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Kandahar City Utility Interconnected 10 MW_p Photovoltaic Power System Feasibility Assessment (May, 2010)

Example 10 MW_p PV power plant installed by CH2MHILL for MASDAR in Abu Dhabi (2009)

May, 2010

EXECUTIVE SUMMARY

Scope

The feasibility of a ten MegaWatt (MW_p) photovoltaic power system (PVPS) is assessed for Kandahar City of southern Afghanistan.

System Performance

The average annual solar resource in Kandahar is very good with one axis tracking providing an annual average of about 5.8 kWh/m^2/day (sun-hours) at latitude tilt (optimal tilt for maximum annual energy generation). A large MW scale PVPS for Kandahar could be installed in approximately 9 months and serve as a daytime peaking plant. About 40 acres of land are required. An annual PV system capacity factor of 23% was determined. This analysis optimistically assumes that the system is reliable and operates without long periods of downtime during daylight hours and minimal maintenance actions are required. It would not provide electricity at night, and installing sufficient energy storage to do so would double costs, as well as having complicated technical challenges.

Table 1. Kandahar 10 MW_p Solar System Specifications

PV Array Specifications		
Size of PV Array	10,000	kWp
PV Array Area w/tracking	167,000	square meters
Annual PV Energy Generation	20,183	MWh/year (Yr 1)
Array Slope	32	degrees
Array Azmuth	0	degrees (due south)
Tracking Method	1 Axis (E-W)	Lat Tilt
PV Plant Capacity Factor	23.0%	Avg Annual

System

Economics

Life cycle cost (LCC) analysis is used including all future costs (O&M and replacements). A 10 MW_p solar system would cost about US$75 million to install. It would generate over 20,000 MWh the first year (about 10 percent of the current Kandahar load), and about 48,000 MWh generated over the next 25 years. LCC value of energy is about 19 cents per kWh.

Table 2. Summary Kandahar 10 MW_p Solar System Expected Performance and Costs

	PVPS
PV Array Size	10 MW
Total Energy Generated (Yr 1)	~20,000 MWh
Total Installed Cost	~$75,000,000
25 Year Net Present Value	~$88,000,000
PV Amortized Energy Value	$0.19/kWh

Stand-Alone Options

Alternatively, individual solar systems could be installed throughout Kandahar City. However, costs for this would approximately double (~US$15/Wp). Thus, 10 MW_p of distributed stand-alone systems throughout the city with batteries would cost over US$150 million. Each system would be as an island unto itself. Likewise, not as much energy would actually be usable due to ~30% roundtrip efficiency losses for batteries from charging and discharging. Batteries would need to be replaced every 6-8 years.

LCC costs would be more than double for a grid-tied system.

1.0 INTRODUCTION

The objective of a proposed 10 MW_p Kandahar photovoltaic power system (PVPS) project would be to use solar energy to supplement grid power production. A grid-tied PVPS allows for generation to meet some of the daily electrical energy demand during peak hours. The system does not provide power at night. PV systems can also include energy storage, but this extremely expensive for very large grid scale systems. Thus, photovoltaic (PV) power is provided to the grid only during daylight with this type of system.

Grid-connected PVPS are made up of a variety of components, which aside from the PV modules, include conductors, fuses, disconnects, controls, trackers, and power conditioning units (i.e., inverters). The PV grid system is only functional when its inverters can operate in synchronization with the regular grid. If the grid goes down, there is no solar power production.
PV systems are modular by nature, thus systems can be readily expanded and components easily repaired or replaced if needed.

Alternatively, stand-alone off-grid systems could be used in a distributed fashion on individual buildings. However, costs would approximately double for installation due to batteries.

1.1 Utility Perspectives on Solar Energy Utilization

A utility generating and selling electricity, such as DABS in Kandahar, must consider the value of PV with respect to the utility's overall objectives. PV power could be used to match with demand peak shaving opportunities. The value of PVPS is calculated relative to the opportunity costs. Opportunities for PV for utility planners fall into several categories: Utility-Owned, Off-Grid Systems; Utility Owned, Off-Grid, Customer-Service Systems; Utility-Owned, Grid-Connected Distributed Generation and Line Support; Customer-Owned, Grid-Connected, On-Site Generation; and Large Scale Utility Applications. A large scale utility PVPS application for Kandahar City is the most economical option as opposed to distributed stand-alone systems, and the one focused on here.

DABS is currently providing electric service to the City of Kandahar and plays an important role in developing any grid connected PV system. Interconnecting a PV system to the utility grid is not trivial. There exist utility interconnection standards for PVPS. Inexperienced utilities such as DABS are generally cautious since they have no experience interconnecting PV systems. Most knowledgeable utilities have adopted IEEE 929-2000 *Recommended Practice for Utility Interface of Photovoltaic (PV) Systems*.

1.2 Large Scale Utility Applications

For grid tied PVPS applications, the value of PV can be compared to the demand profile with the electrical production, both on a daily as well as annual basis. For this type of application, it is important that there be a fairly good correlation between the demand and solar generation curves. It is important to analyze the short-run marginal costs, as well as the long-run marginal costs based on the daily and yearly cycles. Once these correlations are established, DABS will know how much electricity from the sun can be expected to meet on-peak demand. PV can also improve power quality due to local power load spikes resulting in short-term overload on transformers and lines, voltage oscillation due to long line runs and locally varying loads, and poor power quality due to loads with harmonic generating qualities.

Construction Timeframe: The recent 80 kW_p PVPS installed by SESA in Paktiya took 5 months for shipping once the order was placed, including 1 month customs clearance. It took about 2 months to install the system. A larger MW scale PVPS will probably take slightly longer to ship and install, so the system could be operational in approximately 9-12 months after contracting.

2.0 PHOTOVOLTAIC (PV) BASICS (from Foster, 2009)

It is useful to have a basic technical understanding of solar electric operational concepts to fully understand this feasibility analysis. Electricity can be produced from sunlight through a process called photovoltaics (PV). "Photo" refers to light and "voltaic" to voltage. The term describes a solid-state electronic cell that produces direct current electrical energy from the radiant energy of the sun. Solar cells are made of semi-conducting material, most commonly silicon, coated with special additives. When light strikes the cell, electrons are knocked loose from the silicon atoms and flow in a built-in circuit, producing electricity. If a load is connected under these conditions, an electrical current will result, which is capable of doing work. The current produced is proportional to the amount of light absorbed by the device. In a solar cell, the photovoltaic effect is manifested as the generation of voltage at its terminals while being struck by the suns rays.

A thin silicon cell, four inches across, can approximately produce more than one watt of direct current (DC) electrical power in full sun. Individual solar cells can be connected in series and parallel to obtain desired voltages and currents. These groups of cells are packaged into standard modules that protect the cells from the environment while providing useful voltages and currents. PV modules are extremely reliable since they are solid state and there are no moving parts. Silicon PV cells manufactured today can provide thirty or more years of useful service life. Some manufacturers provide warranties of up to 25 years on their PV product (at 80 percent of original power rating). For example, a 100 W_p PV module in full direct sunlight (1,000 W/m^2) operating at 25°C will generate 100 Watts per hour (referred to as a Watt-hour–[Wh] at rated conditions. Modules can be connected together in series and/or parallel in an array to provide required voltages and currents for a particular application.

