PERFORMANCE MONITORING OF THE NUNAVUT ARCTIC COLLEGE PV SYSTEM: NINE YEARS OF RELIABLE ELECTRICITY GENERATION*

Y. Poissant[1], D. Thevenard[2] and D. Turcotte[1]

[1]CANMET Energy Technology Centre, Natural Resources Canada, Varennes (Que), Canada
[2]Numerical Logics Inc., Vancouver (BC), Canada

ABSTRACT

A 3.2 kWp grid-connected photovoltaic (PV) system was installed on the façade of the Nunavut Arctic College, Nunatta Campus in Iqaluit, Nunavut (63.4 °N) in 1995. The project has two main objectives: to gain experience in the construction, monitoring and maintenance of a northern grid-connected PV system, and to serve as a demonstrator of the use of PV in the far North. This paper summarizes nine years of monitoring results. The monitored data includes current from the PV array, array voltage, AC power delivered, horizontal and vertical irradiances (both measured with LiCor and Eppley pyranometers), ambient temperature, and array temperature. Climatic and solar radiation conditions at the site are reviewed, and the performance of the system is assessed from a component perspective (PV array, power conditioning unit) and from a global perspective (system efficiency, reliability, annual yield and performance ratio). The system has delivered on average 2,016 ± 200 kWh of electricity on an annual basis with no interruption of delivery. Thus, the system has demonstrated with success the reliability of grid-connected photovoltaics for the far North.

INTRODUCTION

The costs of PV systems have decreased dramatically in the last 20 years, primarily due to larger production volumes and technological advances. A recent world PV power market update reported that PV module factory prices continue to decline annually as the volume of sales worldwide grows at 30-40% per year [1]. In Canada, there has been a significant price decrease as well: from 11.09 CAD$/Watt in 1999, the average PV module price was 6.18 CAD$/Watt in 2003 [2].

The potential market for PV in the North is significant for Canada as none of the communities are currently tied to the North-American electrical grid. Instead, each community has its own local grid, usually relying on genset generators. Because of the remoteness of the sites and the high costs associated with transportation, diesel fuel can be extremely expensive. Thus, many of these applications could benefit from PV if it was proven to be a reliable and well performing technology under arctic conditions.

In order to increase the visibility and study the performance of PV systems at high latitudes, Natural Resources Canada, in collaboration with local partners, supported the installation of a grid-connected PV system in Iqaluit, Nunavut [3]. The system has been running since summer 1995 and its performance monitored ever since. This paper provides a comprehensive analysis of the local climatic conditions and the PV system's performance.

* Paper based on the article "Performance Monitoring of the Nunavut Artic College 3.2 kWp Grid-Connected Photovoltaic System" presented at the SESCI 2004 conference.

SYSTEM DESCRIPTION

The 3.2 kWp grid-connected photovoltaic (PV) system is installed on the façade of the Nunavut Arctic College, Nunatta Campus in Iqaluit, Nunavut (63.4 °N). A picture and a diagram of the system are shown on Figure 1 and 2 respectively. There are 60 PV modules arranged in 5 parallel groups of 12 modules in series.

Figure 1: Nunavut Arctic College 3.2 kW PV system diagram.

Three of the groups are composed of 36 single crystalline silicon Siemens M55 modules and the remaining two groups are composed of 24 single crystalline Solec S-53 modules. Total module area is 25.62 m^2. The modules are placed vertically on the front façade of the college, which faces 30 ° West of South. The PV array is connected to a Prosine 5000 GT 3-kW inverter, which feeds the building with AC electricity thereby displacing diesel power generation whenever the sun shines.

Both climatic data and PV system performance are monitored. The horizontal and vertical irradiances are measured with LiCor and Eppley pyranometers, other monitored data include date, time, ambient and PV array temperature, DC array voltage, current from each sub-array, and AC power delivered. The data is recorded every 90 seconds, averaged hourly and transferred to a computer in blank-delimited ASCII format. Data is downloaded and analysed on a monthly basis by accessing the computer remotely by modem. Solar radiation has been monitored since July 1995, AC Power since mid-August 1995; the rest of the parameters have been properly monitored only since April 1996. The monitoring setup has not been as reliable as the system itself; it actually failed on several occasions and some data have been lost as a result. A new, upgraded monitoring system was installed in 1999 and has performed better since then (note that for analysis purposes, the missing data have been replaced with an average of values from other years).

