Assuming an average cost of 0.4US$/kWh, then

$$Annual\ saving = 1,664,558 \times US\$0.4 = US\$665,823$$

Fig. 11 Cash flow diagram for the electrical grid alternative LCC

Table 14 Final average LCCA Summary

Power alternative	Average LCC (US$/25 years)	Average cost per kWh (US$/kWh)
PV	5,812,274	0.135
PV/grid	5,955,714	0.140
Grid	6,102,143	0.144
PV-genset	7,848,750	0.185
Genset	9,720,000	0.239

$$PBP = \frac{Initial\ investment}{Annual\ saving} = \frac{3,504,791}{665,523} = 5.25\ years \tag{15}$$

Payback period for the genset system

The initial investment of gensets = US\$200,000

The Annual Saving = Annual Saving (kWh/year) Generated – (Diesel cost + Maintenance cost).

$$Energy\ generated\ yearly\ by\ genset$$
$$= (1,664,558\ kWh/year) \times 3600$$
$$= 5,992,248,800\ kJ$$

$$Amount\ of\ diesel\ consumed\ yearly$$
$$= \frac{Energy\ generated}{Heating\ value} = \frac{5,992,248,800}{44,000}$$
$$= 136,187\ kg = 170,234\ L$$

Assuming an average cost of US\$3/kWh, then

$$Diesel\ cost\ yearly = 170,234\ L \times US\$3/L$$
$$= US\$510,702$$

Yearly Maintenance cost $= \frac{590,948}{25} = US\$23,637$ (see Table 5)

Then, the PBP can be calculated as

$$PBP = \frac{Initial\ investment}{Annual\ saving} = \frac{200,000}{(665,523)-(510,702+23,637)}$$
$$= 1.5\ years \tag{16}$$

Payback period for the 12-h PV day operation, 12-h grid at night combination

If the PV system is working for 12 h, then the annual saving yearly is equal to

$$PV\ Energy\ generated\ yearly = 190.018 \times 12 \times 365$$
$$= 832,279\ kWh$$

$$PBP = \frac{Initial\ investment}{Annual\ saving} = \frac{3,504,791}{832,279 \times US\$0.4} = 10.25\ years \tag{17}$$

Payback period for the 12-h PV day operation, 12-h genset at night combination

$$Energy\ generated\ yearly\ by\ genset = (832,279\ kWh/year)$$
$$\times 3600$$
$$= 2,996,204,400\ kJ/year$$

Amount of diesel consumed yearly

$$= \frac{Energy\ generated}{Heating\ value} = \frac{2,996,204,400}{44,000}$$
$$= 68,096\ kg = 85,119\ L$$

$$Diesel\ cost\ yearly = 85,119\ L \times US\$3/L = US\$255,358$$

$$PBP = \frac{Initial\ investment}{Annual\ saving} = \frac{200,000}{(665,523)-(255,358+23,637)}$$
$$= 3\ years \tag{18}$$

Environmental survey and risk assessment

During normal operation, PV power systems do not emit substances that may threaten human health or the environment. In fact, through the savings in conventional electricity production, it can lead to significant emission reductions. There are, however, several indirect environmental impacts and risk aspects related to PV power systems that require further consideration.

PV and CO_2 emission reduction in Jordan

Electricity in Jordan is being produced through the conventional fuel combustion (oil and natural gas), which is continuously emitting greenhouse gases. Referring to the International Energy Agency IEA report about the CO_2 emission from fuel combustion, the energy supply to Jordan in 2009 reached 312×10^{15} J. This energy emitted a total of 19.2 million tons of CO_2 (almost 61.6 tons of CO_2 per 10^{12} J). At the same time, while the 2009 power output for electricity and heat in Jordan was almost 14.3×10^9 kWh, 8.3 million tons of CO_2 were accordingly emitted, with an emission rate of 581 gm CO_2/kWh. That exceeded the 500 gm CO_2/kWh world average of that year. The average emission in Jordan was 642 gm CO_2/kWh through 2002–2009. By taking the total energy demand of each design well, Fig. 12 summarizes the CO_2 emission that could have been produced using the conventional fuel-combustion power systems, which, through using the PV energy, will all be eliminated.

