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Development and Testing of a Prototype Grid-Tied Photovoltaic Power System

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Development and Testing of a Prototype Grid-Tied Photovoltaic Power System

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Summary

The NASA Glenn Research Center (GRC) has developed and tested a prototype 2 kW DC grid-tied photovoltaic (PV) power system at the Center. The PV system has generated in excess of 6700 kWh since operation commenced in July 2006. The PV system is providing power to the GRC grid for use by all. Operation of the prototype PV system has been completely trouble free.

A grid-tied PV power system is connected directly to the utility distribution grid. Facility power can be obtained from the utility system as normal. The PV system is synchronized with the utility system to provide power for the facility, and excess power is provided to the utility.

The project transfers space technology to terrestrial use via nontraditional partners. GRC personnel glean valuable experience with PV power systems that are directly applicable to various space power systems, and provide valuable space program test data. PV power systems help to reduce harmful emissions and reduce the Nation’s dependence on fossil fuels. Power generated by the PV system reduces the GRC utility demand, and the surplus power aids the community.

Present global energy concerns reinforce the need for the development of alternative energy systems. Modern PV panels are readily available, reliable, efficient, and economical with a life expectancy of at least 25 years. Modern electronics has been the enabling technology behind grid-tied power systems, making them safe, reliable, efficient, and economical with a life expectancy of at least 25 years. Based upon the success of the prototype PV system, additional PV power system expansion at GRC is under consideration.

The prototype grid-tied PV power system was successfully designed and developed which served to validate the basic principles described, and the theoretical work that was performed. The report concludes that grid-tied photovoltaic power systems are reliable, maintenance free, long life power systems, and are of significant value to NASA and the community.

Introduction

The NASA Glenn Research Center has a wealth of experience in photovoltaic power systems. The work was done under the Hybrid Power Management (HPM) Program. The GRC Electrical and Electromagnetics Branch initiated the HPM Program for the GRC Technology Transfer and Partnership Office. HPM is the innovative integration of diverse, state-of-the-art power devices in an optimal configuration for space and terrestrial applications. The appropriate application and control of the various power devices significantly improves overall system performance and efficiency. Applications include power generation, transportation systems, biotechnology systems, and space power systems.

A PV power system can either be a stand alone, off-grid system, or a grid-tied system. An off-grid PV system provides local power only. A grid-tied PV system is connected directly to the utility distribution grid. Facility power can be obtained from the utility system as normal. The PV system is synchronized with the utility system. The PV system provides power for the facility, and excess power is provided to the utility.

Photovoltaic power systems have tremendous potential. The 89 petawatts of sunlight reaching the Earth’s surface is approximately 6,000 times greater than the 15 terawatts of average power consumed by the human population. PV generation has the highest power density of renewable energies with a global mean of 170 W/m^2 (Ref. 1). PV is entirely pollution free during use. PV system production end wastes and emissions are manageable utilizing existing pollution controls. End-of-use recycling technologies are under development to minimize negative environmental effects. PV systems can operate with minimal operator intervention or maintenance after initial setup.

Grid-tied PV power systems provide many benefits. Operating costs of a PV power system are low compared to conventional power technologies. PV can displace the highest cost electricity during times of peak demand in most climatic regions, and thus reduce grid loading. Net Metering is often used, in which independent power producers, such as PV power systems, are connected to the utility grid via the customers' main service panel and meter. When the PV power system is generating more power than required at that location, the excess power is provided to the utility grid. The customer pays the net of the power purchased when the on-site power demand is greater than the on-site power production and the excess power that is returned to the utility grid.

Grid-tied PV power systems can be used locally thus reducing transmission/distribution losses. Transmission/distribution losses in the U.S. were approximately 7.2 percent in 1995 (Ref. 2), thus providing a potential for significant energy savings.

Theoretical power generation has been determined for the prototype grid-tied 2 kW photovoltaic power system. The actual 2 kW PV power system installed at GRC served to validate the theoretical work that was performed.

Analysis

Predicted Power Generation

The National Renewable Energy Laboratory has developed a calculator to determine the energy production of grid-tied PV power systems throughout the world. The calculator is based upon the work of David F. Mennicucci (Ref. 3).

