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PERFORMANCE AND VALUE ANALYSIS OF THE KERMAN 500 KW PHOTOVOLTAIC POWER PLANT

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ABSTRACT

The Kerman Photovoltaic Power Plant is unique, not in the particular photovoltaic equipment selected, but in the siting of the plant in relation to the electric power system and how the plant interacts with that system. Kerman is the world's first plant designed and built specifically to measure the benefits of a photovoltaic system to the local distribution grid. In addition to the traditional energy and capacity values typically attributed to generation sources, several non-traditional benefits were quantified.

In providing energy services to its customers, a utility's expenses can broadly be categorized into capital costs for system expansion and operating costs for the actual generation and delivery of electrical energy. Construction of the Kerman plant allowed the calculation of several benefits which either allow deferral of capital costs or reduced operational costs. Performance of the plant over the past year and an evaluation of all the benefits are discussed. For Kerman, the value of non-traditional benefits doubled the value of the plant compared to the evaluation of only energy and capacity. The Kerman grid-support project challenges current resource planning methods to be expanded to adequately capture the impact of photovoltaics and other distributed generation resources.

INTRODUCTION

California, similar to many other parts of the country, is experiencing relatively flat load growth. Coupled with increased environmental concerns, siting difficulties for plants and lines, long lead time and capital outlay for bulk generation, and a changing regulatory environment, many utilities are looking to distributed generation to minimize risk, solve local problems and boost asset utilization. Since utilities have long embraced the economies of scale of central generation, the issues and methods used to plan for and evaluate such system additions are well understood. This is not the case for distributed generation. Distributed generation will generally not dominate or anchor the system, but complement and interact with, and must be considered part of, the local distribution system in which it operates.

This new paradigm requires that planners broaden their methodologies, matching system needs with the attributes inherent in the various technologies. Hence, while smaller disbursed generation may not compete with central station plants in cost per kW (or kWh), it does provide resource and distribution planners with another option when selecting the least-cost alternative for addressing multiple needs, and may be the best choice when investment uncertainty is considered.

Photovoltaics are well suited for peak shaving in summer peaking areas and can have considerable value in deferring capacity-related upgrades of lines or substation transformers. Line loss savings and emissions avoidance are other obvious non-traditional benefits locally sited photovoltaics can provide.

Designed as an unattended facility, the Kerman plant has been successfully operated since June 1993 by Pacific Gas and Electric Co. (PG&E) through standard SCADA equipment from the local distribution control center. Regular data collection and special testing have allowed a thorough evaluation of each of the benefits, both traditional energy and capacity, and six types of non-traditional. Each benefit was technically evaluated—the actual impact on the grid was quantified—then current system and economic factors were applied to derive a value for the benefit. While the methods are applicable to any site, the results calculated for Kerman are specific for the plant with its intrinsic solar, grid, and load conditions, as well as the prevailing fuel costs, system power and capacity values for PG&E.

BACKGROUND

The Kerman feeder was selected after screening 600 distribution feeders and 175 substation transformers in the San Joaquin Valley area [1]. The screening process was based primarily on the match between the solar resource and transformer and feeder loads during peak load hours along with low projected load growth.

The Kerman plant was built under the Photovoltaics for Utility Scale Applications (PVUSA) project. PVUSA is a national cooperative research and development effort under the auspices of the U.S. Department of Energy. In large part, the Kerman plant was installed to validate whether or not the plant could provide the local peaking capacity necessary to defer the replacement of the substation transformer and deliver a series of other tangible benefits to the utility network. Measured data and a series of special tests were used in the evaluation process [2,3].

SYSTEM DESCRIPTION

The Kerman plant, rated at a nominal 500 kWac[1], is connected to a semi-rural 12 kV distribution feeder about eight circuit miles downstream of PG&E's Kerman substation. The line is one of two connected to a 10.5 MVA transformer bank equipped with a voltage regulator. The town of Kerman is about 15 miles west of Fresno in California's Central Valley. The plant was purchased by competitive bid, with part of the selection criteria allocated to the projected economic value the system would provide to the utility, including site-specific non-traditional benefits. Siemens Solar Industries was selected with a single-axis tracker design to enhance the capture of both annual energy and afternoon solar resource for peaking power.