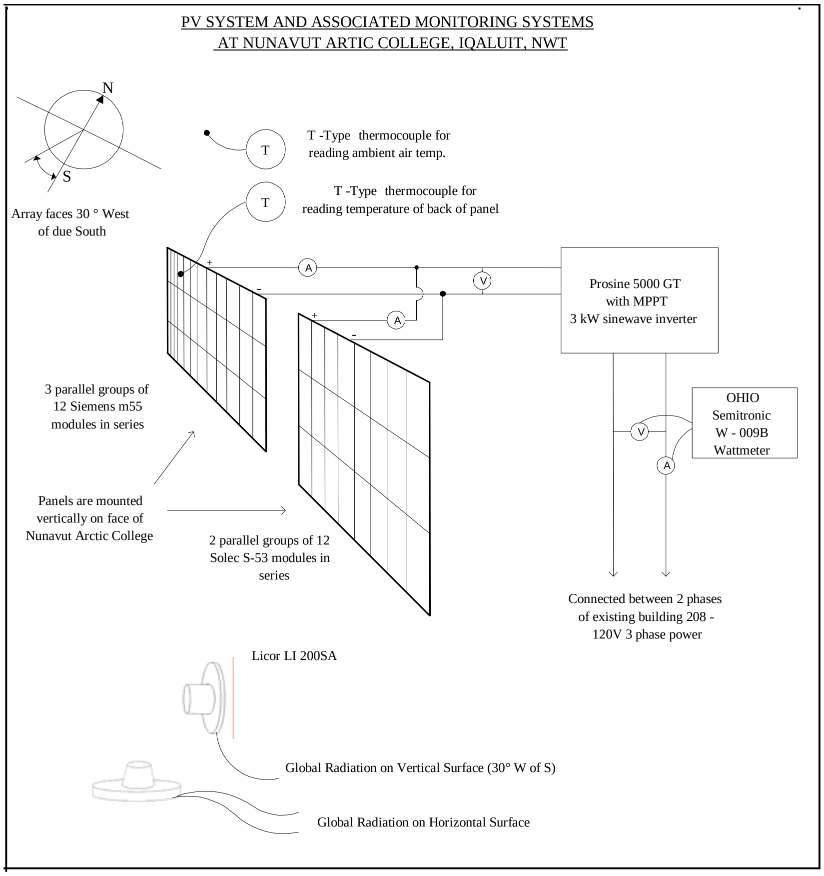

Figure 2: Nunavut Arctic College 3.2 kW PV system diagram.

CLIMATIC DATA ANALYSIS

Because of the location of the system close to the Arctic circle, the PV system is subject to harsh climatic conditions with extreme temperatures ranging from -40°C in the winter up to +30°C in the summer. The mean daily global radiation also exhibits strong seasonal patterns with almost no sunlight in the winter and long daylight hours in the summer. Figure 3 shows the monthly vertical irradiance (as measured by the Eppley pyranometer on the plane of the array) and the mean daily temperatures. As for global horizontal irradiance, aside from 2002 and 2001, all yearly mean global radiation values fall between 9.30 to 9.37 MJ/m^2/day and compare well with the 9.47 MJ/m^2/day Normal reported by Environment Canada for the 1951-1980 period [4].