The elimination of indicated CO_2 emissions, which could reach an average of 27,172 tons per well during the operation period and sum up to almost 1.5 million tons for all 55 wells, has a huge positive influence on the environment. The reduction of environmental costs by reducing contamination has many aspects to be discussed, and it eventually gives a great advantage of using renewable energy over conventional types of energy.

PV environmental challenges

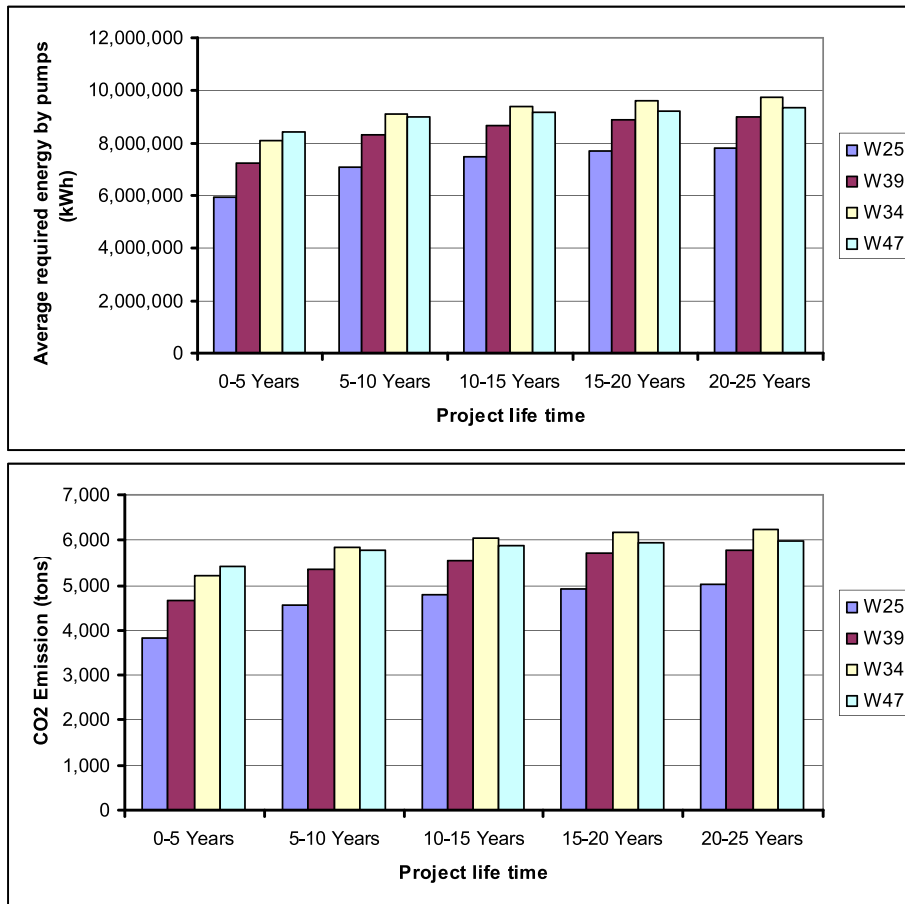The production of present-generation PV power systems is relatively energy intensive, involves the use of large

Fig 12 Possible emission of CO_2 due to use of conventional energy of each design well for an average required energy demand by the pumps in kWh (emitted CO_2 in tons (using a rate 642 gm CO_2/kWh))
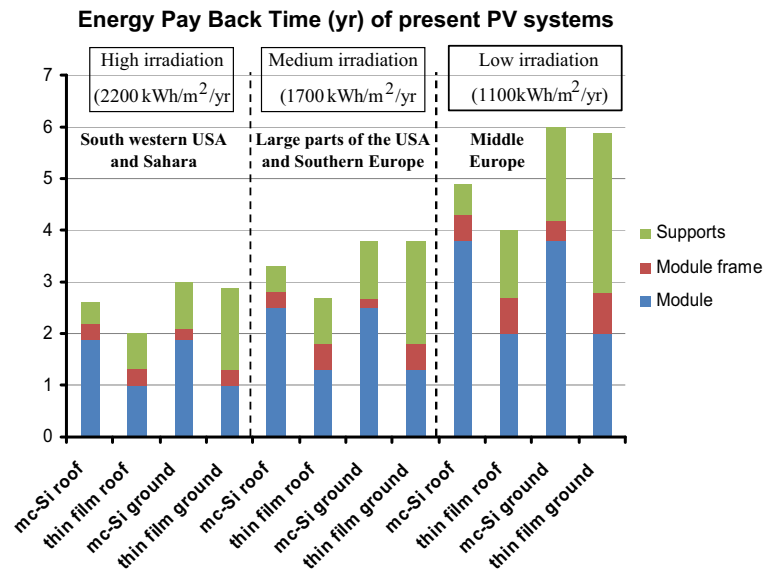

