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Evaluating the Value of Distributed Photovoltaic Generations in Radial Distribution Systems

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EVALUATING THE VALUE OF DISTRIBUTED PHOTOVOLTAIC GENERATIONS IN RADIAL DISTRIBUTION SYSTEMS

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ABSTRACT

The impact of photovoltaic (PV) generations, when added to an existing rural utility's distribution system, is studied. The addition of PV is examined in the light of voltage support, loss reduction, and reduction in peak demand. Comparisons are made with the conventional and widely used methods for voltage control and loss minimization, such as the addition of series and shunt capacitors and voltage regulators. The economics of distributed PV systems in the context of conventional grid power purchases are also studied. Results of this study are meant to be used as general guidelines for evaluating the impact of significant PV penetration in any distribution system.

Keywords: Voltage support, Loss reduction, Utility

1. INTRODUCTION

Many electric utility companies across the United States are utilizing non-conventional power generations in a wide variety of projects today. The utility companies look at these resources as a remedy to the growing concern and problems related to environmental issues, increasing consumer demand, fluctuating fossil fuel prices, and other system related potential constraints.

Numerous benefits are expected for both the utility company and the consumer by integration of photovoltaic (PV) energy resource into the utility's conventional resources. This form of energy, beside being renewable, also possesses other advantages, such as its ability to improve service reliability by reducing the number of system outages and by avoiding line extensions to remote areas. Such systems can also relieve thermal overloads in selected utility distribution systems. Other important benefits also exist, such as loss reduction on both distribution and transmission lines and voltage support. There are many such applications that have proven to be cost effective.

Bigger and Kern [1] report the results of a project conducted by the Electric Power Research Institute (EPRI) to assist electric utilities in identifying and evaluating early, cost-effective applications of photovoltaic systems. A specific cost-effective photovoltaic application involves transmission and distribution sectionalizing switches [2]. In this example, PV was a superior choice over extension of lines and installation of step-down transformers.

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Georgia Power Company and Arizona Public Service are among others who have used PV systems for this purpose. Another application identified for PV is powering the telemetry equipment for temperature sensors on transmission lines [1].

PV systems were once believed to be the ideal choice only for remote applications. However, remoteness from the grid is not a requirement for PV use. PV is used reliably even very close to the grid such as powering the substations' alarms and so on. Jennings [3] reports that about 220 PV systems (26 KW) have been installed during 1970-1989 for numerous applications on the PG&E system. These applications include gas flow computers, water level sensors, automated gas meters, gas SCADA RTUs, cloud seeders, gas samplers, meteorological towers,microwave repeaters, warning sirens, aircraft warning beacons, cathodic protection, an automated gate opener, light, a rupture control valve, a back up generator starter, and a water temperature sensor.

Besides the above applications, utilities also benefit from reducing their peak power by the grid connected PV system as well as avoiding expensive line extensions by installing small stand alone PV systems. A recent example is the installation of PV systems by Colorado's K.C.Electric Association on its remote customers' properties [4]. This was a means to improve the service reliability since the rural customers were located in an area where severe weather condition during winter time made it difficult to rely on utility lines.

1.1 Presence of Distributed PV in the Distribution System

Before embarking on an expensive investment such as a large-scale, distributed, residential PV penetration, it is necessary for the utility companies to study the impact on power quality, system losses, voltage regulation, power flow security, and other problems related to these unique power sources.

A number of studies have been carried out on some of these issues [5-10]. A descriptive report on three major residential PV system projects undertaken in the United States in 1985 prepared by EPRI [11], shows optimistic results. These projects were part of the New England Electric Photovoltaic Research and Demonstration Project (Gardner, MA), John F. Long Properties Solar One Project (Phoenix, AZ) and the Laguna Del Mar Townhouse Project (Carlsbad, CA). Generally the results obtained from the studies of these projects can be a very useful guideline to the utility companies opting for integration of PV systems.

In our study, PV generation is chosen to be added to an existing rural utility system. The addition of PV will be examined in the light of voltage support, loss reduction, and reduction in peak demand. Comparisons will be made with the conventional and widely used methods for voltage control and minimization of losses, such as the addition of series and shunt capacitors and voltage regulators. Results of this study can be used as general guidelines for evaluating the impact of significant PV penetration in any distribution system.