The calculator creates hour-by-hour performance simulations that provide power estimated monthly and annual energy production in kilowatts and energy value. Users can select a location and choose to use default values or their own system parameters, for size, electricity cost, array type, tilt angle, and azimuth angle. The calculator can provide hourly performance data for the selected location.

The calculator uses typical meteorological year weather for the selected location, and determines the incident PV array solar radiation and the PV cell temperature for each hour of the year. The DC energy for each hour is calculated from the PV system DC rating and the incident solar radiation, and then corrected for the PV cell temperature. The AC energy for each hour is calculated by multiplying the DC energy by the overall DC-to-AC derating factor and adjusting for the inverter efficiency as a function of the load. Hourly values of AC energy are summed to determine monthly and annual AC energy production.

A PV system is rated upon its nameplate DC power rating. This is determined by adding the PV panel power listed on the nameplates of the PV panels in watts (W), and dividing the sum by 1,000 to convert the rating to kilowatts (kW). PV panels are rated for standard test conditions of 1,000 W/m solar irradiance, and 25 °C PV panel temperature.

The PV system AC rating is determined by multiplying the nameplate DC power rating by an overall DC-to-AC derating factor. The DC-to-AC derating factor account for losses from the DC nameplate power rating, and is the mathematical product of the derating factors for the components of the PV system. The derating factor components includes PV array nameplate DC rating accuracy, inverter and transformer losses, mismatch, diode and connection losses, DC wiring losses, AC wiring losses, PV array contamination, system availability, and shading.

The derating factor for PV array contamination accounts for snow and other foreign matter on the surface of the PV array that prevents solar radiation from reaching the solar cells. PV array contamination is location and weather dependent. There are greater contamination losses in high-traffic, high pollution areas with infrequent rain. Snow reduces energy produced, and the severity is a function of the amount of snow and the duration that it remains on the PV array. Snow remains the longest when sub-freezing temperatures prevail, small PV array tilt angles prevent snow from sliding off, the PV array is closely integrated onto the roof, and the roof, or another structure in the vicinity, facilitates snow drift onto the array.

The tilt angle for a fixed array is the angle from horizontal of the inclination of the PV array. Thus a tilt of 0° is a horizontal array, and a tilt of 90° is a vertical array. An array is normally tilted at the location's latitude. This normally maximizes annual energy production. Increasing the tilt angle favors energy production in the winter, and decreasing the tilt angle favors energy production in the summer.

The azimuth angle for a fixed array is the angle clockwise from true north that the PV array faces. An azimuth angle of 180° (south-facing) is normally used for locations in the northern hemisphere, and 0° (north-facing) for locations in the southern hemisphere. This normally maximizes energy production. For the northern hemisphere, increasing the azimuth angle favors afternoon energy production, and decreasing the azimuth angle favors morning energy production. For the southern hemisphere, decreasing the azimuth angle favors afternoon energy production, and increasing the azimuth angle favors morning energy production.

The monthly and yearly energy production estimates are modeled using the selected PV system parameters and weather data that are typical or representative of long-term averages. Weather patterns vary from year to year, so the model is a better indicator of long-term performance than of performance for a particular month or year. PV performance is largely proportional to the solar radiation received, which may vary from the long-term average by 30 percent monthly and 10 percent yearly. For these variations, and the uncertainties associated with the weather data and model, future months and years may have actual PV performance that differs from the model. The variations may be as much as 40 percent for individual months, and up to 20 percent for individual years. Long-term performance over many years is expected to be accurate within 10 percent.

There are other factors that affect model accuracy. Nearby buildings, objects, or other PV arrays and array structures that shade the PV array will cause a reduction in actual energy production from the model. Snow or other contamination of the PV array will cause an inconsistency with the model. There is a reduction in power generation over time that is not factored into the model. Aging is due to weathering of the PV array, and is typically 1 percent per year.

The predicted AC energy for a grid-tied 2 kW DC PV power system located in Cleveland, Ohio is shown in Table 1. The assumptions made for this prediction is that the PV array is crystalline silicon, the PV array is fixed at a tilt of 41.4°, the PV array azimuth is 180.0°, and the DC-to-AC derating factor is 0.770. The predicted AC energy is shown graphically in Figure 1.