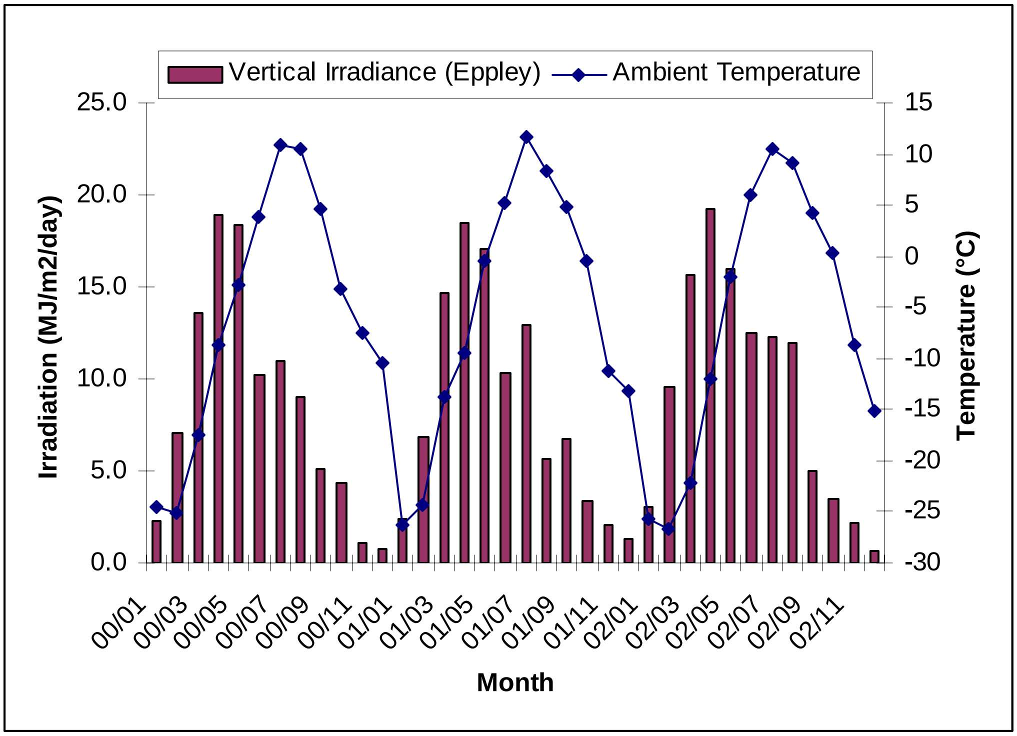

Figure 3: Mean daily irradiation and ambient temperature at the site.

In 1998, we came to realize that the measurement of solar radiation with Li-Cor pyranometers could be questionable, because such devices (built around silicon photodiode detectors) are very sensitive to alterations to the spectrum of incident solar radiation. In Iqaluit, a significant part of solar radiation occurs at low elevation angles; solar rays have to travel through a larger air mass in the atmosphere and therefore their spectrum is altered. In addition, reflection of solar radiation on the ground or snow in front of the array makes up an important part of incident radiation; this also modifies the spectrum of light. For these reasons an Eppley pyranometer (based on the thermopile principle, which is less sensitive to alterations of spectrum) was installed in parallel with the vertical Li-Cor pyranometer in March of 1998. A similar pyranometer was installed horizontally in April 1999.

A comparison of readings from the two vertical pyranometers is shown in Figure 4. Although both instruments record the same trend, it is clear that the Li-Cor pyranometer systematically over-estimates solar irradiance. Relative to measurements with the Eppley pyranometer, the monthly overestimation ranges from 12 % in March 1999 to nearly 300 % in December 1999. Over the whole year 2003 this overestimation reaches 26.9 % (vs. 25.7% in 2002 and 2001 and 25.6 % in 2000). Figure 4 also shows that the over-estimation tends to be relatively more important when light levels are low, presumably because of increased spectral effects.