2. ROLE OF PV IN THE MODERN DISTRIBUTION SYSTEM

A PV system can be placed at strategic locations of the system depending on the objective of the placement. To reduce losses on the system, it can be placed in a remote section which carries a relatively large load. The power drawn by such a load has to travel a long distance from the substation to the area where the load is located. Naturally, this power causes loss along the feeder. Therefore, if the power is provided locally, the losses which are caused by the transmitted power can be prevented. This type of configuration can also potentially relieve overloadings along the route of the power flowing to the remote load.

Reducing system losses by balancing phases is also a situation where PV can be a viable candidate. To reduce losses, PV can be placed on a section to which a relatively large load is connected, regardless of its location. Larger loads can cause more losses even if they are located close to the source.

PV can also support the voltage profile on the system. The rationale is that, besides generating real power, the PV system will also be required to provide reactive power. Voltage drops on a feeder are more prominent in sections with large demands. PV power generation can be placed on those branches where the voltage falls below the limit so as to improve the voltage profile.

The above scenarios were studied in detail and results are demonstrated in this paper. For voltage correction and loss reduction, comparisons will be shown between the performance of PV systems versus those of the conventional means of capacitors and voltage regulators. Later, we will study the economics of distributed PV systems in the context of conventional grid power purchases.

2.1 Voltage Correction by Conventional Means

To correct any voltage problem by conventional means, shunt capacitors and/or voltage regulators are needed on the system. Since developing a new rigorous methodology for optimal placement of var equipment is not the intent of this study, practical methods suitable for small distribution systems are selected. The process is initiated by performing an unbalanced load flow for each feeder for obtaining a realistic voltage profile. The voltages on each feeder are then reviewed and those sections and branches that have violated the voltage regulation limits are identified. Two important parameters that are required for optimal var planning are the size and the location of the var devices. A convenient way to start is to search from the source (substation) side and identify the first section where the voltage has violated the limit. This would be a logical choice for the location of a capacitor bank. In order to choose the size of the bank, an initial value that works well in most cases, particularly for radial systems, is to install a bank such that the total reactive power flow through the section is provided by the capacitor bank. For example, if the reactive power flow through the A-phase of the first voltage-violated three phase section is 150 KVAr, a capacitor bank would be installed such that it supplies 150 KVAr per phase to the section to maintain the system load balance. The exact number of sections or branches that can get their voltage drop problem solved depends on the behavior of the system, and load distribution, as well as connectivity of branches and sections.

Once a voltage drop on a part of the system has been corrected, the process is repeated so as to attempt to correct the voltages in the rest of the system.

2.2 The System Studied

The system studied is a part of Carbon Power and Light's (CP&L) rural distribution system. CP&L is a rural electric utility located in Saratoga, Carbon County, in the southeastern part of Wyoming. This utility company purchases power from Tri-State Utility Company. Tri-State supplies power to CP&L through three sub-transmission stations: Trowbridge, Oasis and Medicine Bow. Several distribution substations are being fed by each of these sub-transmission stations. Each of the distribution substations, in its turn, serves customers through several feeders in many parts of Wyoming including Saratoga, Encampment and Laramie. Two major substations, "Saratoga", and "Big-Laramie", were chosen for this study. The reason was the availability of much of the data for these substations which helped in establishing the physical and electrical representation of the system. Saratoga substation feeds four feeders and Big-Laramie substation feeds two feeders. The diagrams of two of these feeders are shown in Figs. 1 (a) and 1 (b). Information on the feeders out of these substations are shown in Table 1.

