STATISTICAL RELATIONSHIP BETWEEN PHOTOVOLTAIC GENERATION AND ELECTRIC UTILITY DEMAND IN MINNESOTA (1996-2002)

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ABSTRACT

Photovoltaics have an intuitively positive relationship with summer peak electricity demand periods. This study compared photovoltaic output with electric utility demand under various scenarios to determine photovoltaic capacity performance during periods of high electricity demand and certain months and times of day.

Three fixed-tilt and fixed-azimuth photovoltaic installations in the Minneapolis-St. Paul metropolitan area (Minnesota) were analyzed, comparing their electricity output's relationship to Xcel Energy's electrical demand from 1996 to 2002 using hourly output and coincident utility load data.

Using electric utility accreditation standards, two of the sites had capacity values ranging from 24% to 44% from June to September in the late afternoon, while the third site was lower due to shading of the panels. When the data were filtered for electrical demand exceeding 99% of annual peak, one of the sites produced at 62% of capacity, while the other two were less, again, likely due to shading.

1. PHOTOVOLTAIC INSTALLATIONS

1.1 Site Descriptions

Seventeen two to three kilowatt (kW) photovoltaic (PV) systems were installed in 1996 under Xcel Energy's (then Northern States Power) Solar Advantage Program in conjunction with the Solar Electric Power Association (SEPA). Three of the systems, located in Minnetonka (MTK), Rosemount (RMT), and White Bear Lake (WBL), were outfitted with data logging equipment (Figures 1, 2, and 3).

Fig. 1: Minnetonka (MTK) site picture (photo: SEPA).

Fig. 2: Rosemount (RMT) site picture (photo: SEPA).

Fig. 3: White Bear Lake (WBL) site picture (photo: SEPA).

All three sites used ASE 50-volt, 285 watt panels and had fixed-tilt angles flush with the roof (Table 1). A solar pathfinder diagram was not available for the sites to determine the exact amount of shading. Elevation from ground level was not calculated but a comparative ranking would place them in order of lowest to highest as WBL, MTK, and RMT. Subjectively, the amount of shading from lowest to highest was RMT, WBL, and MTK.

TABLE 1: INSTALLATION SPECIFICATIONS

Site	Azimuth	Tilt	Inverter (kW)
MTK	179°	39.8°	Trace 4.0
RMT	180°	33.7°	Omnion 2.5
WBL	180°	22.6°	Trace 4.0

Source: Solar Electric Power Association, 2003 (1) (2).

1.2 Data Description

Averaged hourly Xcel Energy system electric load data for Minnesota was obtained from the Mid-Continent Area Power Pool (MAPP) and converted to a percentage of peak for each year (demand data for each year divided by peak demand number for that particular year) (3).

Fifteen minute photovoltaic site information was obtained from the SEPA website and data were filtered for hours corresponding to the Xcel Energy demand data by hour to provide a "snapshot" of photovoltaic performance from August 1996 to October 2002, sans September 2002, for which data was unavailable (1). Data was only available for the RMT site from August 1996 to December 2000 (2).

1.3 Calculating Total System Ratings

The direct current (DC) panel rating using standard test conditions (STC) was 2.85 kW for MTK and WBL and 2.28 kW for RMT. The peak DC output seen over the six year period for MTK was 2.68 kW and for WBL was 2.56 kW (RMT unavailable) or 6% and 10% less than STC rating respectively. Irradiance did exceed STC of 1000 watts/m^2 during the studied time period.

While photovoltaic panels themselves have a DC rating based on an industry accepted standard, photovoltaic systems do not have one for alternating-current (AC) rating. There are various methods for calculating an AC system rating, including the PVUSA Test Condition (PTC) and the Solar Electric Power Association (SEPA) derating methods (4) (5).

Under the PTC method, the combined DC rating of the solar panels in an array is derated for the normal operating conditions, as well as efficiency losses in the wiring and the inverter. Under the SEPA method, an AC rating is calculated using a regression analysis at modified PTC conditions. The PTC and SEPA methods were low in five of six cases when actual peak AC data was examined (Table 2). The PTC calculation was the closest to the actual peak AC values recorded. However, only roughly 1% of the data exceeded the SEPA rating.