TABLE 1.—PREDICTED ENERGY FOR A GRID-TIED 2 kW DC PHOTOVOLTAIC POWER SYSTEM IN CLEVELAND, OHIO

Month	Solar radiation, $kWh/m^2/day$	AC energy, kWh
January	2.49	122
February	3.34	147
March	4.09	196
April	4.94	222
May	5.48	243
June	5.56	231
July	5.55	237
August	5.47	235
September	4.90	208
October	3.91	177
November	2.18	94
December	1.68	76
Total annual	4.14	2189

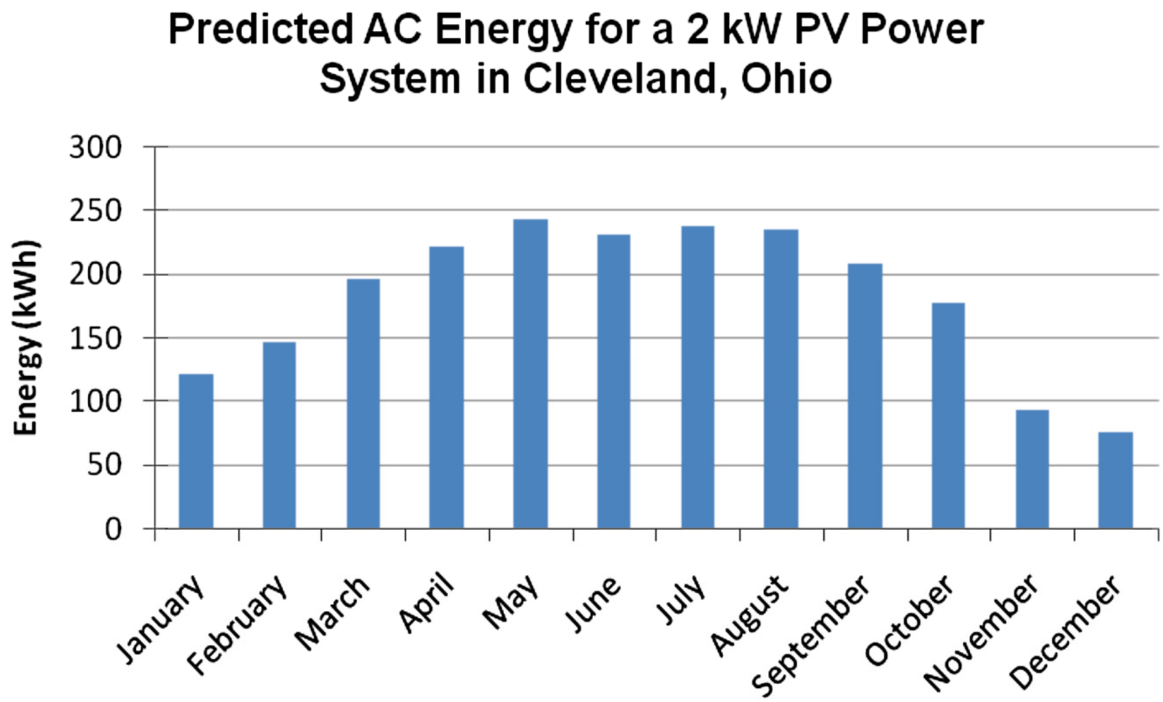

Figure 1.—Predicted Energy for a Grid-Tied 2 kW DC Photovoltaic Power System in Cleveland, Ohio.

TABLE 2.—PREDICTED ANNUAL ENERGY FOR A GRID-TIED 2 kW DC PHOTOVOLTAIC POWER SYSTEM

City	Tilt, degrees	Annual AC energy, kWh
Cleveland	41.4	2189
Tampa	28.0	2728
Los Angeles	33.9	2939
Phoenix	33.4	3234
Las Vegas	36.1	3327
Anchorage	61.2	1588
Montreal	45.5	2201
Berlin	52.5	1508
Matsumoto	36.2	2368
Moscow	55.8	1534
Paris	48.7	1631

The predicted annual AC energy produced from a grid-tied 2 kW DC PV power system for different areas throughout the world are shown in Table 2. The assumptions made for this prediction is that the PV array is crystalline silicon, the PV array tilt is fixed at the appropriate angle for the specific location, the PV array azimuth is 180.0°, and the DC-to-AC derating factor is 0.770. It is interesting to note from the world comparison that Cleveland is a viable location for PV production, with potentially significantly greater annual energy production than Berlin, Moscow or Paris for the same PV system properly oriented for the specific location. In addition, the potential annual energy production from the same PV system in Cleveland is not significantly less than such a system located in Tampa.