In order to generate usable power PV cells are connected together in series and parallel electrical arrangements to provide the required current or voltage to operate electrical loads. PV cells are connected in series, grouped, laminated, and packaged between sheets of plastic and glass, thus forming a PV module. The module has a frame (usually aluminum) that gives it rigidity and allows for ease of handling and installation. Junction boxes, where conductor connections are made to transfer power from the modules to loads, are found on the back of the PV modules. The number of cells in a module depends on the application for which it is intended. Terrestrial solar modules were originally designed for charging 12 volt lead-acid batteries, thus many modules are nominally rated at 12 V. PV modules designed for grid-tied application and rated at higher voltages.

PV cells essentially operate as diodes. The electrical behavior of PV modules is normally represented by current versus voltage curve (**I-V curve**). Likewise, a power curve is generated by multiplying current and voltage at each point on the IV curve. However, the only point desired to operate on this curve is the maximum power point. Figure 1 shows the IV and PV power curves of a representative PV module.

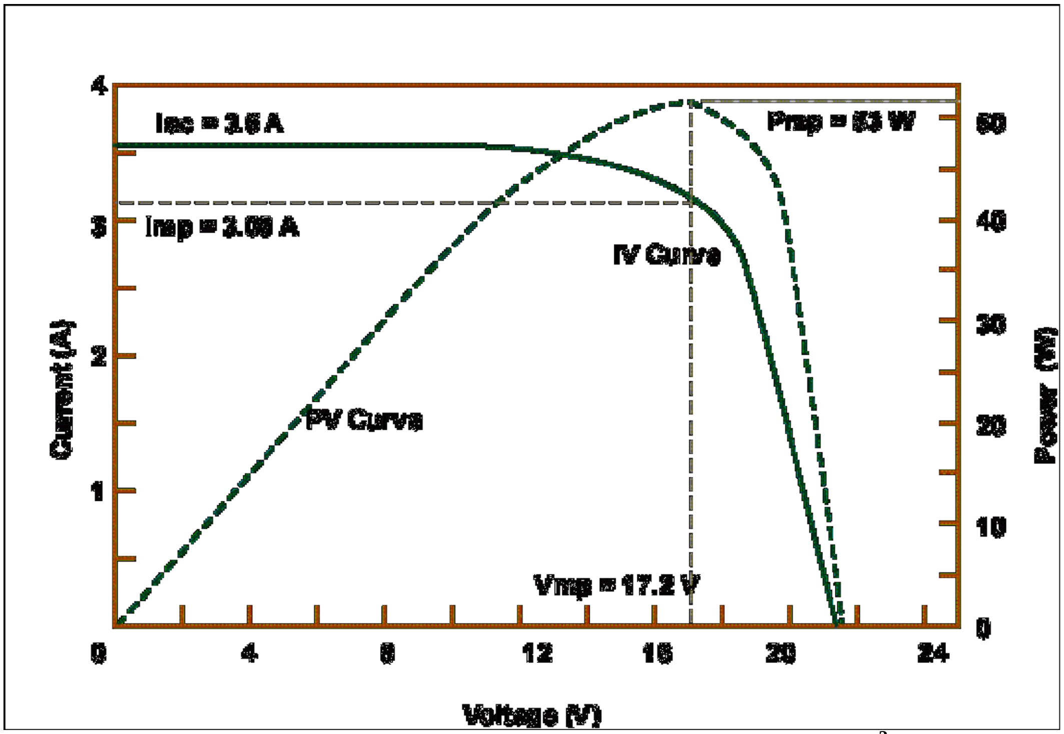

Figure 1. Typical IV and power curves for a PV Module at 1000 W/m^2

Each IV curve has a set of distinctive operation points that should be understood in order to appropriately install and troubleshoot PV power systems.

Short circuit current (I_{sc}) is the maximum current generated by a cell or module, and is measured when an external circuit with no resistance is connected (i.e., the cell is shorted). Its value depends on the cell's surface area and the amount of solar radiation incident upon the surface. It is specified in Amps and since it is the maximum current generated by a cell, I_{sc} is normally used for all electrical ampacity design calculations.

Nameplate current production is given for a PV cell or module at **standard reporting condition** (SRC) as specified by ASTM. The SRC commonly used by the PV industry is for a solar irradiance of 1000 W/m^2, a PV cell temperature of 25°C, and a standardized solar spectrum referred to as an air mass 1.5 spectrum (AM=1.5). This condition is also commonly referred to as standard test condition (STC). However, in reality, unless one is using PV in a relatively cold climate, the cells operate much hotter (often 50°C or more), which reduces their power performance.

Maximum Power Operating Current (I_{mp}) is the maximum current specified in Amps and generated by a cell or module corresponding to the maximum power point on the array's current-voltage (I-V) curve.

Open Circuit Voltage (V_{oc}) is the maximum voltage generated by the cell. This voltage is measured when no external circuit is connected to the cell.

Rated Maximum Power voltage, V_{mp}. The voltage corresponding to the maximum-power-point on the array's current-voltage (I-V) curve.

Maximum Power (P_{mp}) is the maximum power available from a PV cell or module and occurs at the maximum-power-point on the I-V curve. It is the product of the PV current (Imp) and voltage (Vmp).

This is referred to as the maximum power point. If a module operates outside of its maximum power value, the amount of power delivered is reduced and represents needless energy losses.

The power produced by a crystalline PV module is affected by two key factors: solar irradiance and module temperature. The following figure shows how the I-V curve is affected at different irradiance levels. The lower the solar irradiance, the lower the current output and thus the lower the peak power point. Voltage essentially remains constant. The amount of current produced is directly proportional to increases in solar radiation intensity. Basically, V_{oc} does not change; its behavior is essentially constant even as solar-radiation intensity is changing.

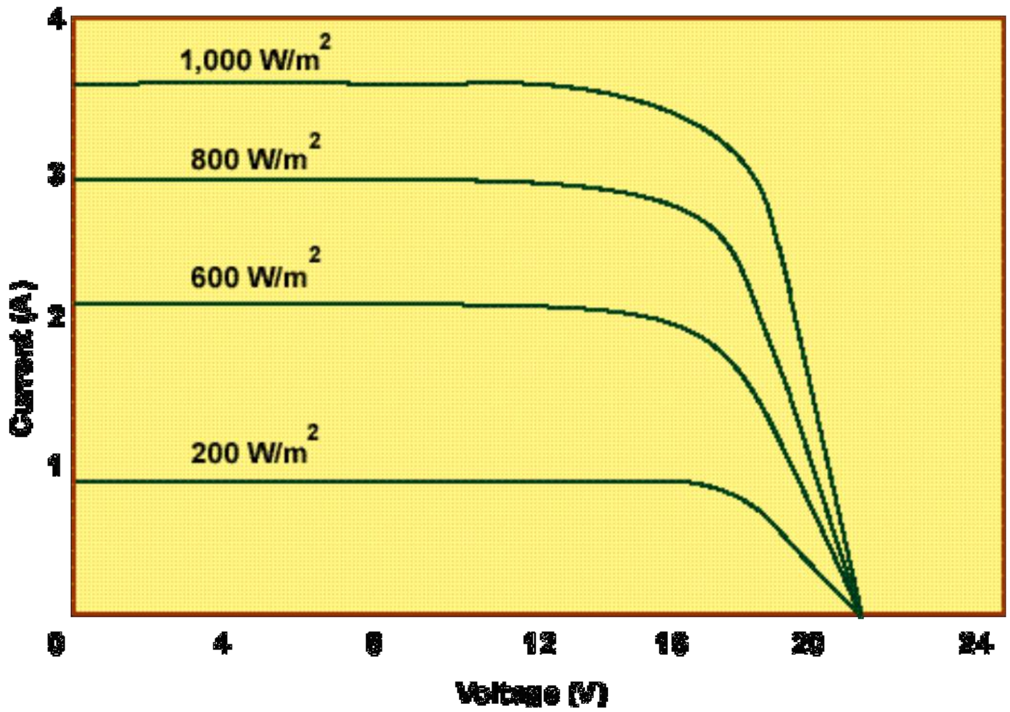

Figure 2. PV module current diminishes with decreasing solar irradiance.