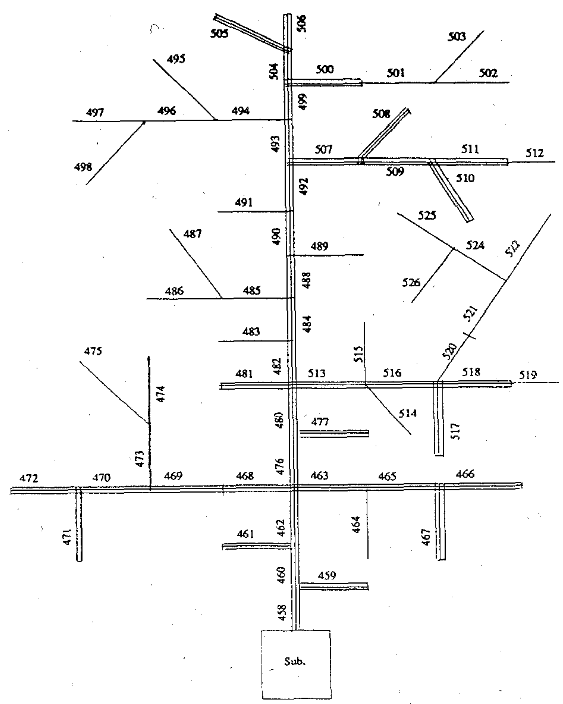

Fig. 1a. Saratoga Substation, Feeder 2.

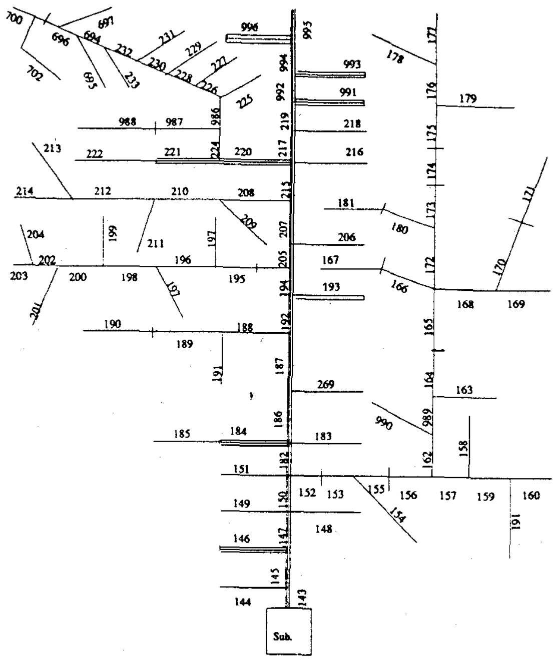

Fig. 1b. Big Laramie Substation, Feeder 3.

Table 1. Feeder information

	SUBSTATIONS					
	Saratoga				Big Laramie	
	TRANSFORMER KVA: 10,000				TRANSF KVA: 3,750	
	Feeder 2	Feeder 3	Feeder 4	Feeder 5	Feeder 2	Feeder 3
Peak KW	936	501	1467	843	276	1635
Type of Load	Res/Agri	Res	Res/Agri/ Ind	Res	Res	Res/Agri/ Ind
Total Length (mi)	57.13	70.253	10.883	37.63	103.33	205.33

In this study, a voltage index is defined for the purpose of observing the effectiveness of the voltage correction in the system. The index is calculated by Eq. 1, shown below.

$$VI = \sum_{i=1}^{N} \left(\frac{V_i - V_s}{\Delta V} \right)^{2n} \tag{1}$$

where

VI is voltage index.

N is number of voltage-violated sections for which VI is calculated.

V_i is the section voltage where voltage is violated.

V_s is substation bus voltage level.

ΔV is the voltage regulation set at $\pm 3\%$ of bus voltage.

n is an index (Equal to 1 or 2).

It is apparent from Eq. 1 that a lower VI implies better voltage profile along the feeder.

2.3 Voltage Correction Results

Most of the feeders that were studied have a series of sections that were seen to have violated their voltage limits prior to the placement of var devices, or photovoltaic systems. For capacitor placement trials, multiple capacitors were most often required to correct all voltage problems along the feeder. In at least one case, a voltage regulator was required for correcting some severe voltage drops. This was the optimal choice in view of the fact that other options either required a large number of capacitor placements or were causing larger line losses.

A summary of voltage correction study using capacitors and voltage regulators is shown in Table 2. As seen from the table, voltages have been corrected for all feeders and loss savings are also achieved in most cases.

Table 2. Summary of Voltage Correction by Capacitors and Regulators.