The plant occupies five acres of a 10-acre parcel of flat agricultural land. A control building, office trailer, and parking area occupy two acres; three acres are unused and unimproved.

General

The Kerman PV system features 12,240 Siemens Solar Industries M55VJ PV modules (with a total module area of 5210 m^2), two 275-kW Omnion Power Engineering Corporation series 3200 power conditioning units (PCU), a Robbins Engineering Inc. one-axis passive tracker system, and a utility-grade Supervisory Control and Data Acquisition (SCADA) system. The inverter output is stepped up through a 500 kVA transformer to 12.47 kV.

Remote operator functions are performed from PG&E's Fresno Distribution Operator's office via a communications link to PG&E's system-wide SCADA network. The SCADA system installed at the Kerman site uses standard PG&E-approved hardware for remote system monitoring and control.

PV Array and Support Structure

Panels consisting of 10 Siemens M55VJ modules are mounted on a horizontal torque tube with five modules on each side. Five-module sub-panels (east or west half of one panel) are wired in parallel with a blocking diode. One array is made up of eight panels, there are nine arrays per half row, and there are a total of 17 half rows feeding two Omnion PCUs (nine feeding Unit #1 and eight feeding unit #2). The input voltage to each PCU is a nominal ±477 Vdc.

Single axis (east to west) tracking is achieved through the use of Robbins SunSeeker tracker actuators. The SunSeeker consists of a pair of evaporator tubes and a double action actuator. The two evaporator tubes are connected to opposite sides of the actuator via hydraulic hose. The tubes and actuator are filled with a non-CFC refrigerant (R134a, tetrafluoroethane). The original units were installed with refrigerant only; newer replacement units contain a mixture of R134a and a lightweight oil. The tubes are placed on the east and west sides of the array. An imbalance in the amount of sunlight on the evaporator tubes causes a pressure differential in the actuator. The actuator piston is attached to a lever arm on the array and drives the array to a position where the evaporators are in equilibrium.

Power Conditioning Units

For the Kerman PV plant, Siemens selected two Omnion 275kW Series 3200 PCUs. Each self-commutated PCU contains six 50-kW insulated gate bi-polar transistor (IGBT) bridges. All bridges operate in parallel and are fired synchronously. Each unit is microprocessor controlled and operates with a switching frequency of about 7 kHz. Controls are designed to vary the bridge firing to maintain maximum power generation as irradiance and array temperature vary throughout the day.

PERFORMANCE

Plant performance for 1994 is summarized in Figure 1 which shows monthly values of generation, plane of array (POA) insolation, and performance index. The performance index (PI) is calculated by dividing the capacity factor by a similarly defined insolation factor and correcting the result back to the module temperature at rating conditions (PV efficiency is inversely proportional to operating temperature). A PI of greater than 90% implies good plant performance: there was no significant down time, soiling, or component failure during the period. A PI of near 100% is a performance goal.

The plot shows that the plant performed well during the first half of the year. The low performance index in April was