The next figure shows the effect that temperature has on the power production capabilities of a module. As module operating temperature increases, module voltage drops while current essentially holds steady. PV module operating voltage is reduced on average for crystalline modules approximately 0.5 percent for every degree C above STC (i.e., 25°). Thus, a 100 Wp crystalline module under STC now operating at a more realistic 55° C with no change in solar irradiance will lose about 15 percent of its power rating and provide about 85 W of useful power. In general when designing PV systems, one should expect a fifteen to twenty percent drop in module power from STC. Kandahar CIty will rarely see its PV systems operate at STC conditions and given the hot climate there will be a substantial derate.

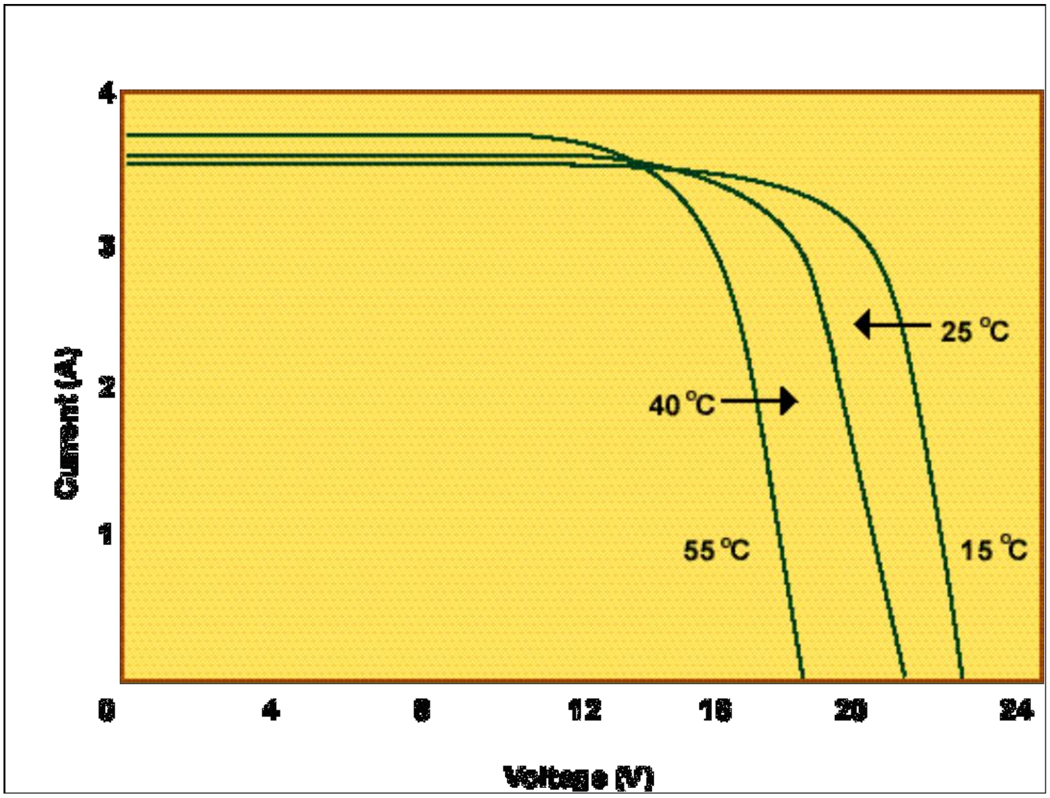

Figure 3. PV module voltage drops with temperature, as does power.

2.1 Grid-Tied PV Systems

A grid-tied PVPS only operates when the utility is available. However, in the event of an outage, the system is designed to shut down until utility power is restored. While a PV system can help serve as a good peak shaving generation system for Kandahar, inevitably there will be an overcast day where solar power production will be much less.

PV Array: Consists of PV modules interconnected in series and parallel to obtain the desired voltage and current. All PV modules should be IEC or UL listed and installed in accordance with National Electrical Code (NEC) guidelines (UL & NFPA, 2008)

Balance of System components (BOS): BOS includes mounting systems and wiring systems. The wiring systems include disconnects for the dc and ac sides of the inverter, ground-fault protection, and overcurrent protection for the solar modules. Most systems include a combiner board of some kind since most modules require fusing for each module source circuit.

Power Conditioning Unit: This is the device (i.e., inverter) that takes the dc power from the PV array and converts it into standard ac power for the grid.

Monitoring: Metering that indicates system performance and assists with operation.

2.2 Array Mounting Options

PV systems can produce as much as 10 Watts per square foot of array area. Typically, about 36,000 square feet (400' x 90') per 200 kw (ac output) of unobstructed area is used for tracking PV crystalline systems for a typical area in the feasibility study (or ~16.7 m^2 per kW). About half this for lower efficiency thin-film technologies. Typically, anywhere from 1,700 (x-Si) to 3,000 (a-Si) square meters per 100 kW (ac output) of unobstructed area is required, depending on module type and tracking used. The final actual area will depend on the type of modules and tracking system selected and their efficiencies. For Kandahar latitude, will need about 40 acres for a 10 MW one axis (E-W) tracking system using crystalline PV technologies.

2.2.1 Roof mount

PV arrays of a few kiloWatts are often mounted on individual rooftops. The weight of the PV array is typically about 5 lbs/ft^2. Depending on structure, this can be the most inexpensive mount for an array for an existing substrate. Sometimes, such as with flat roofs commonly found in Afghanistan, a separate structure with a more optimal tilt angle is mounted on the roof. Proper roof mounting is labor intensive. Particular attention should be given to the roof structure and the weather proofing of roof penetrations. Typically, there is one support bracket for every 100 Watts of PV modules. There are also additional building shade issues.

Generally speaking, roof mounted PV arrays are most typically less than 10 kW in size. There are only a few rooftop PV arrays in the hundreds of kW range. Rooftop arrays are more complicated to plan for large MW systems and only make sense for very large buildings and rarely exceed 1 MW in size (e.g., an airport terminal). To plan out multiple small rooftop installations throughout Kandahar City will be very difficult and expensive to implement and operate. Each individual system would need its own inverter, therefore driving up overall system costs. Likewise, experience has shown in Japan and the U.S. that if there are many small systems (hundreds), grid stability suffers as overall grid voltage tends to drift upward due to the interaction of many small inverters.

2.2.3 Ground Mount

A ground mounted PV array is the least expensive and most viable option for a 10 MW Kandahar PVPS from a logistics, budget, operational, and planning perspective. The required size for a 10 MW PV 1 axis tracking array is about 167,000 square meters (roughly 40 acres). The vendor will have to create the substrate for the PV installation, which requires somewhat extensive civil works to install. A single ground-mounted system with a few large inverters is the best option for Kandahar city for a large 10 MW grid interactive PVPS.