FEEDER	CAPACITOR PLACEMENT			VOLTAGE PERFORMANCE INDEX (VI)					
				BASE-CASE			AFTER CAPS. PLACED		
	SIZE (KVAr)	SECTION PLACED (PHASE)	TOTAL %LOSS REDUCTION	PHASE A	PHASE B	PHASE C	PHASE A	PHASE B	PHASE C
Saratoga Sub. Feeder 2	25	520(C)	3.22	0	0	2.30204	0	0	0
Saratoga Sub. Feeder 3	25 25 25 25	443(C) 444(C) 438(C) 456(A)	20.37	0	0	9.89543	0	0	0
Saratoga Sub. Feeder 4	250 250 250 50 50	331(A) 331(B) 331(C) 350(C) 396(C)	15.35	0	0	26.3905	0	0	0
Saratoga Sub. Feeder 5	not placed		0	0	0	0	0	0	0
Big-Laramie Sub. Feeder 2	not placed		0	0	0	0	0	0	0
Big-Laramie Sub. Feeder 3	Three phase regulator placed on section 187 and regulator settings changed on 224(A,B)		0.11	72.547	327.89	0	AFTER REGULATORS PLACED		
							0	0	0

2.4 PV for Voltage Support and Loss Reduction

Examples of PV placement on certain feeders and their impact are now demonstrated in the following sections.

Saratoga Substation, Feeder 2

The largest load in this feeder is connected in section 467 which is located close to the substation. Phase A of this section carries 173 KW, Phase B carries 163 KW and phase C carries 163 KW. A 450 KW PV system was considered for installation so as to provide 150 KW/phase power locally in section 467. Resulting simulations showed that the voltages improved on all three phases and were fully corrected in at least one section of the voltage-violated branch. In addition, the real power losses could also be reduced by nearly 39%.

Saratoga Substation, Feeder 4

Voltages had been violated on the entire phase C of the feeder as seen from a base case run. In order to correct the voltage problem and reduce losses, the loads were balanced on all phases by placing PV systems. The loads through the first section of the feeder are 483 KW on phase A, 463 KW on phase B and 551 KW on phase C. To balance loads, 85 KW PV generation was needed on phase C and 20 KW was needed to be installed on phase A, so that finally, the loads on all phases were equal and balanced. The location of the generators were selected such that they provided power locally first, for the largest load carrying section of the voltage-violated single phase branch, and then for the largest load carrying section of the phases.

For 85 KW installation on phase C, a 50 KW PV generator was placed on section 397(phase C) to provide the power needed on that section locally. The remaining 35 KW was placed on section 350(phase C) which carries the largest load. For 20 KW installation on phase A, a 20 KW PV generator was placed on section 372 (phase A). This section carries the largest load on phase A of the branch.

The voltage problem was corrected on phase C, and at the same time, voltages were improved on the other phases. The real power losses were also reduced by nearly 16.82%.

Big-Laramie Substation, Feeder 3

From a base run, it was observed that the voltages had been violated mostly in phases A and B. The voltages were rather low. The losses on the system were also high. This was assumed to be due to the unbalanced loading on the phases. The loads are 487 KW on phase A, 790 KW on phase B and 482 KW on phase C. Balancing of loads was considered on this feeder to improve voltages and losses. A 305 KW PV system was placed on the five heavily loaded sections of phase B in such a way as to possibly balance the loads on the sections. As a result, the voltage problem was corrected on phase B. The voltages went down somewhat on phase C but remained within the limits except for section 155. The real power losses were reduced by 48%.

A summary of the PV placement study is given in Table 3. The table shows that much better loss savings can be achieved by PV placement than by capacitor and voltage regulator placement. The actual base case kW losses and the kW losses after the PV system is added are shown in Table 4.

Table 3. Summary of PV Placement for Loss Saving and Voltage Improvement.