TABLE 2: SYSTEM AC RATINGS (kW)

Site	DC Rating	Peak AC	PTC Rating	SEPA Rating
MTK	2.85	2.49	2.40	2.10
RMT	2.28	2.08	1.90	1.80
WBL	2.85	2.36	2.40	2.10

Determining the appropriate AC capacity is important in calculating the percentage of peak capacity. Dividing a 1.5 kW output during a peak demand period by 2.49 kW results in 60% of peak rating. Dividing it by 2.10 kW results in 71% of peak rating. The percentages, although in-exact, provide an easy to read format.

Unless noted, in the interest of a conservative analysis, the actual peak exhibited was used to determine the percentage of peak. For reference, the use of the PTC or SEPA ratings would increase the percentages roughly 3% to 10%.

2. PHOTOVOLTAIC PERFORMANCE

2.1 Average Annual Electricity Generation

The sites generated varying amounts of electricity in total over the study period and on an annual basis, but RMT was 0.57 kW (DC rating) smaller than MTK and WBL and had two less years of data. When the electricity generation is standardized on the DC system rating, RMT generated 1,042 kWh per DC kW, with MTK and WBL generating 3% and 16% less respectively (Table 3). When standardized, based on the peak AC current measured during the study period, WBL was again lower than MTK and RMT.

TABLE 3: ANNUAL ELECTRICITY GENERATION

Site	Total (kWh)	Annual (kWh/yr)	DC Annual (kWh/kW/yr)	AC Annual (kWh/kW/yr)
MTK	17,800	2,892	1,015	1,161
RMT	10,501	2,376	1,042	1,142
WBL	15,468	2,508	880	1,062

A previous study by the author calculated that 3% of electricity generation was compromised by snow loading on the WBL site, which has the lowest tilt angle of the three sites, and did not as readily shed snow (6). Site visits on March 8, 2001 showed the WBL site with snow on much of the roof and panels and the MTK site completely free of snow (Figures 4 and 5).

Fig. 4: White Bear Lake (WBL) site on March 8, 2001.

Fig. 5: Minnetonka (MTK) site on March 8, 2001.

2.2 Visual Relationship to Electricity Demand

The data can be looked at visually to provide a picture of the photovoltaic and electric demand relationship. The two peak demand days for 1999 and 2000 were selected to illustrate a sunny and a cloudy day.

The peak demand day for 1999 occurred on July 29 and the photovoltaic production was continuous and uninterrupted (Figure 6). MTK, RMT, and WBL peaked around noon, while the peak demand for the year occurred around 4 pm. Demand exceeded 95% of that year's peak from 10 am to 7 pm, so the sites' electricity production was valuable the majority of the day.

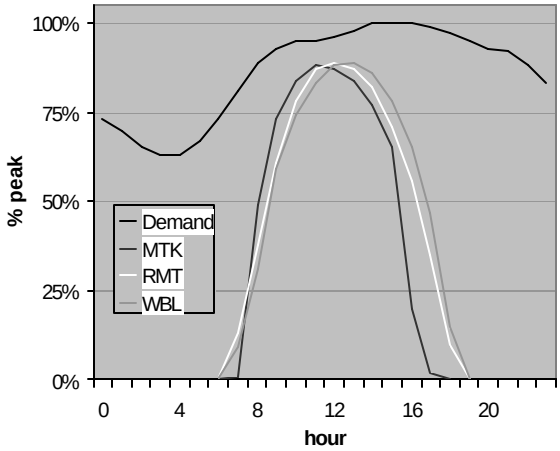

Fig. 6: Photovoltaic production and Xcel Energy electric demand on July 29, 1999.

The peak demand day for 2000 occurred on August 15 around 5 pm (Figure 7). Demand exceeded 95% of peak from 12 pm to 9 pm, a shift toward the evening that would tend to decrease the relationship between photovoltaic generation and demand. However, the photovoltaic sites did not exhibit a bell curve, as clouds affected MTK and RMT production during the noon hour. No AC electricity output was recorded for the WBL site, which was either not generating, the data logging equipment was malfunctioning, or both. The WBL site was recording erratic solar irradiance, indicating a data collection problem.