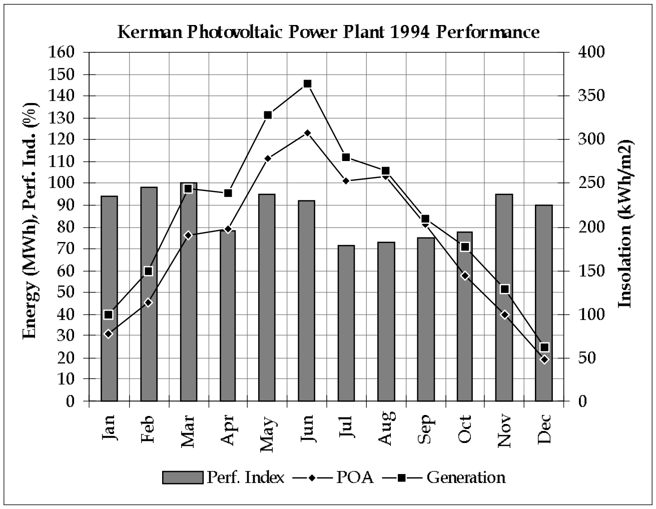

Fig. 1 Kerman 1994 Generation and Performance

primarily a result of SCADA equipment failures that prevented operation of one of the PCUs for one week. In June the plant tripped off due to a utility undervoltage condition. The system was down for six hours until the utility voltage rose to the threshold, and then provided 150V of voltage support per phase (out of 7,200 V per phase). In July through October, plant downtime and lost production were caused by intermittent PCU trips related to low utility feeder voltage, a 6 hour utility outage, a PCU failure, a failed tracker actuator and a failed module. Though none of the problems were major, each hour of downtime during daylight hours has a significant impact on capacity factor. Repairs made in September and October returned the system to normal operation by November.

Fig. 2 shows some additional plant statistics including plant efficiency, capacity factor, and peak ac output. Like generation, capacity factor is strongly influenced by insolation as well as plant availability. Efficiency is influenced more by temperature—higher temperatures yield lower efficiency—and module soiling. Peak plant output therefore occurs during periods of high irradiance and low temperature (typically clear spring days).

Because the sun powers the tracking system, tracking error (difference between actual tilt angle and a calculated optimum angle) is significant when the irradiance is low: in the early morning, late afternoon and during overcast conditions. Cold weather exacerbates the error. However, these are also conditions of low energy content. Inclinometers attached to each row indicate a consistent 5° lag under clear warm conditions. The arrays also tend to backtrack in the afternoon as a result of inter-array shadowing. Backtracking will actually improve array output since even partially shaded modules will put out little or no power. Total annual energy loss due to tracking error is estimated at about 5 percent.

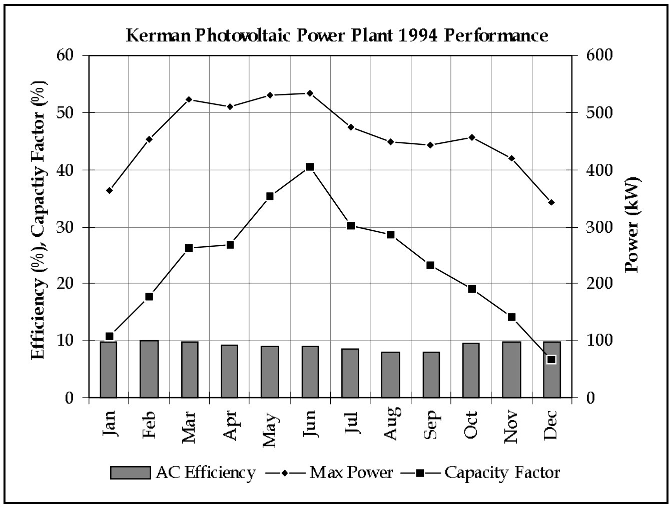

Fig. 2. Efficiency, Max. Power, and Capacity Factor

UTILITY BENEFITS DESCRIPTION

The benefits of electric supply- and demand-side resources must be determined by utility planners in order to ascertain economic viability and make investment decisions. There are two basic categories of benefits that the Kerman PV plant affords the utility. These benefits are termed "traditional" and "non-traditional".

Traditional benefits, namely avoided energy and capacity costs, are commonly used by utility planners. Avoided costs are the incremental marginal costs the utility would otherwise incur if it were to produce or purchase additional electric power. Avoided energy costs are typically driven by prevailing and projected fossil fuel prices (for PG&E, natural gas pricing dominates). Avoided capacity costs are driven by the utility’s projected need for generation capacity to ensure a minimum level of customer outages.