FEEDER	PV PLACEMENT			VOLTAGE PERFORMANCE INDEX (VI)					
				BASE-CASE			AFTER PV PLACED		
	SIZE (KW)	SECTION PLACED (PHASE)	TOTAL %LOSS REDUCTION	PHASE A	PHASE B	PHASE C	PHASE A	PHASE B	PHASE C
Saratoga Sub. Feedr 2	150 150 150	467(A) 467(B) 467(C)	39	0	0	2.30204	0	0	1.405854
Saratoga Sub. Feedr 3	25	444(C)	24	0	0	9.89543	0	0	0
Saratoga Sub. Feedr 4	50 35 20	397(C) 350(C) 372(A)	16.82	0	0	26.3905	0	0	0
Saratoga Sub. Feedr 5	90	293(C)	26.14	0	0	0	0	0	0
Big-Laramie Sub. Feedr 2	6	253(C)	4	0	0	0	0	0	0
Big-Laramie Sub. Feedr 3	30 60 60 130 25	145(B) 183(B) 696(B) 700(B) 205(B)	48	72.5471	327.892	0	73.52312	0	0.45897

Table 4. Comparison of kW Losses in the feeders

Saratoga Substation							
Feeder 2		Feeder 3		Feeder 4		Feeder 5	
Base	With PV	Base	With PV	Base	With PV	Base	With PV
71.1	43.3	39.1	29.74	105.6	87.9	66.6	49.2

Big Laramie Substation			
Feeder 2		Feeder 3	
Base	With PV	Base	With PV
17.9	16	100.8	52.3

3. THE PV SYSTEM POWER FACTOR

The operating power factors for PV systems can become an important issue if these systems are to be seen as a means of voltage support. A number of different power factors ranging between 60% and 90% were tried at 5% increments for the PV systems already placed on three feeders. The voltage performance index(VI) for the three feeders and the total losses on the feeders have been calculated for each power factor trial. The power factor profile versus VI and total loss profiles are plotted in Figs. 2 thru 4. The losses have been normalized.

It can be seen from the figures that different feeders behave differently. For instance, Fig. 2 shows that the higher the power factor, the better the voltages. The VI approaches zero at 85% power factor for all three phases of Saratoga Substation, Feeder 4; however, the VI for phase A increases slightly at high power factors. The total loss is higher for higher power factors for this particular feeder.

In Fig. 3, the VI for two phases of Saratoga Substation, Feeder 2 is zero for all power factors. The VI for phase C of the feeder increases with higher power factors. The losses, however, decrease till the power factor increases to 80% and then begins to increase with higher power factors. Fig. 4 shows that the VI and total losses for Big-Laramie Substation, Feeder 3, generally decrease with increased power factors.

In general, for at least two out of the three feeders studied for power factor impact, a power factor of 85% would be favorable.

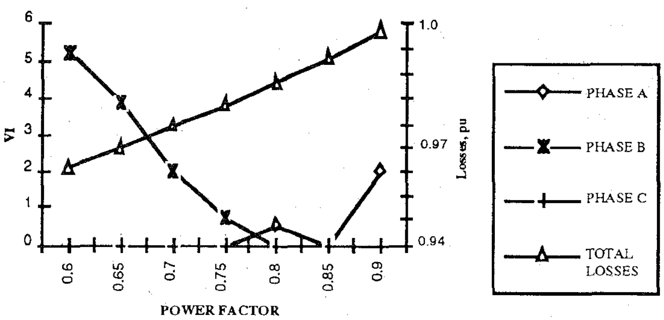

Fig. 2. Power factor profile versus VI and total losses for Saratoga Substation, Feeder 4.

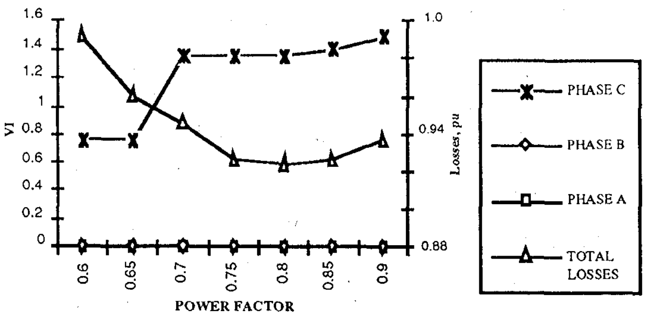

Fig. 3. Power factor profile versus VI and total losses for Saratoga Substation, Feeder 2.