2.3 System Output Considerations

For a large Kandahar PVPS, the PV array will provide power to the power grid via a few utility-interactive inverters (or power conditioning unit, PCU). PV systems produce power in proportion to the intensity of sunlight striking the solar array surface. The intensity of light on a surface varies throughout a day, as well as day to day, so the actual output of a solar power system varies substantially over a day. There are other factors that affect the output of a solar power system. DABS should understand these variables so as to have realistic expectations of overall system output and economic benefits under variable weather conditions. It is important to think in terms of overall system design. A PV system should be engineered to work together as a unit. Thus, good PV system designers think in terms of overall system design and systemic operational performance. For the Kandahar project, PV system interaction with the existing grid will need to be evaluated.

2.3.1 Output Factors - Standard Test Conditions

PV modules produce dc electricity. The dc output of solar modules is rated under Standard Test Conditions (STC). These conditions allow for consistent comparisons of products, but need to be modified to estimate output under common outdoor operating conditions. STC conditions are:

solar cell temperature = 25 °C;
solar irradiance = 1000 W/m^2; for a

solar spectrum through 1.5 thickness of atmosphere (ASTM Standard Spectrum).

A solar module will be rated at a given output, e.g., 100 Watts of power, under STC. Modules often have a production tolerance of +/-5 percent of this rating in actuality.

2.3.2 Temperature

Module output power reduces as module temperature increases. A solar module will heat up substantially above ambient temperature, often reaching operating temperatures of 50-75 °C. For crystalline modules, a typical temperature reduction factor is about .05 percent per °C above 25°C. For the Kandahar analysis, the monthly average maximum temperature is used to calculate the daily average module operating temperature is estimated as follows (Pate, 1992):

$$Tm = 20.4 + 1.2(Ta)$$

Where Tm – module operating temperature °C
Ta - ambient temperature °C

2.3.3 Environmental Factors

Key environmental factors affecting PV system performance are total solar energy available and module operating temperature. For the Kandahar analysis, 1 axis E-W tracking of the PV arrays are assumed using solar energy data (NREL). PV modules are assumed to conservatively operate in ambient temperatures equal to the average daily maximum high temperature for each month.

Table 3: Kandahar Insolation and Average Daily Maximum Temperature

Month	1 Axis Tracking Latitude Tilt kWh/m2/day	Avg Daily Max Temp °C
January	4.0	13.0
February	5.3	17.0
March	6.7	22.0
April	8.8	28.0
May	9.9	33.0
June	12.3	37.0
July	11.5	39.0
August	9.8	37.0
September	8.9	34.0
October	6.9	29.0
November	4.6	23.0
December	3.7	25.0
Average	7.7	28.1

2.3.4 Mismatch and wiring losses

For the dc side of the system, the maximum power output of the total PV array is always less than the sum of the maximum output of the individual modules. This difference is a result of slight inconsistencies in performance from one module to the next and is called module mismatch and amounts to at least 2 percent loss in system power. Power is also lost to resistance in the system wiring. These losses should be kept to a minimum but it is difficult to keep these losses below 3 percent for the system. For purposes of the Kandahar analysis, such losses are considered to be a total of four percent for the dc side of the system and included in the analysis.

2.3.5 dc to ac conversion losses

The dc power generated by the solar module must be converted into ac power using an inverter. Some power is lost in the conversion process, and there are additional losses in the wires from the array to the inverter and out to the grid. Inverters commonly used in PVPS have peak efficiencies of 92-94 percent indicated by their manufacturers laboratory conditions. Actual field conditions usually result in overall dc-to-ac conversion efficiencies of about 88-92 percent. For the Kandahar analysis, an average of 90 percent conversion efficiency is considered.

2.4 System Warranties

There are several types of warranties available for PV systems. These include (a) product warranties covering defects in manufacture; (b) system warranties covering proper operation of equipment for a specific time period (e.g., 10 years); and, (c) annual energy performance warranties covering the guaranteed output of the PV system. The vendor, to guarantee proper system installation, should be asked to cover the system and annual energy performance warranties. A typical system level warranty might state that the PV system is guaranteed to produce X kilowatts of AC power at PVUSA Test Conditions (PTC) (PTC is 1kW/m2 irradiance, 1 m/s wind speed, 20°C ambient temperature) in the fifth year of operation.

2.4.1 Product Warranties

PV modules may have warranties for as much as 25 years by some manufacturers. However, there are many other components in PV systems that will not have the same life expectancy. Inverters may have a warranty of ten years or less. DABS should look also closely at the individual product warranties.

2.4.2 Performance Warranties

An energy performance warranty guarantees that the system will perform consistently over a period of time. This is particularly helpful in ensuring that Kandahar receives the bill savings expected. Adequate metering to verify the system power output and energy generation is necessary to understand whether the system is operating properly, or has warranty-related performance issues. With an adequate metering system, Kandahar can identify when the system is malfunctioning. There are a few PV companies selling systems with this type of warranty for larger systems.

3.0 GENERAL PV SYSTEM PERFORMACE ANAYLSIS

3.1 Kandahar Electric Generation

A utility-interactive PVPS for Kandahar in southern Afghanistan is proposed to provide power for the city load. The city, which is home to about 850,000 people, receives about 16-24 MW of power (this represents only 20-30 Watts per person!). Currently, approximately 10-12 MW is coming from Kajaki Dam, 7 MW for 24/7 power is generated by KTA50 Diesel gensets, and 7 MW for 24/6 is generating by QSK60 gensets. The QSK60 gensets are generating power for Kandahar for 24/16 if the Kajaki – Kandahar transmission line is off. Therefore, the daily energy production in Kandahar is under 500 MWh/day (Wardak, 2010). Military officials estimate potential demand at about 50 MW (Washington Post, 2010).

Electricity tariffs for Kandahar are way below cost, especially given the limited generation. DABS only charges users Af 3.00 per kWh (or ~US$.06/kWh). Thus, the value of the electricity generated in Kandahar is heavily subsidized and there simply is not nearly enough electricity to meet the demand. Diesel generated electricity is probably running over 40 cents per kWh. Hydropower (Kajaki Dam) is always the cheapest long term electricity solution.

3.2 System Capacity Determination

System capacity defines the PV system's generating capacity. Among the items to consider are the PV capacity and inverter capacity. Regardless of the system being considered, it is important for the system design and capacity (PV and alternatives) to guarantee the same reliability of supply. For the Kandahar analysis, it is assumed that the PV system is going to help provide a portion of the city load during daylight hours only (there is no energy storage).

3.3 PV System

Tracking Method: 1-axis E-W tracking
Array Slope: 32° (~latitude tilt for Kandahar – maximum annual energy production)
Array Azimuth: 0 ° (due south)

3.3.1 PV System Component Efficiencies:

Modules: Temperature derate of 0.5% per °C above 25°C using the average monthly daily max average temperature as a base.
PCU: 90% average efficiency
Total wire, switchgear, fuses, mismatch losses: 5%

Total Average PV System Efficiency: 75% on average for the first year, varies by month and dependent on ambient temperature.

3.3.2 PV Array Degradation

PV modules degrade slightly each year. For this analysis, the PV array was considered to degrade at an average rate of 0.8% each year. After 25 years, total array degradation is expected to be 20% below nameplate rating. This is typical of the warranty offered by several manufacturers (e.g., Sharp). Actual PV array degradation will vary by climate and module manufacturing methods.