Test Objectives

The objective of testing the prototype 2 kW grid-tied photovoltaic power system is to validate the theoretical analyses and verify long-term system performance. This validation provides confidence in using the analyses for developing and optimizing conceptual grid-tied photovoltaic power system designs.

Testing of the prototype 2 kW grid-tied photovoltaic power system was performed at the NASA Glenn Research Center. Of particular interest is the long term performance of the system. Power and energy were monitored on a regular basis.

Test Hardware Description

Prototype 2 kW Grid-Tied Photovoltaic Power System

The prototype 2 kW grid-tied photovoltaic power system test hardware includes the photovoltaic panels, and the DC/AC inverter. The photovoltaic panels are shown in Figure 2 and the photovoltaic inverter is shown in Figure 3. The system block diagram is shown in Figure 4. System component specifications are included in the Appendix.

The photovoltaic panels are semiconductor panels that convert energy from sunlight to DC electrical power. The panels are unbreakable and maintenance free. The system consists of ten, 200 W (at 27.1 V) panels connected in series. Each panel consists of 54 silicon poly-crystalline cells in series. The panel efficiency in providing power from the sunlight is rated at 15 percent. Each panel weighs 39 lb, and is 58.5 by 38.6 in. The life expectancy of the PV panels is 25 years or greater. The support structure for the panels is a fixed mount to orient the panels southerly with a tilt of 41.4° from horizontal to align the panels for the latitude of Cleveland, Ohio. Solar trackers are available to increase the available power from the Sun. Under ideal conditions, a tracker can provide up to 50 percent additional daily power from a PV array. In temperate latitudes, a tracker can provide an annual 25 percent increase in power from a PV array. Numerous technologies are available for trackers, including electric drives and fluid drives. Trackers are mechanical devices, and thus have potential life and maintenance issues. To avoid life and maintenance issues, a fixed mount was used for the prototype 2 kW PV power system.

The photovoltaic inverter converts the DC electrical power derived from the photovoltaic panels to single phase, 60 Hz, sinusoidal AC power synchronized to the AC utility power system. The inverter integrated into the prototype PV power system is rated at 3.3 kW, 208 VAC with an efficiency of 94 percent. The inverter weighs 49 lb, and is 28.5 by 15.9 by 5.75 in. The life expectancy of the inverter is 25 years or greater.

Figure 2.—Prototype 2 kW System Photovoltaic Panels.

Figure 3.—Prototype 2 kW System Photovoltaic Inverter.

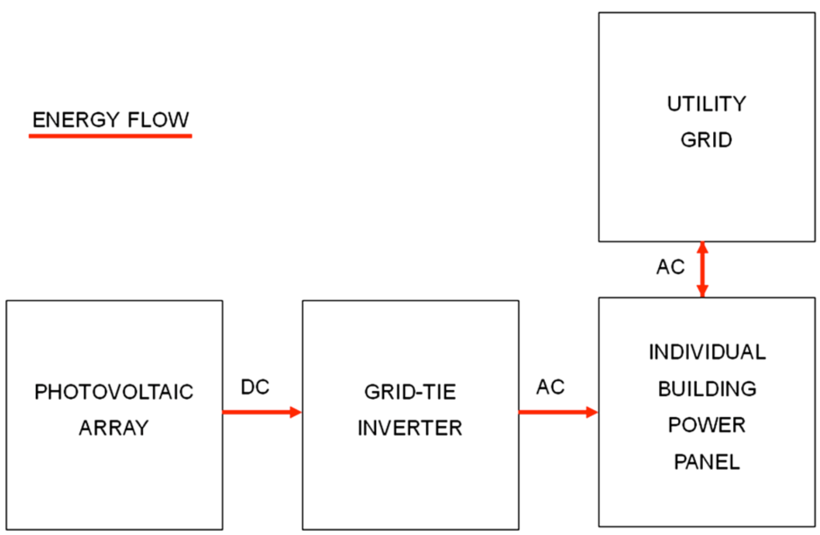

Figure 4.—Prototype 2 kW Grid-Tied Photovoltaic System Block Diagram.