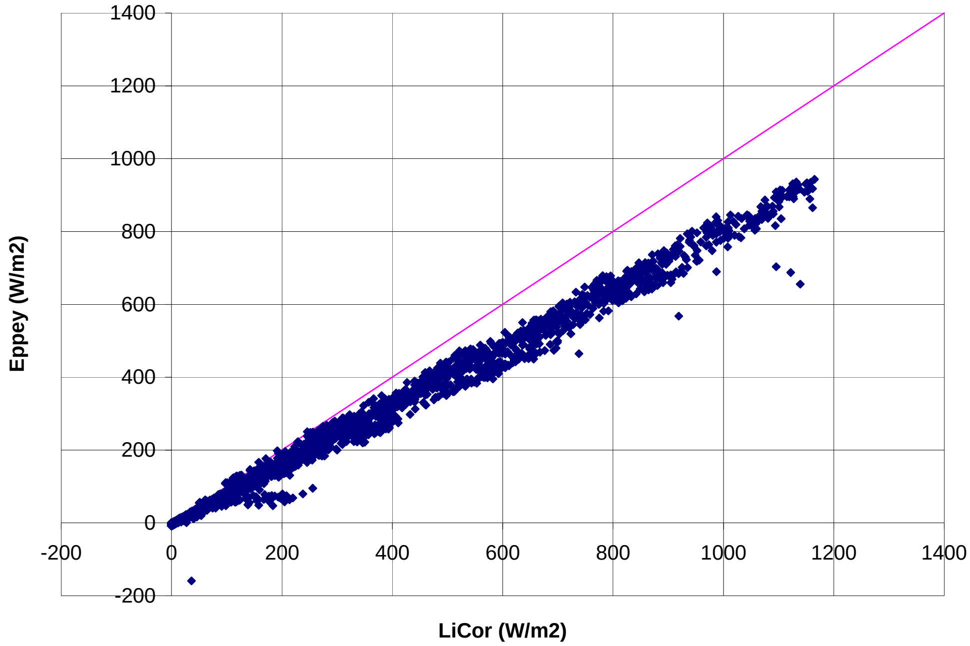

Figure 4: Comparison between Eppley and LiCor irradiance readings.

PV ARRAY PERFORMANCE

Monthly efficiency of PV array

Figure 5 shows the monthly DC electricity production of the PV array, and its efficiency (based on Eppley irradiation measurements). The array output follows closely the seasonal patterns of solar radiation, with as little as 13.2 kWh produced in December 2003 and as much as 471 kWh in April 2003. On a yearly basis, the DC array output is fairly constant at 2,600 ± 200 kWh. As for array efficiency, maxima of about 12.5% are recorded in February, March and April, and a minimum of 6-8% is recorded for December. Maximum efficiencies are obtained when solar radiation is abundant while the temperature remains low, which provides optimum working conditions for the PV modules (see [5] for more details regarding the impact of local climatic conditions on the performance of PV modules). On the other hand, lower efficiencies are observed from June to November due to higher module operating temperature. Finally, the lowest efficiency is obtained in December due to the very low light conditions under which the array has to work.

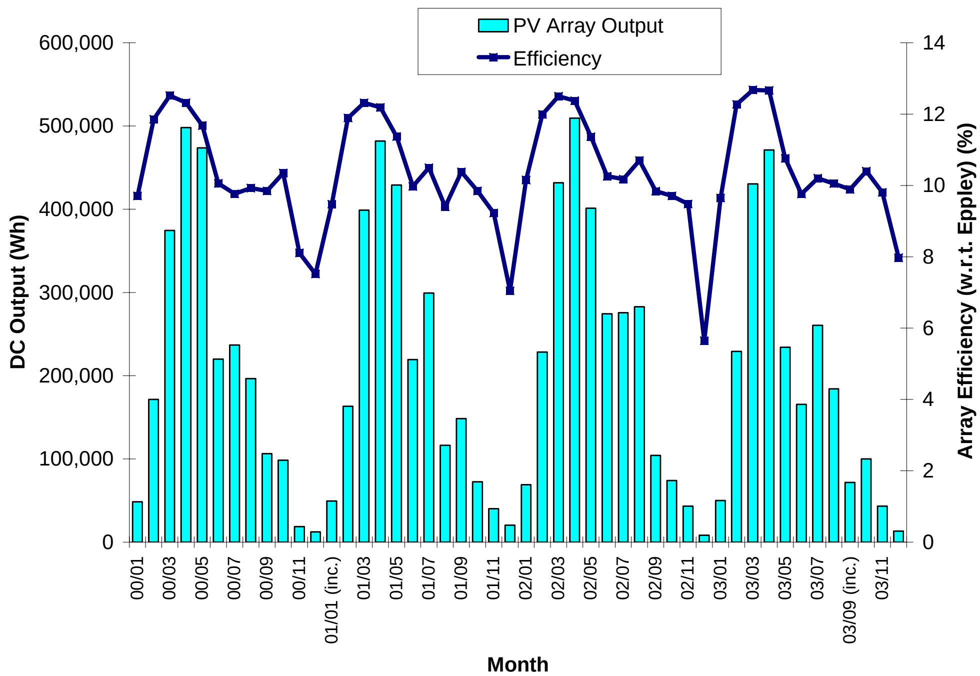

Figure 5: PV array DC output and efficiency on a monthly basis.