3.3.3 PV Plant Capacity Factor: This represents the total 24 hour operating capacity for the PV plant, which give Kandahar solar resource is considered as ~23 percent for the first year. This assumes no significant downtime for maintenance. This range of capacity factor has been met by other large PV grid tied plants in similar desert regions in the U.S. and Middle East. This factor will gradually decline over time as the array gradually degrades, maintenance actions, etc.

3.4 Energy Production

Energy production for the Kandahar solar electric system can be estimated given the solar resource for Kandahar and ambient termperature. Note that solar resource can vary as much as ten percent from year to year (especially due to global volcanic activity in the northern hemisphere). For the proposed Kandahar 10 MW solar electric system, it was estimated that given an average meteorological year is should generate about 20,183 MWh during the first year of operation. Average expected PV plant size for Kandahar are provided in Table 4.

There are three calculated parameters commonly applied to PV systems: availability; energy production; and capacity factor. System availability is the ratio of the time the PV system is producing energy to the time sunlight is available. A plant that produces between sunrise and sunset is 100% available, and no penalty for sundown is imposed. Availability relates to system or plant reliability but is not of great value to planners determining a utility-wide application. PV plants are modular, and a plant is deemed available even when it is only partially on-line. For the Kandahar analysis, the system is optimistically always considered to be available. This is a best case assumption and in reality there will probably be downtime periods for parts of the system during daylight hours.

Table 4: Kandahar PVPS Specifications

PV Array Specifications		
Size of PV Array	10,000	kWp
PV Array Area w/tracking	167,000	square meters
Annual PV Energy Generation	20,183	MWh/year (Yr 1)
Array Slope	32	degrees
Array Azmuth	0	degrees (due south)
Tracking Method	1 Axis (E-W)	Lat Tilt
PV Plant Capacity Factor	23.0%	Avg Annual

Capacity factor is the ratio of the PV energy produced in a given time to the energy that could be produced in that time if the plant had been continuously generating its fully rated output. Because PV plants can only produce during daylight hours and output is reduced to heat, a capacity factor of about 23% is realistic for southern Afghanistan for crystalline PV modules. Similar installed utility PV power plants in the Southwest U.S. and Middle East operate at about this same capacity factor.

Fig. 4.

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are needed to see this picture.

Kandahar Estimated PV Power System Plant Capacity Factor by Month

Fig. 5. 10 MW

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Kandahar PVPS Plant Monthly kWh Generated (Year One)

Table 5: Kandahar 10 MW PVPS Plant Performance Summary (Year One)

Expected Performance for a Kandahar 10 MW PV System								
Month	**Days**	**1 Axis Tracking Latitude Tilt kWh/m2/day**	**Avg Day Max Temp °C**	**Avg Mod Temp °C**	**x-Si Temp Derate %**	**PV System Efficiency %**	**Plant Capacity Factor**	**kWh produced**
January	31	4.0	13.0	36.0	94.5%	80.8%	13.5%	1,001,889
February	28	5.3	17.0	40.8	92.1%	78.7%	17.4%	1,168,583
March	31	6.7	22.0	46.8	89.1%	76.2%	21.3%	1,582,269
April	30	8.8	28.0	54.0	85.5%	73.1%	26.8%	1,929,906
May	31	9.9	33.0	60.0	82.5%	70.5%	29.1%	2,164,796
June	30	12.3	37.0	64.8	80.1%	68.5%	35.1%	2,527,115
July	31	11.5	39.0	67.2	78.9%	67.5%	32.3%	2,404,931
August	31	9.8	37.0	64.8	80.1%	68.5%	28.0%	2,080,589
September	30	8.9	34.0	61.2	81.9%	70.0%	26.0%	1,869,654
October	31	6.9	29.0	55.2	84.9%	72.6%	20.9%	1,552,689
November	30	4.6	23.0	48.0	88.5%	75.7%	14.5%	1,044,212
December	31	3.7	25.0	50.4	87.3%	74.6%	11.5%	856,138
Average		7.7	28.1	54.1	85.5%	73.1%	23.0%	1,681,898
Annual Total	365							20,182,772

Over time, the PV arrays will gradually degrade and performance and energy production will likewise drop. Actual PV array degradation varies depending on installation, environment, and modules used. The Kandahar PVPS is assumed to degrade within PV module manufacturer specifications of providing 80 percent of rated power after 25 years, which implies an annual module degradation rate on average of 0.8 percent per year. The figure below tracks expected annual Kandahar performance trends for an average meteorological year. Actual performance will vary. Total 25 year expected energy production is approximately 472 million kWh. Actual production will vary with insolation, ambient temperature, and overall PV plant availability.

Fig. 6.

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are needed to see this picture.

Expected 10 MW PVPS plant annual energy generation over 25 years.

4.0 KANDAHAR PVPS ECONOMICS

In order to understand the economics of a large-scale PV power system (PVPS), it is imperative to conduct financial analyses of such a system as compared to conventional alternatives on a life-cycle cost basis. PV modules are guaranteed by manufacturers up to 25 years of 80% of rated wattage at standard test conditions (25°C and 1,000 W/m^2). The useful module lifetime is probably actually 35 years or more, although the actual end of life mechanism for PV modules (Block V modules) is still unknown as the oldest modules of the type currently produced have only about 30 years of operation to date. Long term lifetime for many thin film modules is even less known as most have less than a decade in production. Thus, when a user purchases a PV array, they are actually purchasing the equivalent of 40 years or more of power production. The only way to make a fair economic assessment of the equipment is to look at a levelized life-cycle cost analysis over a reasonable time frame.

Any solar project subjected to financial evaluation will have its costs and benefits spread out over a number of years. In order to compare one project with another, or to determine the financial viability of a particular project, it is necessary to streamline the costs and benefits to a single number over time. This is most easily done by calculating the present value. There are a variety of methods used for calculating financial feasibility of solar energy projects. For life-cycle cost comparison considered here, the Net Present Value (NPV) method of comparison is most easily applied and commonly used for this type of analysis.

4.1 Net Present Value Method

The NPV of any particular investment project (solar, etc.) at the point in time for t = 0 is the sum of the present values of all the cash inflows and outflows related to the investment. Expenditure and income are generally balanced to obtain annual returns so that the NPV of an investment is simply the sum of the present values of its return plus the present value of its liquidation yield less the present value of its investment costs:

$$\text{NPV} = \text{annual returns} - \text{investment costs} + \text{liquidation yield}$$

An investment project is only profitable when its NPV is greater than or equal to zero. When there are several alternative investment possibilities (e.g., investing in a PV system or a wind energy system), the NPV of the different projects can be compared with one another and investment with the highest NPV selected.

5.0 LIFE CYCLE COSTING METHODOLOGY (LCC)

It is reasonable to use a life cycle cost approach, particularly when dealing with renewable energy technologies which typically have high initial capital costs, as opposed to conventional energy sources which typically have relatively low capital cots, but high operational and maintenance costs. Electrical generation costs can be classified under different criteria. The costs for electrical generation can be broken out into five main categories:

- Capital costs
- Operation and Maintenance Costs
- Fuel Costs
- Replacement Parts Costs
- Environmental Costs

Depending on the type of power production required, these costs will vary. For instance, if coal or oil electrical generation plants are compared to a utility scale PV energy system, the initial costs of the fossil fuel based plants per MW are lower, the operation and maintenance costs and fuel costs are relatively high. Conversely, PV systems have high initial costs but zero fuel costs and low operation and maintenance costs.