Fig. 13 The energy pay-back time (in years) for present-day PV applications (Alsema and Nieuwlaar 2000)

Table 15 Energy consumption and CO_2 emission for PV module production

PV Type	CO_2 emission for PV production (Kg CO_2/kW$_p$)	Total tons of CO_2 emission for each well			
		W25	W39	W34	W47
		3403 panels (1021 kW$_p$)	3916 panels (1175 kW$_p$)	4226 panels (1268 kW$_p$)	4031 panels (1209 kW$_p$)
Mono-crystalline	360	368.0	423.0	356.0	435.0
Poly-crystalline	170	174.0	200.0	217.0	206.0

Source: Krauter and Ruther (2003)

quantities of bulk materials and smaller quantities of substances that are scarce and/or toxic. During operation, damaged modules or a fire may lead to the release of environmentally hazardous substances. Finally, at the end of their useful lifetime, PV power systems have to be decommissioned, and resulting waste have to be managed.

Although PV power systems do not require finite energy resources (as it is the case for fossil and nuclear systems) during their operation, a considerable amount of energy is needed at present for their production. Alsema and Nieuwlaar (Alsema and Nieuwlaar 1997) stated that energy payback time (EPBT) depends on several factors including cell technology, PV system application, location and irradiation. Further studies (Alsema and Nieuwlaar 2000) showed that the EPBT for present-day systems is 2 to 3 years in a sunny climate and increases to 4 to 6 years (or more) under less favourable conditions as shown in Fig. 13. Also note that the contribution from the supports and the module frames is significant, especially for the ground mounted systems.

The amount of energy in kWh required for the manufacturing of each kW$_p$ of PV panels (poly-crystalline-silicon selected for this project) and the corresponding emission of CO_2 are listed in Table 15 based on studies conducted in the developing countries (Krauter and Ruther 2003). The

total CO_2 emission related to the number of PV panels to be used in for the W25 (see Table 6) can be calculated for mono and poly-crystalline as follows:

$$\text{Emission of } (CO_2)_{W25} = (\text{No. of PV panel} \times kW_P) \\ \times \frac{(CO_2)\,kg}{kW_P \times 1000} \quad (\text{tons})$$

$$(19)$$

Mono-crystalline: $CO_2 \text{emission} = (CO_2)_{W25} = \left(3403 \times \frac{300}{1000}\right) \times \left(\frac{360}{1000}\right) = 368.0\,(\text{tons})$

Poly-crystalline: $CO_2 \text{emission} = (CO_2)_{W25} = \left(3403 \times \frac{300}{1000}\right) \times \left(\frac{170}{1000}\right) = 174.0(\text{tons})$

Similar calculation for wells W39, W34 and W47 are carried out, and the results are listed in Table 15.

Note that these emission values are very tiny compared to those produced by fossil fuel combustion. However, the grid system components will also consume a considerable amount of energy for its production. In fact, the manufacturing of cement, steel, copper, insulation materials and the other grid components can cause a much larger amount of CO_2 into the atmosphere, (Krauter and Ruther 2003). However, several other environmental challenges can be associated with the use of PV system