The prototype PV system was designed per the National Fire Protection Association (NFPA) 70, the National Electrical Code (NEC). The system concurs with all articles of the NEC, and in particular addresses Article 690, Solar Photovoltaic Systems. In addition, the system was designed to be completely in concurrence with the NASA GRC Safety Manual. The PV panels meet the requirements of Underwriters Laboratories Standard for Safety UL-1703 concerning flat-plate PV modules and panels. The PV panels are fused to provide overcurrent protection. The PV panels, and the entire PV system, are bonded and grounded per the NEC. A lightning arrestor is included to protect the PV system from lightning strikes. The PV inverter includes an NEC compliant DC and AC disconnect switch to provide complete system isolation whenever the disconnect switch is opened. The inverter is configured to automatically open the inverter circuits whenever utility power is lost to prevent power from the PV system from feeding back into the utility power system, thus preventing a potential safety hazard.

Instrumentation

The prototype 2 kW grid-tied photovoltaic power system contains an internal instrumentation system. The photovoltaic inverter includes an integral backlit 2-line, 16-character, liquid crystal display (LCD). The display provides instantaneous inverter output power, daily and lifetime inverter output energy, PV array voltage and current, utility voltage and frequency, time online, and fault messages.

Test Procedures

The tests described in this report were conducted at the NASA Glenn Research Center in Cleveland, Ohio. The lifetime energy production of the prototype 2 kW grid-tied photovoltaic power system is monitored at the PV inverter. The measured monthly energy production is compared to the analytical monthly energy production.

Test Results

System Performance

Table 3 summarizes the monthly and annual energy production results for the first year of use of the prototype 2 kW grid-tied photovoltaic power system, along with the analytical results. Figure 5 indicates the monthly energy production, and Figure 6 indicates the total energy production.

TABLE 3.—PROTOTYPE 2 kW DC GRID-TIED PV POWER SYSTEM PERFORMANCE

Month	Predicted AC energy, kWh	Measured AC energy, kWh
January	122	82
February	147	94
March	196	164
April	222	251
May	243	262
June	231	274
July	237	246
August	235	247
September	208	246
October	177	174
November	94	91
December	76	62
Total annual	2189	2193