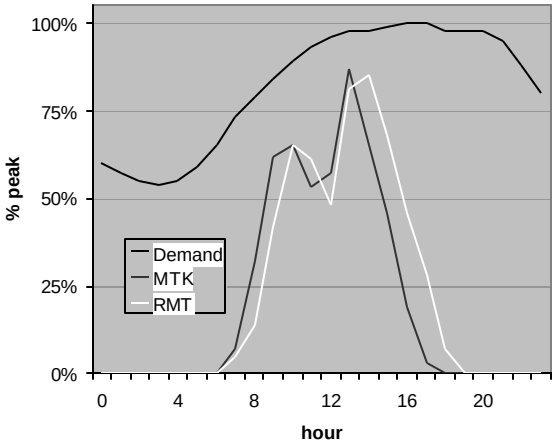

Fig. 7: Photovoltaic production and Xcel Energy electric demand on August 15, 2000.

These two scenarios are diametric snapshots of how photovoltaic production and electric demand interact. The next section calculates the statistical relationship over longer time periods.

2.3 Statistical Relationship to Electricity Demand

The statistical relationship between photovoltaic generation and electric demand can be studied under various scenarios to determine photovoltaic capacity performance during periods of high electricity demand and certain months and times of day.

The photovoltaic systems have azimuths facing due south, which optimizes annual electricity production. The WBL site has the lowest tilt angle of the three sites, in theory, optimizing it for summer electricity production, when the sun is higher in the sky. Xcel Energy's annual peak demand hour typically occurs in July around 4 pm so it is not expected that these sites are sited for optimal performance in relationship to electric demand. The systems' peak capacity performance during high demand periods could be increased if they were on active tracking mechanisms or if the system azimuths were directed more westerly. The latter case would decrease overall annual electricity production however.

2.3.1 General Capacity Performance

During daylight hours the systems' performance was 7% to 12% of peak capacity, which increased during Xcel Energy's general summer peak demand of June to September from 9 am to 9 pm, to 19% to 32% of peak (Table 5) (7). As would be expected, the noon hour window of 11 am to 1 pm from June to August exhibited very high peak percentages of 65% to 69%. All three sites performed very similarly during the noon hour summer analysis, indicating a robust data set across the three sites. When the data were filtered for a typical afternoon electric utility demand peak of June to August at 4 pm, the percent of peak ranged from 18% to 44%.

TABLE 4: PHOTOVOLTAIC PERFORMANCE DURING VARIOUS PHYSICAL AND TIME SCENARIOS (KW)

Site	Daylight hours	Jun-Sep, 9am-9pm	Jun-Aug, 11am-1pm	Jun-Aug, 4 pm
MTK	0.22 kW	0.48 kW	1.65 kW	0.44 kW
RMT	0.25 kW	0.66 kW	1.43 kW	0.88 kW
WBL	0.17 kW	0.69 kW	1.52 kW	1.05 kW

TABLE 5: PHOTOVOLTAIC PERFORMANCE DURING VARIOUS PHYSICAL AND TIME SCENARIOS (%)

Site	Daylight hours	Jun-Sep, 9am-9pm	Jun-Aug, 11am-1pm	Jun-Aug, 4pm
MTK	9%	19%	66%	18%
RMT	12%	32%	69%	42%
WBL	7%	29%	65%	44%

The MTK site dropped off appreciably during the June to August at 4 pm analysis, which may be indicative of late afternoon shading of the panels.

2.3.2 MAPP Capacity Performance

The MAPP organization accredits the rated capacity of various electricity generating technologies, including renewable technologies (8). Electric utilities need to have enough generating capacity to meet their anticipated demand each year and the sum of all of their purchased and owned capacity is counted toward this requirement.

Firm capacity generators, such as a natural gas power plant, have accredited capacities near their nameplate capacity. Renewable energy technologies, being variable in their output, have a specific MAPP protocol that involves calculating the median value of the generating technology's performance over a historical 4-hour peak electrical demand "window" by month for a particular electric utility over a ten year period. For example, Xcel Energy's historical peak demand window in August is from 3 pm to 6 pm.

During the MAPP accredited 4-hour window from June to September, the three sites studied ranged from a low of 8% for MTK during August to a high of 44% for RMT during July (Table 7). The four-hour window moves an additional hour into the evening in August, decreasing the capacity value for the photovoltaic systems, which are optimized around solar noon. For reference, the current MAPP accredited capacity value for wind turbines in Minnesota is roughly 10% to 15%.