Table 16 PV hazards

|	Description
Hazard no. 1	Electric shock may cause personnel injury to installers, occupants or others (would include local Disi animals and birds)
Risk level	Negligible risk region
Risk reduction	Installation of a well-engineered system and understanding of potential hazard by design team, installation crew and system user. And installation of complete set warning signs where applicable inside and around the PV system
Hazard no. 2	Initiation of contact fire due to increased temperature of Disi area or the possibility of ray reflection from flat surfaces on flammable objects
Risk level	Tolerable risk region
Risk reduction	Insulate structure with fire proofing materials and implement a fire safety procedure, along with continuous check for flammable objects that might be available
Hazard no. 3	Theft of PV equipment
Risk level	Tolerable risk region
Risk reduction	Hour-round surveillance on the PV plant through either physical present of personnel or computerized systems
Hazard no. 4	Communication Interference (e.g. inverters)
Risk level	Tolerable risk region
Risk reduction	Appropriate design and system installation based on good engineering practice must be adopted
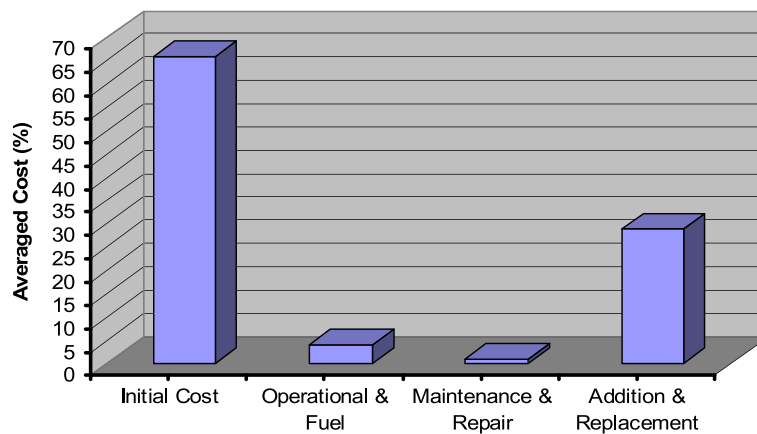
Fig. 14 PV alternative life cycle cost banks (averaged for all design wells)

components, mainly PV panels and batteries. The main environmental problems related to photovoltaic panels, if not properly disposed, are as follows: leaching of lead, leaching of cadmium, loss of conventional resources (primarily aluminum and glass) and loss of rare metals (silver, indium, gallium and germanium). These issues require more intense care during the recycling and disposal of PV system components. At the same time, rare metal recovery and component recycling is very essential for the durability of such materials in the natural cycle. The land required by PV arrays may sometimes take over natural life, through tree cutting or even soil desertification, and then the environmental aspects of this issue would have to be considered. In the case of this study, the available land is almost barren and lacks any form of natural life expect for some desert plants. Therefore, the effect on natural life can almost be discarded.

Risk assessment

Risk assessment is the process of evaluating risks to workers' safety and health from workplace hazards. It is a systematic examination of all aspects of work that considers the following:

- What could cause injury or harm,
- Whether the hazards could be eliminated and, if not,
- What preventive or protective measures are, or should be, in place to control the risks.

Several types of minor hazards can be related to a PV plant; these hazards can be easily controlled and reduced through identifying them, and then preparing a suitable plan for safety procedures to avoid risk. Some PV hazards may be described as shown in Table 16. However, that for each hazard identified, action plan should be prepared and implemented to minimize accidents during the lifetime of the project.

Discussion
Life cycle cost analysis (LCCA)