A series of *non-traditional benefits* were identified and estimated prior to installing the Kerman plant, and were documented in a 1992 PG&E report referred to as the Kerman Case Study [4]. The Kerman Case Study broke new ground by developing methods to evaluate non-traditional benefits that an appropriately-sited distributed generation resource can provide and suggesting that these benefits be included in resource planning decisions.

BENEFITS EVALUATION APPROACH

A two-step approach is used to determine the value of the Kerman PV plant to PG&E. Step 1 is technical. Measured data are combined with existing utility engineering models and improved evaluation techniques to determine the operational effect of the grid-support PV plant on the utility system. Step 2 is economic: the technical results are combined with economic models to estimate the plant's value to the utility.

Table 1 presents an overview of the traditional and non-traditional benefits evaluated and results [3]. These results are specific to the Kerman plant and its location within the distribution system, as well as PG&E's present economic and regulatory operating environment.

Technical Results

The Kerman PV plant provides the PG&E system every benefit listed in Table 1. Data analysis and testing confirm that both traditional and non-traditional benefits are measurable and predictable for grid-support PV. By locating generation near customer loads, the plant is able to deliver benefits spanning the entire utility system; from the distribution feeder to the substation, and from the high voltage transmission system to the generation fleet.

The technical (and economic) benefits are driven in two predominate ways. First, the PV plant's annual energy production, aggregated as a function of time of day and

Table 1. Kerman PV Plant Benefits Evaluated and Validation Results ($1995).

Non-Traditional Benefits	Definition & Economics Driver	Technical Validation Results	Economic Results	
			Nominal ($/kW-yr)	**High ($/kW-yr)**
EXTERNALITIES	*Fossil fuel emissions reduction*. Driver: Generation fleet fuel mix and externality valuation method.	Pollution is reduced by 155 tons of CO_2 and a half a ton of NO_x each year.	31	34
RELIABILITY	*Local reliability enhancement*. Driver: Postpone planned expenditures to improve reliability.	Voltage support is predictable and almost 3 volts provided (on a 120 V base). Testing proves customer outage time can be reduced.	4	4
LOSS SAVINGS	*Real and reactive loss savings*. Driver: PV plant capacity factor and interconnection location.	Real energy losses reduced by 58,500 kWh/yr (or 5 percent of plant output). Reactive power losses reduced by 350 kVAR.	14	15
SUBSTATION	*Transformer replacement and load-tap-changer maintenance deferral*. Driver: Magnitude of planned upgrade expenditures and load growth rate.	Transformer cooled by more than 4 °C and its capacity increased by 410 kW on peak day. Load-tap-changer maintenance interval extended by more than 10 years.	16	88
TRANSMISSION	*Transmission capacity deferral*. Driver: Marginal cost of transmission capacity.	Transmission system capacity increased by 450 kW on peak.	45	45
MINIMUM LOAD	*Power plant dispatch savings*. Driver: Marginal cost of keeping peak load-following units on-line.	Minimum load savings confirmed. PV plant delivers 90 percent PV capacity coincident with peak load-following unit dispatch.	28	28
Traditional Benefits	**Definition & Economics Driver**	**Technical Validation Results**	**Nominal ($/kW-yr)**	**High ($/kW-yr)**
CAPACITY	*System reliability enhancement*. Driver: Utility need for capacity to improve system reliability.	Generation system capacity increased by 385 kW (ELCC about 77 percent.)	12	53
ENERGY	*Energy generation displacement*. Driver: Fuel price of avoided energy generation resource.	Plant achieved about 25 percent capacity factor, over 1080 MWh/yr, highly correlated to PG&E loads.	143	157
TOTAL VALUE			**293**	**424**

season, drives externalities, loss savings, and energy generation benefits. Second, the extent to which PV plant capacity coincides with peak loads drives the remaining benefits of substation, transmission, minimum load, and system capacity.