Efficiencies of the Siemens and Solec subarrays

Figure 6 shows separately the efficiencies of the Solec and Siemens sub-arrays. As can be noted, the efficiency of the Solec subarray is about 2 to 3 percentage points (or more) lower than that of the Siemens subarray. This was confirmed through detailed evaluation with an on-site PV array tester, as well as by testing 2 Solec and Siemens modules with a calibrated indoor solar simulator at CETC-Varennes.

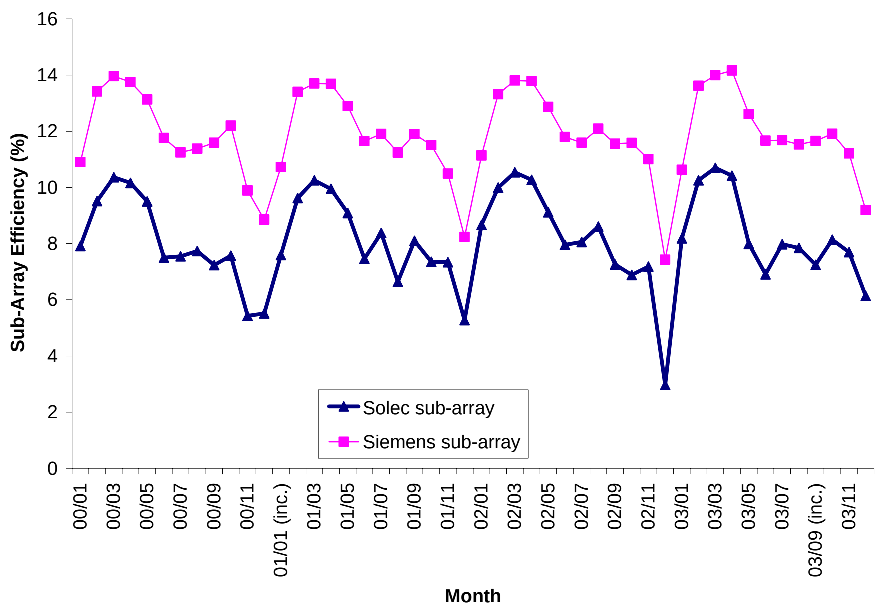

Figure 6: Siemens and Solec sub-array efficiencies.

Inverter Performance

The performance of the DC to AC power inverter is plotted as a function of hourly DC Power in Figure 7 (with January to December 2003 data) and on a monthly basis in Figure 8. The hourly curve shows that the inverter efficiency drops dramatically when the DC power drops below 1000 W. The maximum efficiency is close to 90% at high power. This trend can be attributed to the electronics of the inverter, which are fine tuned for an optimal operating point and do not perform as well at low power; and to the base load amount drawn by the unit for its own operation. The inverter starts to draw power from the grid when the power delivered by the PV array falls below 100 W. Laboratory tests show that the power drawn from the grid then reached a maximum of about 35 W when no power is available from the PV array. Subsequently, the inverter turns off at night and the power consumption fall below 2W. For a typical day, the inverter turns on at dawn and starts to consume 35 W of power from the grid. As the output of the modules increases, consumption of grid power decreases until 100 W is available from the PV array. During winter months in the far North, the inverter may operate for a long period of time with less than 100 W available from the PV array, thus consuming power and reducing its overall efficiency. This explains the significant dip, and even negative efficiency, observed in Figure 8 for the months of December. In overall, the reliability of the Prosine 5000 GT 3-kW inverter built by Statpower Technologies of Burnaby, B.C. has been exceptional. Although the mean time to first failure (MTFF) for present-day inverters is estimated to be 5 years [6], the Prosine inverter has experienced no failure in the last 9 years of operation.