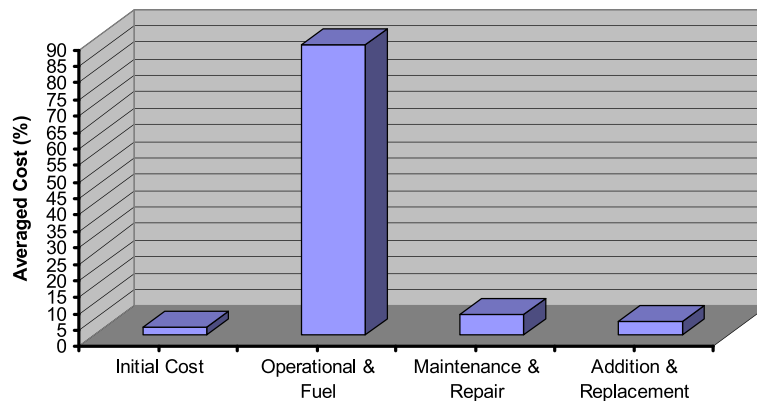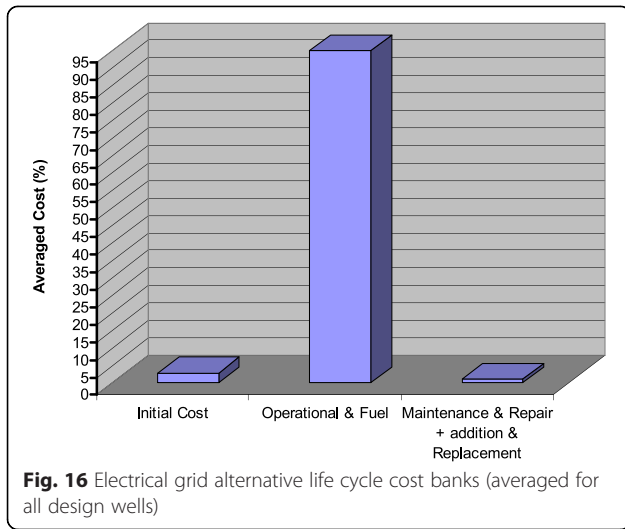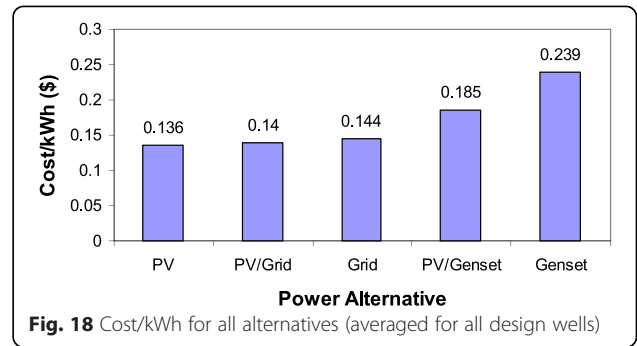The use of a 1 % real interest rate depended on an optimistic consideration of the inflation rate history in Jordan.

Fig. 15 Genset alternative life cycle cost banks (averaged for all design wells)

Fig. 16 Electrical grid alternative life cycle cost banks (averaged for all design wells)

Fig. 18 Cost/kWh for all alternatives (averaged for all design wells)

More conservative prediction of real interest rates would be preferable, but in the case of this study, the effect of low interest rate can be normalized since it was applied evenly to all alternatives. Looking at the well-averaged cost banks for each alternative, as illustrated in Figs. 14, 15 and 16, it can be noticed that the operational and fuel costs are the major cost banks for the genset and grid alternatives, contributing in 88 and 95 % of its total costs, respectively. While for the PV alternative, the operational cost (e.g. no fuel cost) only represents 4 %. On the other hand, initial costs contribution in the total cost represents 66 % for the PV alternative, where it only equals 2 % for the genset and 3 % for the grid.

Based on these observations, it can be concluded that operational costs for PV systems are very minimal and can almost be discarded. On the other hand, the continuous research in the field of renewable energy, along with commercial competitiveness among PV component manufacturers, would only help in decreasing the high implementation costs of those components, which will result in significantly reducing the total PV energy costs. As per the steep increase of fuel prices and electricity tariffs due to the economical situation worldwide, the total life cycle costs of genset and grid electricity will increase more in the future. Accordingly, the conventional energy costs will continue to rapidly increase,

Figure 17 compares each cost bank among all alternatives. It demonstrates that the initial cost of the PV system, even if considered relatively high, is still much smaller than operational and fuel costs of the grid or the genset alternatives.

It can be noticed that combining a PV array system with a grid network would result in lower costs than that of a PV-genset network. That would be returned to the expensive diesel costs and high fuel consumption by the generator.