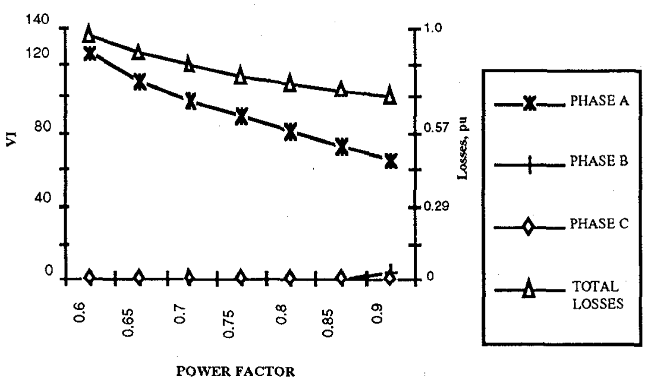

Fig. 4. Power factor profile versus VI and total losses for Big-Laramie Substation, Feeder 3.

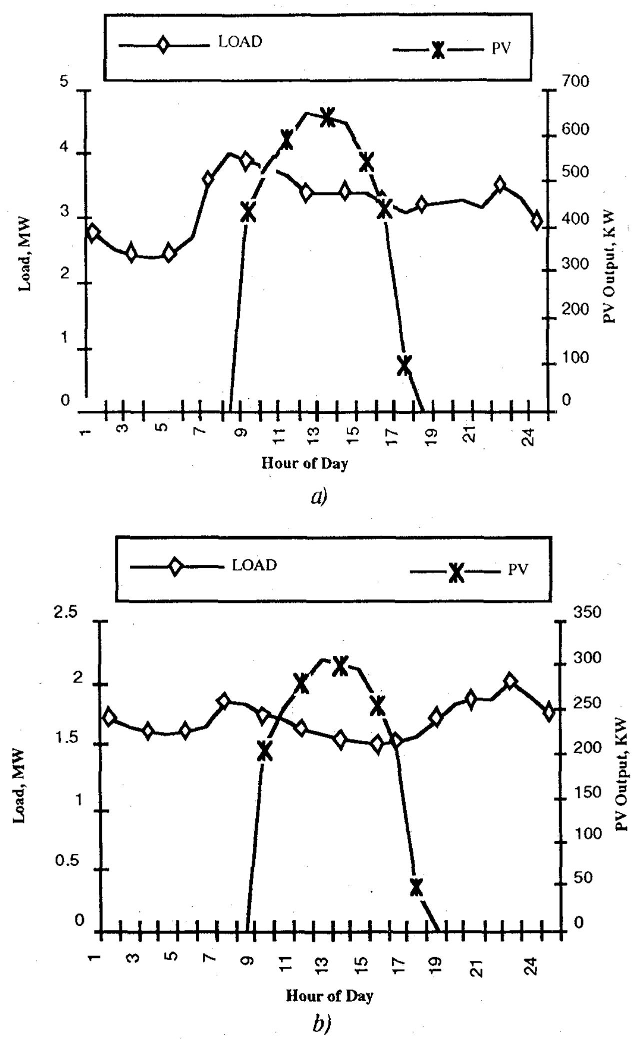

Fig. 5. Demand Profile versus PV Generation Pofile: a) Saratoga Sub. b) Big-Laramie Sub.

4. ECONOMIC CONSIDERATIONS FOR PV

An economic analysis has been considered for the presence of PV generations in the distribution system. To be able to do an economic study, the demand profiles had to be known for both the distribution system and the PV generation. The demand profiles of a typical day for two sub-transmission stations were obtained from CP&L. Since CP&L's customers are mostly residential, it has been assumed that each substation has a demand profile similar to its sub-transmission stations. Therefore, the sub-transmission station demand profiles were scaled down by a pre-determined factor to determine the profiles for both Saratoga substation and Big-Laramie substation under study. (See Figure 5). Similarly, the power generation profile for the PV systems representing a typical day in each month at Cheyenne, Wyoming (approximately 120 miles east of Saratoga, Wyoming) was known from SOLMET data [12]. It will be assumed that these profiles represent average days of the month for Saratoga and Laramie areas where the two substations are located. The profile was scaled up in order to obtain power generation profiles for the PV systems installed on the two substations. The daily profiles for the month of July are shown in Figs. 5a and 5b. Similar profiles were generated for each month of the year.