TABLE 6: PHOTOVOLTAIC PERFORMANCE UNDER MAPP ACCREDITATION METHOD (KW)

Site	June 2-5 pm	July 2-5 pm	August 3-6 pm	September 2-5 pm
MTK	0.44 kW	0.50 kW	0.19 kW	0.30 kW
RMT	0.75 kW	0.92 kW	0.51 kW	0.78 kW
WBL	0.97 kW	0.95 kW	0.57 kW	0.73 kW

TABLE 7: PHOTOVOLTAIC PERFORMANCE UNDER MAPP ACCREDITATION METHOD (%)

Site	June 2-5 pm	July 2-5 pm	August 3-6 pm	September 2-5 pm
MTK	18%	20%	8%	12%
RMT	36%	44%	24%	38%
WBL	41%	40%	24%	31%

2.3.3 High Electric Demand Capacity Performance

A previous study determined that the actual peak demand for a day may or may not fall within the 4-hour accreditation window (6). An alternative measure of the relationship is to filter the data for demand thresholds that exceed 90%, 95%, and 99% of peak for each year. This pairs up photovoltaic generation with specific time periods of high demand.

The percent of peak ranged from 20% to 51% at 90% of demand and 21% to 54% and 19% to 62% at 95% and 99% of demand respectively. The RMT site consistently increased its percentage across the increasing demand thresholds, while the WBL site decreased performance with each threshold. The WBL site had the lowest elevation from ground-level and the lowest tilt angle, which may be indicative of shading during evening hours but not to the extent of the MTK site, which performed poorly relative to the other two sites.

TABLE 8: PHOTOVOLTAIC PERFORMANCE DURING PERIODS OF HIGH ELECTRIC UTILITY DEMAND (KW)

Site	Demand > 90%	Demand > 95%	Demand > 99%
MTK	0.44 kW	0.49 kW	0.44 kW
RMT	1.03 kW	1.06 kW	1.28 kW
WBL	0.90 kW	0.81 kW	0.55 kW

TABLE 9: PHOTOVOLTAIC PERFORMANCE DURING PERIODS OF HIGH ELECTRIC UTILITY DEMAND (%)

Location	Demand > 90%	Demand > 95%	Demand > 99%
MTK	18%	20%	18%
RMT	50%	51%	62%
WBL	38%	34%	23%

Electric utility demand exceeded 90% of annual peak when no measurable irradiance was occurring about 7% of the time, i.e. at night. Filtering the data for high demand periods during daylight hours only adds roughly 1% to 6% to the peak capacity values listed in Tables 7 and 9.

The RMT site is clearly the highest performer under all measurements of annual electricity generation and its electricity output's relationship to electric utility demand. Depending on the method of filtering, RMT produced a low of 24% capacity during August from 3 pm to 6 pm and a high of 62% when filtered for periods when electric demand exceeded 99% of annual peak.

MTK, while producing an equivalent amount of electricity to RMT on an annual basis, has lower peak capacity values than either RMT or WBL. This is likely due to shading during evening hours.

WBL, while producing less electricity than MTK and RMT on an annual basis, doesn't appear to be as affected by late afternoon shading in terms of peak capacity values. However, when the data is filtered for periods of demand greater than 90%, WBL actually decreases, but it is unclear why since all other data analysis produced similar results to RMT.

3. CONCLUSION

These photovoltaic sites were located in a metropolitan area with some degree of shading and technical difficulties that affected the annual electricity generation performance and the relationship with electric demand to some degree. They do represent real-world operational data however and in this conservative analysis one of the sites showed strong results across all measures of performance.

The RMT site had the least degree of shading and the fewest operational issues, producing the most annual electricity on a standardized basis (1042 kWh/kW/yr), the highest peak capacity using the MAPP accreditation method (24% to 44% from June to September), and the highest peak capacity at 90%, 95%, and 99% of annual peak demand (50%, 51%, and 62% respectively). The RMT site's performance under the alternative demand analysis to the MAPP accreditation method was significantly higher and may be a better method for calculating photovoltaic generating capacity during periods of high electrical demand.

Further investigation is needed to determine the economic benefits of a traditional net metering arrangement versus a time-of-day payment option that would increase the value of electricity generation during periods of peak demand.

4. ACKNOWLEDGEMENTS

The author wishes to thank the Minnesota Department of Commerce State Energy Office.

5. REFERENCES

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