Conclusions

A complete economic analysis for the Disi project of 13-MW power output was conducted for all five powering options. These are grid, genset, PV, PV-grid

Fig. 17 All alternatives life cycle cost banks (averaged for all design wells)
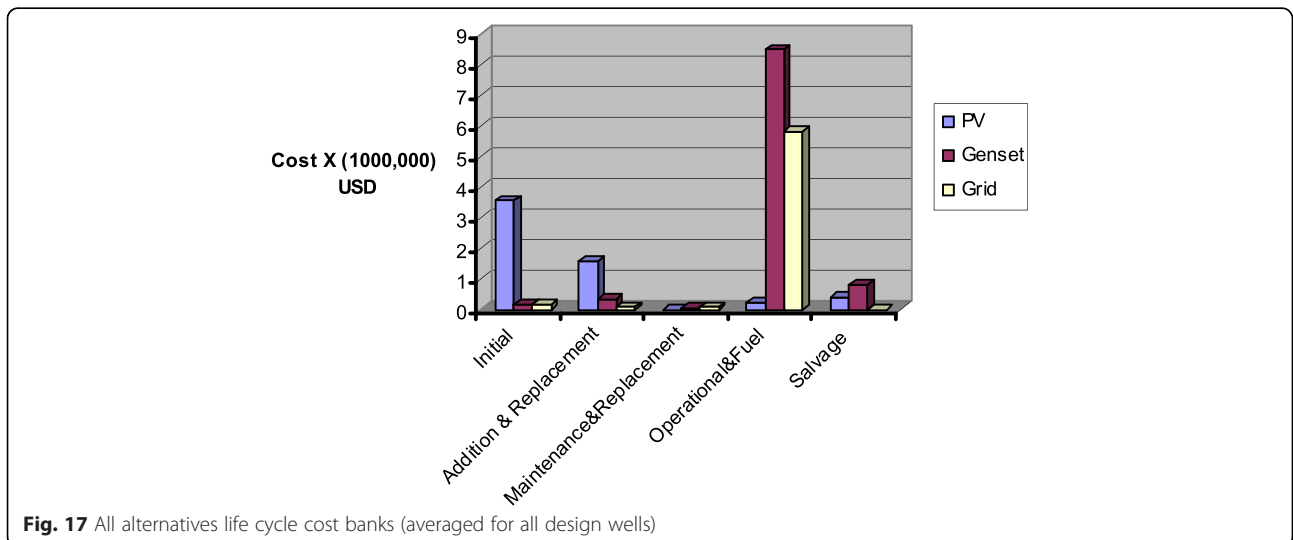
and PV-genset and the method used was based on the life cycle cost method (LCC). Comparison of the cost per kWh for all five powering options is illustrated in Fig. 18. It clearly shows that the order of best-to-worst alternative from an economical point of view would be the 24-h PV system, the PV-grid option, the grid option, the PV-genset, and finally the worst option is using a diesel generator for 24-h operation.

It can be noticed that the operational and fuel costs are the major cost banks for the genset and grid alternatives, contributing in 88 and 95 % of its total costs consecutively, respectively. While for the PV alternative, it only represents 4 %. On the other hand, initial costs contribution in the total cost represents 66 % for the PV alternative, where it only equals 2 % for the genset and 3 % for the grid. Based on these observations, it can be concluded that operational costs for PV systems are very minimal and can almost be discarded.

As we project into the future, the price of PV is surely to come down while the price of oil is likely to go up. This can lead to a reduction in the years to break even. It has also been proved that PV systems are an environment friendly source of energy, in which, the resulting savings in CO_2 emission reached 30,000 tons per well throughout the study period (25 years), which summed up to about 1.5 million tons of CO_2 for all Disi wells.

Nomenclature

A present value of an annuity
A_{DC} direct current
CF contingency factor
D_i inner diameter of a pipe (m)
DD drawdown (m)
Wp watt peak
E_{Useful} total useful energy (kJ)
H_L head loss (m)
i normal interest rate (%)
i_r real interest rate (%)
i_f inflation rate (%)
i_{eff} effective real interest rate
f friction factor
n total life (years)
PW present worth value of money
P present value
P_m motor power (kW)
P_p pump power
P_w water power
$\dot{Q}$ volume flow rate $(m^3/_s)$
SWL static water level (m)
THP total pump head
V velocity of water (m/s)
η_P pump efficiency (%)
η_m motor efficiency (%)

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