During the July 1993 through June 1994 study period, the plant produced over 1080 MWh of electricity, achieving a respectable annual capacity factor of about 25 percent. In addition, the plant's output is highly coincident with the timing of local and system peak loads. For example, the substation transformer load peaks around 4:00 p.m. in the summer. At that time about 430 kW of PV plant load reduction capability, or 86 percent of the plant's capacity, is available. In summary, the Kerman plant merits high performance marks from both energy and PV-load match perspectives.

Economic Results

The second essential step of the benefits evaluation process is to translate each of the technical benefits into economic values. These values are then summed to derive the total value of the Kerman PV plant.

The economic analysis is based on a life-cycle approach commonly used in utility resource planning. The results are levelized, expressed in $/kW-year based on the plant's 498 kW rating. The economic analysis is based on a 9 percent utility discount rate, a 3.5 percent general inflation rate, and a 30-year project life.

These results represent tangible economic benefits. For example, every kWh of energy produced by the PV plant replaces a kWh that PG&E would have otherwise had to supply. The economic value of not having to supply this energy from some other source is calculated over the 30 year projected lifetime of the PV plant, brought to the present using the utility's discount rate, and then levelized to provide an annually recurring value.

Table 1 and Fig. 3 present the final economic analysis results for the Kerman PV plant [5]. Two sets of results are presented. The "nominal" value of the plant, at $293/kW-yr, represents the baseline evaluation under present (existing) conditions. The "high" value of $424/kW-yr represents a sensitivity to the Nominal Case. The High Case considers three factors that are different from the Nominal Case:

1. PG&E will need bulk system generation capacity for reliability purposes sooner than forecasted in the Nominal Case (capacity value);
2. The Kerman feeder is assumed to be an isolated radial line (thereby eliminating load switching capability) which maximizes the amount of time the PV plant can defer the substation transformer (substation value); and
3. Kerman PV plant production is increased by about 10 percent to 1190 MWh/year reflecting expected plant performance over its 30 year life (externalities, loss savings, and energy values).

Regardless of which set of factors are considered, one predominant conclusion is clear: The value of the Kerman plant is *doubled* by capturing non-traditional benefits. In other words, the distributed PV plant is worth twice what it would be if evaluated as a traditional central station resource. The equivalent levelized value of the PV generation is about 14 to 20 cents/kWh as a distributed resource versus 7 to 10 cents/kWh evaluated as a central station resource.

Economic PV Price

The economic PV system price can be calculated once the value of the plant is established. The economic PV price, often referred to as the "break-even" price, is the PV system price required to just balance the value plus cost of ownership, including cost of capital, O&M, rate of return, depreciation, property tax, and insurance.

Fig. 4 presents economic PV price as a function of plant value for two ownership scenarios: Investor-Owned Utility (IOU), represented by PG&E, and Independent Power Producer (IPP).[2] The economic PV price for the Kerman PV plant ranges between $2,700/kW and $3,800/kW for PG&E ownership, and from $3,400/kW to over $5,000/kW for IPP ownership.

The IPP scenario is considered to be as likely as utility ownership in the near-term since construction and ownership of new generation may no longer be in the

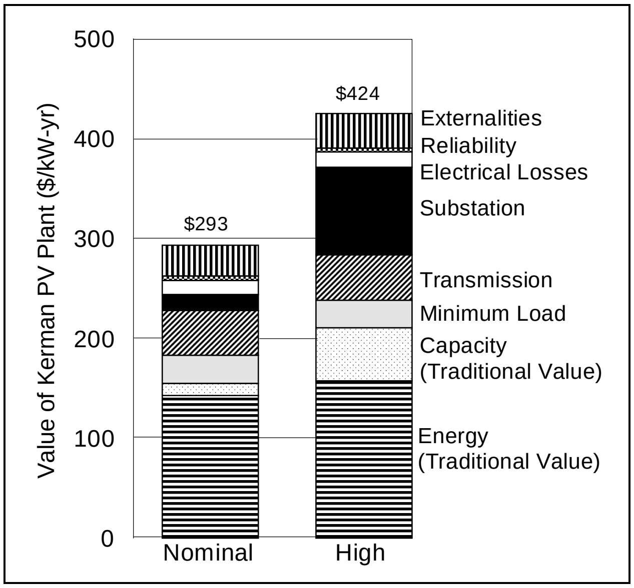

Fig. 3. Value of the Kerman plant to PG&E ($1995).