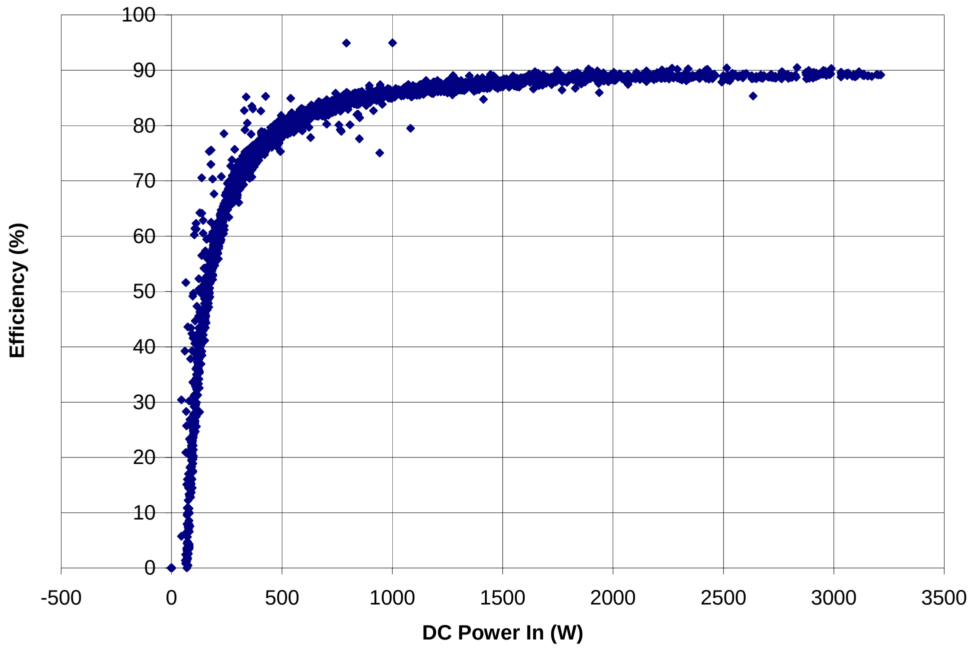

Figure 7: Inverter unit hourly efficiency curve.

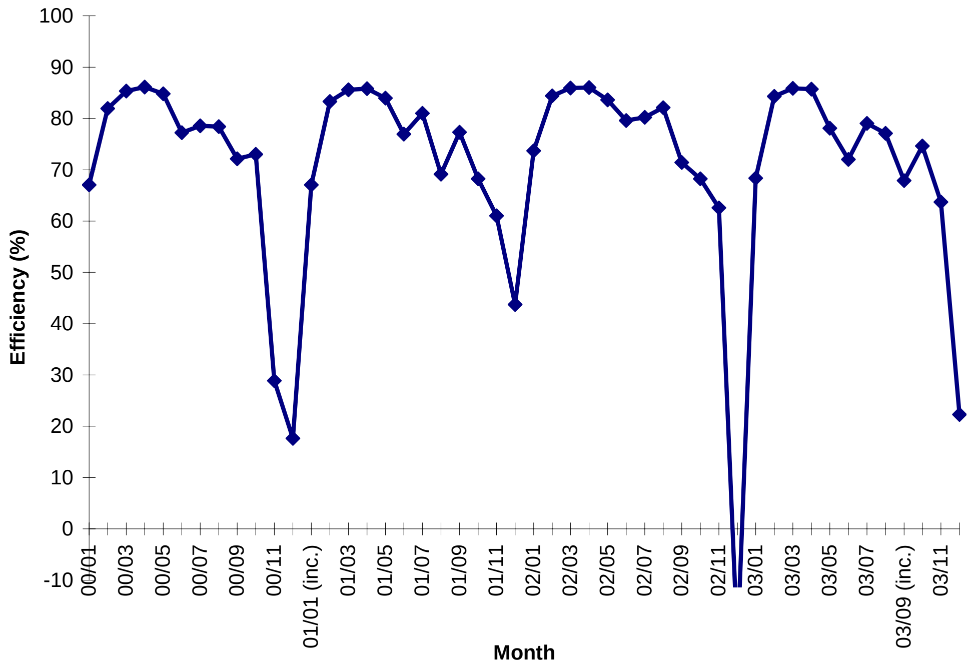

Figure 8: Monthly efficiency of the Inverter.

WHOLE SYSTEM PERFORMANCE

The system has been operating continuously since July 1995; the only interruptions of power delivery occurred when the AC side in the building was down. When this happens, the PCU ceases to operate and no power is delivered to the building.