Thus, viable economic decisions cannot be made only on the basis of one type of costs (e.g., capital cost), but rather must consider all the costs incurred over the lifetime of the system. Levelized life cycle costing (LCC) analysis methods make it possible to compare different alternatives by adding up the project costs over its lifetime.

The life cycle cost (LCC) method of economic analysis calculates a system's total cost over its useful life. This method takes into account the initial (capital) outlays and all other costs required for the system to operate properly over its life. The LCC method helps quantify the economic impacts of a project using different cost components with varying reliability factors. It helps optimize the overall system analysis from a traditional economic standpoint. It also allows a method to assess the impact of changing economic variables such as interest rates and inflation. While it is very difficult to accurately predict how these variables will change in the future, it does provide a relatively good method to assess impacts based on what the most likely future assessment for these variables is. The LCC can be calculated as follows:

$$LCC = Cpv + O\&Mpv + Fpv + Rpv + Epv - Spv$$

where,

Capital investment (Cpv) present value is the cost of equipment, including systems design and installation costs. This is a one-time payment at the start of a project. Various investment costs for a PV system can be indexed according to their time of accrual in ways that make it possible to order the investment expenditures clearly, according to a time schedule as is needed for the proper calculation of financial acceptability of a project. Typical investment costs are as follows, most of which are applicable to Kandahar:

Possible Kandahar Applicable PV System Costs

- Planning/Administrative
- Environmental impact studies
- Land acquisition/leasing
- Civil works (e.g., PV structure)
- Plant building/structures (power house)
- Machinery (e.g., inverters)
- Utility connections (e.g., roads, grid interconnects)
- Shipping/transportation including insurance
- Assembly and commissioning
- Taxes, custom duties, fees
- Other costs (e.g. security)

PV project costs are determined from reported industry averages, with PV modules representing about a third of project costs. Large grid interconnected PV systems in the Southwest U.S. ad the Middle East typically range from a low of about $6.00/Watt and a high of $8.00/Watt. Costs vary with location, vendor, system size, module technology, local labor rates, contractor experience, insurance, etc.

The largest regional grid-tied PVPS is the recent 2009 Masdar Abu Dhabi 10 MW_p installation by CH2MHILL shown on the front cover. This single-axis tracking PV system cost US$6/Wp (5 MW_p First Solar CdTe modules and 5 MW_p x-Si). Thin-film (e.g., a-Si) PV modules take about double the area for the same power production as compared to crystalline (x-Si) modules due to lower conversion efficiencies.

However, projects always cost more in Afghanistan due to security issues, difficult logistics, overland shipping, etc. With shipping and logistics, the recent Paktiya 80 kW_p fixed array x-Si PV system installed by SESA in Jan. 2010 cost US$2.3 million (including ~$800k for battery bank and ~$700k for transmission). Thus about $10.00/Wp without energy storage and transmission. A larger MW sized PVPS will have greater economies of scale. However, since no such project has ever been undertaken in Afghanistan, actual costs will

Thus, a Kandahar MW size PVPS should cost somewhere between the Abu Dhabi and Paktiya examples cited. For this analysis, ~US$7.50/Wp +/- 20% is probably is assumed to be a reasonable installed cost estimate for a 10 MW_p scale grid-tie installation with single-axis tracking for Kandahar.

Thus, about US$75 million +/- 20% would be a reasonable expected installed cost for a 10 MWp Kandahar PVPS. This excludes transmission needed to move the power. Costs for this will be dependent on the location for the MW system. Ideally, a flat open publically owned land site of approximately 40 acres chosen near existing transmission or power plant is where to install such a large system to keep transmission costs to a minimum.

Operation and Maintenance costs (O&Mpv) present value is the total sum of annual costs taken as a present worth for operator's salaries, equipment inspections, insurance, tax, prepaid maintenance. These costs here are not reflecting the cost of fuel consumption or replacing major equipment items. Estimations of personnel costs over the project lifetime, particularly in labor-intensive projects of long duration can be an important component of any LCC analysis. It is necessary to carefully consider any increase in these costs on the basis of the anticipated general inflation rate. If opportunity costs of self-employment become significant, these should also be accounted for by an appropriate sum in the financial evaluation.

The actual expenses related to maintaining and servicing a PV or other plant can vary greatly, thus in practice it is very difficult to accurately predict what these costs will be. This type of comparison should also be done in light of what the DABS on-site staff are capable of carrying out themselves with local parts. In practice, a best guess based on previous experience with similar equipment in the Southwest U.S. and Middle East region should be made for estimating annual maintenance and repair costs. For the Kandahar analysis, an annual maintenance cost of $12,000 per MW is reported for maintenance including replacements for DOD PV power plants (Black, 2003). The military DOD experience is probably most analogous to the proposed Kandahar PVPS case. General annual maintenance outside of replacements is considered to be .012/kW installed for this analysis, which essentially covers the equivalent of one full time maintenance person for the Kandahar 10 MW PV system.

Fuel cost (Fpv) present value is the total expenditures for fuel consumed by the system. These costs vary at a rate often quite different from operation and maintenance costs. Grid electricity price for Kandahar is assumed to escalate at an average 1 percent per year in addition to the real discount rate. Obviously, there are no fuel costs for the Kandahar PVPS.

Replacement costs (Rpv) present value reflect major repairs and equipment replacements which occur when the normal duty life of any system components is shorter than the life expectancy of the entire system. For the Kandahar analysis, the PCU is assumed to be replaced halfway through the system lifetime (i.e., 12.5 years).

Environmental costs (Epv) present value are those costs not normal reflected in conventional economics that take into account the externalities associated with environmental damage and risks. For some analysts, they may not be allowed to use this very real cost since these costs are often not borne directly by the user, but by society as a whole. For the Kandahar PVPS analysis, environmental costs are excluded.

Salvage value (Spv) present value or recovery value of the equipment is the net value of the equipment used at the end of the system's service life. The salvage or residual value of a plant and/or components is based on the possibilities of alternative uses at the end of the project lifetime. Assuming that equipment or plant parts can be sold, the expected liquidation yield from the sale at a fixed point in time is usually taken as the residual value. If a later sale is improbable, than a salvage value of zero would be appropriate. Any possible dismantling costs and costs for making a sale must be deducted from the project salvage value. For the Kandahar PVPS, the salvage value after 25 years are assumed to be zero.

When applying LCC methodology, it is easiest to evaluate all costs from different years correlated to one year (e.g., net present value). Costs that arise in the future must be discounted due to the time value of money. Typically, all future costs are transformed to their present value. Appropriate discount factors must be applied to this end as can be commonly found in many financial tables or formulas. To calculate present worth, the following equation is used:

$$PV = FV/(1+i)^n$$

where PV = Present Value
FV = Future Value
i = interest rate
n = number of years

Other factors such as annuity type costs require similar calculations as well. For instance, to calculate the present worth where annual payments are known and the total present worth of all payments needs to be determined, the following equation can be used:

$$PV = A * UPW$$

$$UPW = [(1 + i)^n - 1]/i(1 + i)^n$$

where A = annuity payment
UPW = Uniform Present Worth

Choosing realistic discount rates will be the most difficult and one of the most influential variables in the LCC analysis. If a low discount rate is chosen, this will emphasize future costs, since they will be discounted less than the initial costs, as opposed to a high discount rate which emphasizes initial costs over future costs. The discount rate should reflect the system owner's potential for saving funds in conventional economic terms. It is important to note that the nominal investment rate is not the effective rate of return received by the end-user since this if affected by inflation and will reduce the value of future savings. Thus, it is important to subtract the inflation rate from the nominal investment rate to obtain the real discount rate. Since the fossil fuel inflation rate is often higher than that of products, it is reasonable to assume a separate fuel escalation rate as well.