The cost of demand (KW) and energy (KWHr) for conventional generation was obtained from CP&L to be $11.82/KW and $0.01738/KWHr respectively. In order to find the amount of energy contributed by PV, it is assumed that the PV power generation is constant for each one hourly interval. This approximation is justifiable because it is used only in the context of planning. Under the assumtion that PV energy will be available 365 days per year, the energy produced and contributed by a 670-KW PV system on Saratoga substation amounts to approximately 1.21 GWHr per year, and the energy contributed by a 311-KW PV system on Big-Laramie substation amounts to approximately 0.71 GWHr per year. These figures are considered as 100% energy yield in the subsequent simulations. A sample savings analysis for the test system follows.

Saving in energy cost/yr:

Saratoga substation: (@17.4 mils/kWHr)	$21,030
Big Lar. substation: (@17.4 mils/kWHr)	$12,340

Loss reduction revenue/yr:

Saratoga: (4 feeders: 72.26 kW @$11.82/kW/mo)	$10,250
Big Lar.: (2 feeders: 50.4 kW @$11.82/kW/mo)	$ 7,150

- *Total saving on energy and demand cost per year.* $ 50,770

Savings from avoided var device placement:
975 kVar cap. on 3 feeders at Saratoga (@$15/ kVar) $14,600
300 kVar voltage reg. on 1 feeder at Big Lar. (@ $30/kVar) $ 9,000
- *Total saving on var devices.* $23,600

4.1 Cost Benefit Analysis

To find the cost of PV energy produced by PV, a life cycle analysis is run. Since the amount of energy produced by a PV system is dependent on the average insolation levels at a site, the PV energy availability and the installed cost are both varied in order to calculate the cost of energy produced by PV. The results are shown in Table 5. Taking pertinent economic considerations into account, the annualized cost of the grid energy for CP&L (over a 20 year period) is calculated to be $0.115/KWHr. From the table, one can easily determine the conditions when PV energy can become a cost-effective option.

Table 5. Cost of PV Energy ($/KWHr) versus the Energy Yield and the Installed Cost.

Installed PV Cost ($/W$_p$) \ Annual Energy Available (%year)	100%	90%	80%	70%	60%
9	0.281	0.318	0.364	0.423	0.502
8.5	0.263	0.298	0.341	0.397	0.472
8	0.245	0.277	0.318	0.371	0.441
7.5	0.226	0.257	0.295	0.345	0.411
7	0.208	0.237	0.272	0.319	0.38
6.5	0.19	0.216	0.25	0.292	0.349
6	0.171	0.196	0.227	0.266	0.319
5.5	0.153	0.176	0.204	0.24	0.288
5	0.135	0.155	0.181	0.214	0.258
4.5	0.116	0.135	0.158	0.188	0.227
4	0.098	0.114	0.135	0.161	0.197
3.5	0.08	0.094	0.112	0.135	0.166
3	0.061	0.074	0.089	0.109	0.135
2.5	0.043	0.053	0.066	0.083	0.105
2	0.025	0.033	0.043	0.057	0.074
1.5	0.006	0.013	0.02	0.03	0.044

5. CONCLUSIONS

This work, by means of a case study, emphasizes on certain primary factors which should be considered during the planning stages of introducing significant photovoltaic generations into an existing distribution system. Investment in PV is undoubtedly an expensive proposition. Yet, if carefully planned, it can provide valuable service to the utility. Besides simply producing power for supplying customer demands, PV systems have the potential for system loss reduction and voltage support. Of course, two critical factors that need to be determined, by extensive off-line studies, are the size and location of these distributed PV systems. Improper PV sizing and placement can potentially cause adverse effects on the system, thereby reducing, or even negating the benefits of this important renewable resource.

Utility-integrated PV can be most cost-effective if its power production occurs during the utility's peak demand periods. PV can not only save money from peak shaving, it also saves from system loss reduction. This can translate into significant revenues, at the high peak demand rate, attributable to the PV system during its life time. It is also obvious from the paper that PV can also save from improving the voltages thus reducing the installation of capacitor banks and voltage regulators.

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