On a yearly basis, the system delivered between 1,813 and 2,210 kWh of AC electricity (see table 1). As this is a 3.2 kWp PV system, its annual yield has varied between 567 and 691 kWh/kWp. The system performance ratio is about 0.70. This means that on a yearly basis, the system provides 70% of its rated capacity (or alternatively, the system losses due to unfavourable climatic conditions such as low irradiance and other balance of system losses such as the inverter amount to 30% of the rated capacity). A performance ratio of 0.70 is a fairly common figure, even for PV systems installed at lower latitudes. This shows that PV systems can perform just as well in Northern climates.

The monthly system output and efficiency are shown in Figure 9. As noted before, the energy delivered varies strongly with the time of the year. During the calendar year 2003 the system delivered between 2.9 kWh (December 2003) and 404.1 kWh (April 2003) per month. Recorded total output is 1,804.7 kWh for the year. Whereas year 2002 recorded the highest output ever (see table 1), 2003 is the lowest ever observed; this result is due to the lower-than-normal amount of solar radiation that fell on the system in 2003.

Table 1: Annual energy production (1996-2003).

Year	AC energy delivered [kWh]	Eppley Vertical irradiation [kWh]	Specific Yield [kWh/kWp]	Performance ratio [Eff_{out}/Eff_{STC}]
1996	2,083.00	NA	650.94	NA
1997	2,077.00	NA	649.06	NA
1998	2,020.00	NA	631.25	NA
1999*	1,926.00	22,111.00	601.88	0.70
2000	1,989.00	22,054.00	621.56	0.72
2001*	2,009.00	22,429.00	627.81	0.72
2002	2,210.00	24,131.00	690.63	0.73
2003*	1,813.00	20,659.81	566.56	0.70
average	*2,016±200*	*22,276.96*	*629.96*	*0.71*

(*missing hours pro-rated to the average system output for the month).

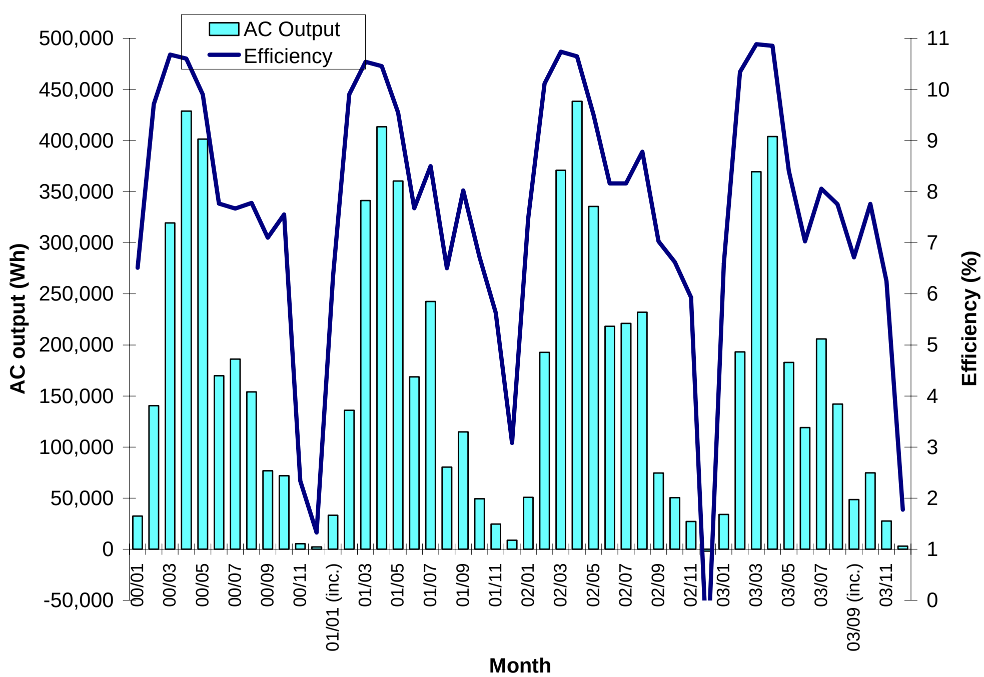

Figure 9: Monthly system output and efficiency.