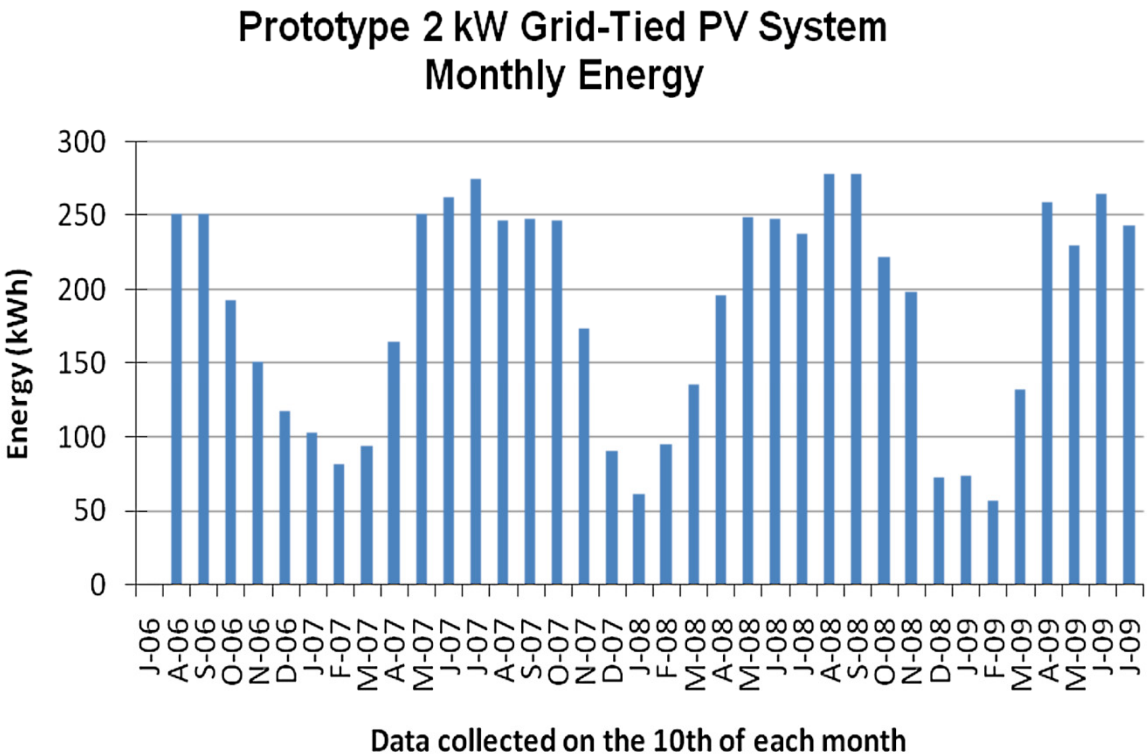

Figure 5.—Prototype 2 kW DC Grid-Tied PV Power System Monthly AC Energy.

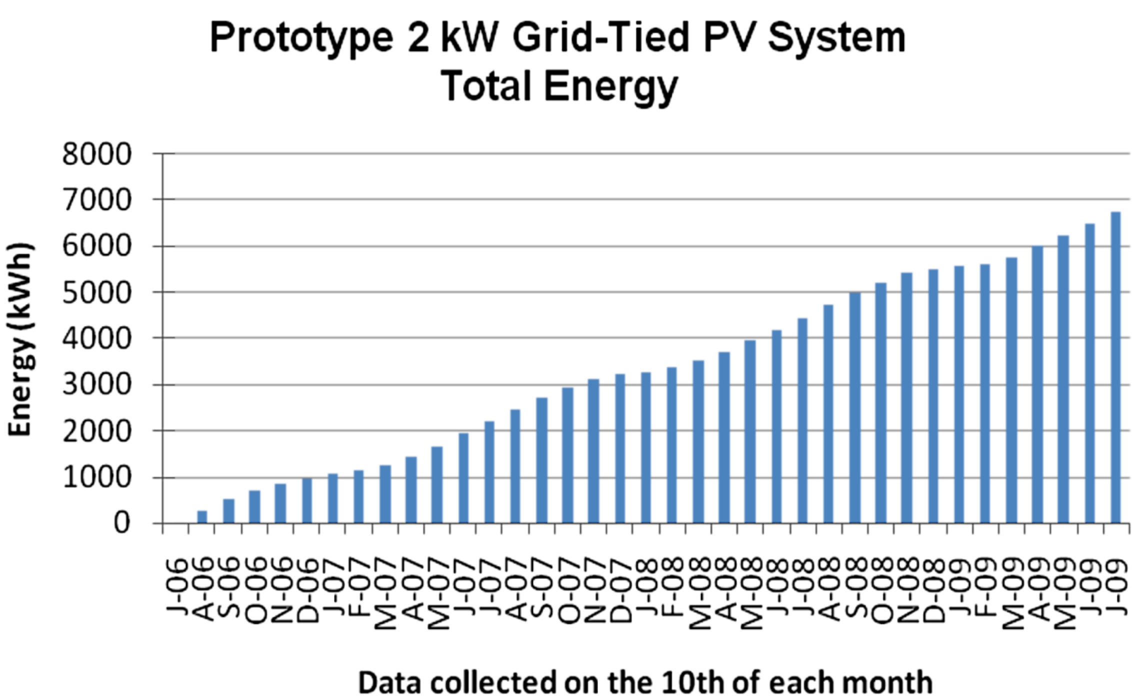

Figure 6.—Prototype 2 kW DC Grid-Tied PV Power System Total AC Energy.

Discussion

The objective of testing the prototype 2 kW grid-tied photovoltaic power system is to validate the theoretical analyses, and verify long-term system performance. The analytical model effectively predicts the annual AC energy produced by a grid-tied photovoltaic power system.

The rather large monthly variation in energy production of the prototype 2 kW PV power system shown in Figure 5 indicates the large seasonal variation in sunlight in Cleveland, Ohio. A grid-tied PV power system is advantageous in regions, such as Cleveland, in which utility power is essential in times of limited sunlight to meet the power requirements of the load. The significant power produced by the PV power system in the summer months is valuable in meeting the high utility system power demand at that time.