5.1 Economic Parameters for LCC Analysis

For any type of economic analysis, the critical economic parameters and type of financial analysis procedure for the analysis must be carefully thought out. This is an inexact task in that it requires making estimations about the future.

Project Lifetime

The service life of an installation is the number of years beyond which the system becomes more expensive to maintain than a new acquisition or when the efficiency of the system deteriorates such that the output product is unacceptable in quality and/or quantity. There are several different methods to estimate the useful service life of capital assets. The more sophisticated methods use actuarial analysis, while other methods that are more convenient and simple use national tax guidelines. The service lives used as the basis for depreciation accounting should be determined by the asset's particular operating conditions and experience. Actuarial approaches to estimating service life are more involved and consist of construction of frequency curves, survivor curves and probable-life curves. For this analysis, a total PV project lifetime was assumed to be 25 years, at the end of which the PV system would be providing 80 percent of its nameplate power rating.

Inflation Rate

Inflation is the increase of prices paid for goods and services over time. The increase in prices results from either cost inflation or price inflation or some combination thereof. Cost inflation is the result of a real cost increase to produce goods and services. Price inflation may be caused by an increase in the amount of money held in a national economy. It may also be caused by the speed and spending habits of people within a society. Thus, cost inflation and price inflation can occur at the same time, causing the value of money to change at different times.

Government's use price indexes to track the value of money over time. Wholesale Price Indexes and Consumer Price Indexes are used which cover specific types of products. Inflation is normally expressed as an annual percentage over a time period. The annual rate of inflation can be determined by

$$f(t) = - (PI_t / PI_{to}) - 1$$

where

$f(t)$ = annual inflation rate
PI_t = current price index
PI_{to} = reference year price index

Afghanistan has experienced relatively low inflation over the past few years, typically only a few percent per year. For the Kandahar analysis, an average annual inflation rate of 3 percent was used as a projection for the next 25 years.

Discount Rate

In determining the financial viability of solar energy projects, one of the logical manners to determine this is to reduce the time stream of costs and benefits to a single number by calculating the net present value (NPV) of the project. For any single project the discount rate will affect whether the NPV is greater or less than zero. For comparing projects, the discount rate will affect the NPV ranking.

Ideally, the correct discount rate is the rate when applied to future costs and benefits yields the actual present social values. Thus, this is the rate at which society as a whole is willing to trade off the present for future costs and benefits. The choice of a proper rate is not over numerical values *per se*, but rather concerns the idea of what the discount rate should measure.

The critical discount rate is that where the NPV of a project changes sign. Sensitivity analysis can be helpful to determine how critical the discount rate of a project is. Following are the different types of rates that can be considered for project development.

Real Discount Rate

Once the most appropriate discount rate category has been selected (e.g., corporate rate or market interest rate), the real discount rate is calculated as the difference between the discount rate and the inflation rate. For the Kandahar analysis, the final real discount rate used is 1 percent.

Fuel Escalation Rate

For the Kandahar PVPS, it can be assumed that solar power will be directly available in the required quantity and quality, free of charge, after the installation of the necessary plant and equipment for the project site. When using grid power sources, additional costs arise for the procurement, transport, processing and storage of the relevant energy source for fueling the plant, as well as any costs associated with discarding or discharging residues within legal requirements are already included in the grid price of electricity. The present worth of grid power over the project lifetime needs to be calculated.

The determination of the annual energy escalation rate is based on the price index of the particular energy source in question. The energy escalation rate can also be calculated from the expected real increase in the cost of energy and the general inflation rate as follows:

$$e(t) = [1 + e^{*}(t)][1 + f(t)] - 1$$

where

$e(t)$ = annual energy escalation rate

$e^{*}(t)$ = real annual rate of increase in the cost of energy

For the Kandahar PVPS, an average annual grid electricity modest price increase of two percent per year was assumed over the next 25 years. Obviously current subsidized electricity tariffs in Kandahar cannot be maintained. It's possible actual price increases could be much more and will depend on what happens with the Kajaki hydropower system.

Externalities

LCC methodology generally is not used to incorporate externalities related to energy production and usage. However, probably the best single way to incorporate externalities for an LCC analysis is by assigning additional costs (or subsidies) to the fuel source in question. The difficult part is in assigning a value of improved security, reduced emissions, spill risks, noise pollution, etc. No externalities are included for this analysis.

6.0 Kandahar PVPS LCC Analysis

The following analysis is a life-cycle cost estimate for the proposed Kandahar 10 MW_p grid-tied PVPS as compared to the conventional electric grid. The LCC analysis has been conducted assuming average annual production with normal PV system losses based on one axis tracking at latitude tilt No salvage value has been given to either the grid or PV systems, although in reality used PV modules could be worth as much as 20% or more of their original value at the end of 25 years. No externalities are assumed.

Economic Conditions

The useful lifetime for the Kandahar grid-tied PVPS is assumed to be 25 years using net present value life-cycle cost analysis over a 25 year lifetime. Actual project development costs for southern Afghanistan could vary by as much as 20 percent from those estimated here. However no MW scale PV arrays have been installed in Afghanistan and the nearest such type installations are in UAE. So final costs could vary depending on local factors and costs. The following table details the common base case financial assumptions.

Large grid interconnected PV systems have been installed at a range of costs. System costs, especially for ground mounted systems with extensive civil works, are typically between US$6-8 per installed peak Watt (Wp). For the Kandahar PVPS cost estimate, an installed cost is assumed to be US$7.50 per installed Watt.

6.2 Kandahar Financial Assumptions:

Table 6. Kandahar 10 MW_p PV Economic Assumptions

Parameter	Solar System
Project Lifetime	25 years
Salvage Value	none
Installation Cost	$7.50/Wp
Fuel Cost	none
Demand Cost	none
Fuel (Grid) Escalation Rate	2% per year
O&M Costs	$.012/kW installed per year
General Inflation	3% per year
Discount Rate	2% per year
Real Discount Rate	1% per year

The LCC analysis was conducted to bring all costs into their present worth. This information is included in Table 7. Again, this analysis optimistically assumes no PV system downtime during daylight hours. Obviously, the PV system will not be available for nighttime usage. If energy storage was added, the system cost would approximately double. There are no MW sized PV systems in the world using energy storage due to the high cost.

Likewise, installing numerous stand-alone PV systems with battery storage will actually be a much more expensive option. Installed costs would double to at least US$15/$W_p$. There are also significant roundtrip energy losses associated with batteries (over 30 %), so much of the solar generated power is never used for loads at night due to these losses. It is far less expensive to install a single large solar plant than many smaller solar plants.