Figure 10 shows the AC power produced by the system vs. incident solar irradiance, on an hourly basis for 2003, for irradiances (recorded by the Eppley vertical pyranometer) greater than 60 W/m^2. The system output is close to linear ($R^2 = 0.97$) and can be approximated by the following relationship:

$$\text{AC output} = 0.1199 \times \text{Incident radiation} - 165.6$$

where both AC output and incident radiation (Eppley reading times array area) are expressed in Wh. This relationship is very similar to the one derived in previous years. The outliers in Figure 10 are, for the most part, hours when the AC power in the building is in an abnormal condition (outage or poor quality power) and, as a consequence, the inverter ceases to deliver as a protective measure (protect inverter from electronic damage).

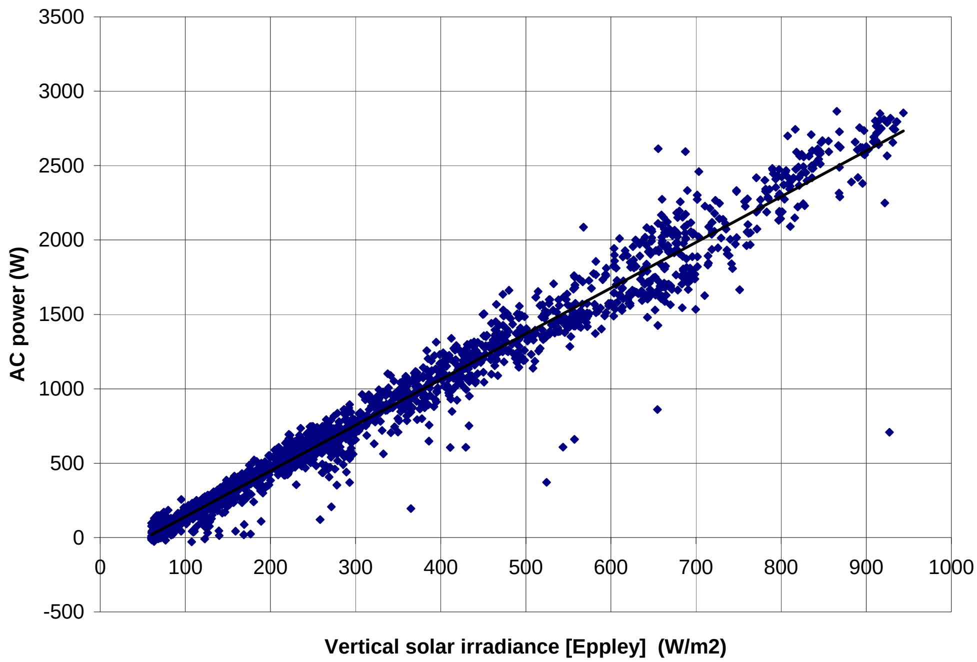

Figure 10: Hourly system output vs. incident irradiance for year 2003.

CONCLUSION

The PV system has worked reliably and well during its first nine years of operation and generated on average 2,016 ± 200 kWh of electricity each year, with no interruption of delivery except for times where the AC side in the building was down. System output is higher from March to May when the irradiance is high while the ambient temperature is cooler, and very low or even negative in December when there is very little sunshine available and the inverter must draw power from the grid in order to operate in a standby mode.

The array efficiency typically varies between 7 and 11% throughout the year, while the inverter average efficiency is 81% and can attain 90% under optimal conditions. This leads to a yearly average system efficiency of 7.2% and translates into an average yearly output of 630 kWh per kWp of solar array installed (depending on the amount of solar radiation available each year). On an annual basis, the system performs at 70% of its rated capacity, which corresponds to a typical value obtained for PV systems installed at lower latitudes. This shows that PV systems can perform just as well in Northern climates.

In summary, over the past nine years of operation, the system has demonstrated with success the potential of grid-connected PV for the far North with no operation and maintenance cost. As the cost of PV technology decreases, the lessons learnt from monitoring the system will help to encourage the broader acceptance of this new and reliable renewable energy source.

ACKNOWLEDGEMENTS

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