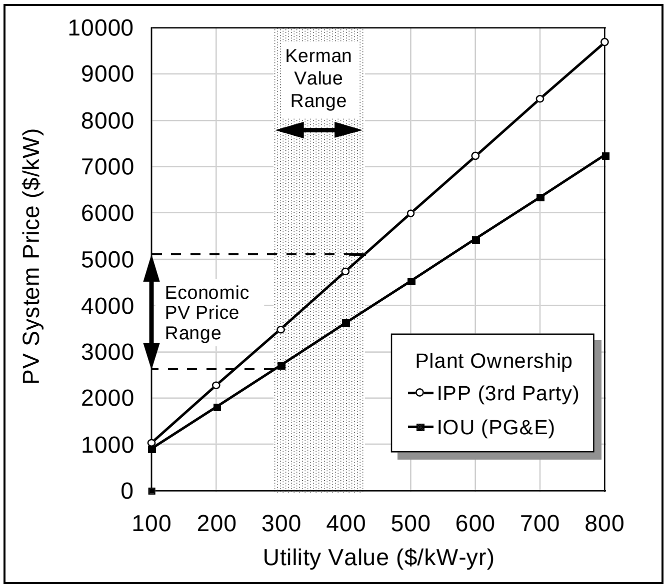

Fig 4. Economic PV price depends on plant ownership.

domain of the IOU as a result of electric utility restructuring. A very plausible scenario is that third party IPPs, perhaps even unregulated subsidiaries of IOUs, will finance and construct distributed generation resources as this market develops.

IPPs presently have several unique advantages over IOUs to finance and build power plants. Advantages include access to tax credits, accelerated depreciation, flexibility with debt to equity ratios and financing, and, in many cases, access to sources of lower cost capital. These advantages enable the IPP to afford up to a 30 percent more expensive plant than an IOU, while maintaining profitability. Electric co-operatives and municipal utilities enjoy similar ownership advantages and would, in general, have an economic PV-cost-line comparable to the IPP line in Fig. 4.

CONCLUSIONS AND LESSONS LEARNED

The following conclusions can be drawn from the construction and operation of the Kerman Plant:

- commercial PV systems can be designed and installed with a plant efficiency of 10 percent (at the 12 kV interface);
- PV systems sited in favorable areas can achieve 25 percent annual capacity factor even with modest downtime; and
- utility-standard SCADA hardware can be effectively employed to monitor and control an unattended PV plant.

Although the market price of grid-support PV systems is presently higher than the economic, or break-even, price of PV at Kerman, the validation process provides concrete evidence that non-traditional utility benefits are measurable and significant.[3] With respect to the value of a strategically sited PV plant,

- data analysis and testing confirm that non-traditional benefits, in addition to traditional benefits, are measurable, predictable, and significant for grid-support PV;
- non-traditional benefits double the overall value of the Kerman plant relative to a traditional central station resource planning perspective; and
- methods to evaluate the Kerman grid-support plant are repeatable and generally applicable to other forms of distributed resources and applications.

The Kerman validation results are promising from a renewable and distributed resource perspective. The research should help non-traditional benefit evaluation gain acceptance by utility and regulatory personnel for resource planning and regulatory oversight.

ACKNOWLEDGMENTS

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[1] PVUSA has assigned a plant rating of 498 kWac at PVUSA Test Conditions (PTC) of 1000 W/m^2 irradiance, 20°C ambient temperature, and 1 m/sec windspeed.

[2] Chart concept: Mike Lotker, formerly of Siemens Solar Industries.

[3] Utility grid-support PV system prices are presently between $6,500-$8,500/kW.