For the Kandahar 10 MW_p PVPS, the following estimates were determined:

Table 7. Kandahar 10 MW_p PVPS Estimated Component Costs

	$ Aprox.	% Costs		TOTAL COST $
$/Wp	$ 2.25	30.0%	PV Modules	$ 22,500,000
$/Wp	$ 1.30	17.3%	Mounting Structure (tracking	$ 13,000,000
$/Wp	$ 0.50	6.7%	Switchgear & Interconnect	$ 5,000,000
$/Wp	$ 0.85	11.3%	Inverters	$ 8,500,000
$/Wp	$ 0.40	5.3%	Monitoring/SCADA	$ 4,000,000
$/Wp	$ 1.50	20.0%	Design & Installation	$ 15,000,000
$/Wp	$ 0.70	9.3%	freight/contingency	$ 7,000,000
	$ 7.50	100%	TOTAL	$ 75,000,000
			$/Wp	$ 7.50

Table 8. Net Present Value of Kandahar 10 MW_p PVPS with O&M

Item	Year	Cost $	PVIF, PVIFA	Net Present Value $
1. Costs				
PV Modules	0	$ 22,500,000	1.0000	$ 22,500,000
Mounting Hardwa	0	$ 13,000,000	1.0000	$ 13,000,000
Switchgear & Inte	0	$ 5,000,000	1.0000	$ 5,000,000
Inverter	0	$ 8,500,000	1.0000	$ 8,500,000
Metering	0	$ 4,000,000	1.0000	$ 4,000,000
Installation	0	$ 15,000,000	1.0000	$ 15,000,000
Miax	0	$ 7,000,000	1.0000	$ 7,000,000
2. O&M for 25 ye	0.012			
Labor .012/kW	per year	$ 120,000	28.2430	$ 3,389,160
3. Replacements				
PCU	12.5	$ 8,500,000	1.1270	$ 9,579,500
NPV Total Life Cycle Cost				**$ 87,968,660**

Table 9. Kandahar 10 MW_p Solar System Annual Expected Energy Production and NPV

Item	Year	PV Array Degradation	PV EnergyProduction kWh/yr	Grid Price $/kWh	Electricity Value Saved $	PVIF	Net Present Energy Value $
1. Costs		0.80%					
	0	100%	20,182,772	0.06383	$ 1,288,262	1.00	$ 1,288,262
	1	99.2%	20,021,310	0.06574	$ 1,316,295	1.01	$ 1,329,458
	2	98.4%	19,859,847	0.06772	$ 1,344,850	1.02	$ 1,371,747
	3	97.6%	19,698,385	0.06975	$ 1,373,933	1.03	$ 1,415,151
	4	96.8%	19,536,923	0.07184	$ 1,403,552	1.04	$ 1,461,097
	5	96.0%	19,375,461	0.07400	$ 1,433,711	1.05	$ 1,506,830
	6	95.2%	19,213,999	0.07622	$ 1,464,416	1.06	$ 1,555,210
	7	94.4%	19,052,537	0.07850	$ 1,495,673	1.07	$ 1,603,362
	8	93.6%	18,891,074	0.08086	$ 1,527,488	1.08	$ 1,654,270
	9	92.8%	18,729,612	0.08328	$ 1,559,866	1.09	$ 1,706,493
	10	92.0%	18,568,150	0.08578	$ 1,592,811	1.11	$ 1,760,056
	11	91.2%	18,406,688	0.08836	$ 1,626,329	1.12	$ 1,814,984
	12	90.4%	18,245,226	0.09101	$ 1,660,425	1.13	$ 1,871,299
	13	89.6%	18,083,763	0.09374	$ 1,695,103	1.14	$ 1,929,027
	14	88.8%	17,922,301	0.09655	$ 1,730,367	1.15	$ 1,988,192
	15	88.0%	17,760,839	0.09944	$ 1,766,222	1.16	$ 2,050,584
	16	87.2%	17,599,377	0.10243	$ 1,802,670	1.17	$ 2,114,532
	17	86.4%	17,437,915	0.10550	$ 1,839,716	1.18	$ 2,178,224
	18	85.6%	17,276,453	0.10867	$ 1,877,362	1.20	$ 2,245,325
	19	84.8%	17,114,990	0.11193	$ 1,915,611	1.21	$ 2,314,058
	20	84.0%	16,953,528	0.11528	$ 1,954,465	1.22	$ 2,384,448
	21	83.2%	16,792,066	0.11874	$ 1,993,927	1.23	$ 2,456,518
	22	82.4%	16,630,604	0.12230	$ 2,033,997	1.25	$ 2,532,327
	23	81.6%	16,469,142	0.12597	$ 2,074,677	1.26	$ 2,607,869
	24	80.8%	16,307,680	0.12975	$ 2,115,967	1.27	$ 2,687,279
	25	80.0%	16,146,217	0.13365	$ 2,157,868	1.28	$ 2,766,386
Total 25 Year	Total		472,276,859		$ 44,045,565		**$ 47,826,601**
				PV LCC Generation Cost	$	0.186	/kWh

Based on annual energy savings alone, the PVPS levelized life cycle cost per kWh generated the value of the electricity generated amortized over 25 years would be approximately $0.19 per kWh, which is over triple the current electric rate paid by Kandahar electric consumers. Diesel generated electricity probably costs nearly double this for Kandahar. The electricity generated by a large MW scale PV plant would only be available during daylight hours, but would help displace diesel fuel use and cut fuel bills. It would also help with peak shaving opportunities to displace daytime loads such as air conditioners. Off-grid stand alone systems would likewise cost double with battery storage.

7.0 CONCLUSIONS

The life cycle cost analysis showed that a large ten MW scale photovoltaic power system (PVPS) for Kandahar over a 25 year amortization would provide electricity at a cost of about US$0.19 per kWh. The installed cost for such a large PVPS would probably run upwards of US$75 million, excluding any transmission upgrades required. The system could be installed in 9-12 months by an experienced contractor (e.g., CH2MHILL). The PVPS would generate sufficient power to cover about ten percent of the current annual load provided in Kandahar (~500 MWh/day). While such a PV system would not provide any power at night, it would help displace diesel fuel consumption during the day. The large PVPS would help with peak shaving during the daylight hours, especially for summertime afternoon loads (e.g., air conditionrs/fans). Other renewable energy options, such as installing individual distributed stand-alone PV systems throughout the city would cost more than double. The most cost effective long term electrical supply solution for Kandahar City is undoubtedly upgrading the Kajaki dam hydroelectric system to its full operational potential for 24/7 power generation.

8.0 REFERENCES

Black, Bill, and Greg Kolb, "DOD Solar Energy Assessment," Sandia National Labs, DOE SETP PV Systems Symposium, Albuquerque, New Mexico, October 15, 2003.

Foster, R., Ghassemi, M., Cota, A., Solar Energy, Renewable Energy and the Environment Series, Volume 2, Taylor and Francis Publishing, CRC Press, ISBN: 13:9781420075663, Boca Raton, Florida, August, 2009.

IEEE Standard 929-2000, Recommended Practice for Utility Interface of PV (PV) Systems, 2000.

NREL - National Renewable Energy Laboratory, Solar Energy Radiation Database, from HOMER

NFPA - National Fire Protection Association, National Electrical Code 2002 (NEC) Article 690, 2008

Pate, Ron, Robert Foster, et al, "PV Water Pumping Guidebook," Sandia National Laboratories, Albuquerque, New Mexico, 1992.

UL Standard 1703, Standard for Flat-plate PV Modules and Panels

Wardak, Rasool, USAID – OIEE, personal communication, May, 2010.

Washington Post, "U.S. Military, Diplomats at Odds Over How to Resolve Kandahar's Electricity Woes," p. 1, April 23, 2010