The monthly energy production of the prototype 2 kW PV power system shown in Figure 5 over the past four years indicates very consistent long-term system performance. No effort has been made to clean the PV panels, or to clear them of snow for these tests. Providing cleaning and snow clearing of the PV panels would improve PV system performance, but the test results obtained without cleaning or snow clearing indicate the excellent performance attainable from this system under no maintenance conditions.

Consistent long-term PV system performance is obvious from the total PV system energy production shown in Figure 6. Long-term system performance has been excellent over the past four years with no system failures, no down time, and no required system maintenance.

Concluding Remarks

The NASA Glenn Research Center has successfully designed, developed, analyzed, and tested a prototype 2 kW DC grid-tied photovoltaic power system. The goals of the project include reducing the Nation's dependence on fossil fuels, and reducing the production of harmful emissions. The objective of this work is to develop a viable prototype 2 kW DC grid-tied photovoltaic power system to validate the theoretical analyses, and to verify long-term system performance.

Theoretical analyses have been performed successfully to predict the energy produced by a grid-tied PV system in Cleveland, Ohio. Empirical test results obtained from the experimental hardware successfully validated the basic principles described, and the theoretical work that was performed. Of particular value, are the analytical tools and capability successfully used for this project. Performance predictions can be made confidently for grid-tied PV systems of various scale.

The prototype 2 kW DC grid-tied PV system has provided consistent long-term performance over the past four years with no system failures, no down time, and no required system maintenance. From the analyses and empirical test results, it is apparent that grid-tied PV systems are viable in Cleveland, Ohio.

The report concludes that the implementation of grid-tied photovoltaic power systems can provide significant improvements in power system performance, reduce dependency on fossil fuels, and reduce the production of harmful emissions. The prototype system has been efficient, reliable, and maintenance free. The prototype grid-tied PV power system has been of great value to GRC and to the local community.

Appendix—Equipment Under Test Summary Data Sheet

Prototype 2 kW Photovoltaic System

1.0 Photovoltaic Panels

1.1	Type	Silicon Poly-Crystalline
1.2	Peak Power (Wp)	200 W
1.3	Max Power Voltage (Vmp)	27.1 V
1.4	Max Power Current (Imp)	7.4 A
1.5	Open Circuit Voltage (Voc)	34 V
1.6	Short Circuit Current (Isc)	7.8 A
1.7	Short Circuit Temp Coefficient	5.6 mA/°C
1.8	Open Circuit Voltage Coefficient	–0.12 V/°C
1.9	Max Power Temp Coefficient	–0.5%/°C
1.10	Max Series Fuse	15.0 A
1.11	Normal Operating Cell Temp (NOCT)	45.0 °C (113 °F)
1.12	Width	98.1 cm (38.6 in.)
1.13	Length	148.5 cm (58.5 in.)
1.14	Depth	5.5 cm (2.2 in.)
1.15	Weight	17.7 kg (39.0 lb)

2.0 Inverter

2.1	Type	Sine Wave
2.2	Max AC Power Output	3300 W
2.3	Nominal AC Output Voltage	208 VAC
2.4	AC Output Voltage Range	183 to 228 VAC
2.5	Nominal AC Frequency	60 Hz
2.6	Max Continuous Output Current	18 A
2.7	Max Total Harmonic Distortion	3%
2.8	Power Factor	>0.9
2.9	DC Input Voltage Range	195 to 600 VDC
2.10	Peak Power Tracking Voltage Range	195 to 550 VDC
2.11	Peak Inverter Efficiency	94.7%
2.12	Night Time Power Consumption	1 W
2.13	Output Overcurrent Protection	25 A
2.14	Operating Temperature Range	–25 to 65 °C (–13 to 149 °F)
2.15	Enclosure Type	NEMA 3R (outdoor rated)
2.16	Disconnect	PV/Utility disconnect
2.17	Cooling	Convection
2.18	Communications	One RS 232 and two RJ45 ports
2.19	Display	Liquid Crystal Display
2.20	Width	40.3 cm (15.9 in.)
2.21	Height	75.5 cm (28.5 in.)
2.22	Depth	14.6 cm (5.7 in.)
2.23	Weight	22.2 kg (49.0 lb)

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3. Mennicucci, David F., "Photovoltaic Array Simulation Models," *Solar Cells*, 1986, pp. 383–392.

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