Commercialization of a 2.5kW Utility Interactive Inverter for Distributed Generation

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Executive Summary

Through this project, Advanced Energy Conversion (AEC) has developed, tested, refined and is preparing to commercialize a 2.5kW utility-interactive inverter system for distributed generation. The inverter technology embodies zero-voltage switching technology that will ultimately yield a system that is smaller, less expensive and more efficient than existing commercial technologies. This program has focused on commercial success through careful synthesis of technology, market-focus and business development. AEC was the primary participant. AEC is utilizing contract manufacturers in the early stages of production, allowing its technical staff to focus on quality control issues and product enhancements. The objective of this project was to bring the AEC inverter technology from its current pre-production state to a commercial product. Federal funds have been used to build and test production-intent inverters, support the implementation of the commercialization plan and bring the product to the point of UL certification.

Advanced Energy Conversion has made a strategic decision to focus on a 2.5kW utility interactive inverter for solar photovoltaic applications because: 1) the solar photovoltaic regulatory environment is stable; 2) the solar photovoltaic market is enjoying sufficient expansion at this power level to support many competing technologies; 3) the power level is consistent with significant activity in the wind energy industry where many wind turbine manufacturers are interested in transitioning from battery charging to utility interaction; 4) the power level is close to that of the emerging residential fuel cell market; 5) the technical risks for our inverter concept are lowest at this power level; and 6) it will be easiest to form strategic manufacturing and distribution relationships at this power level.

Our inverter technology is based on using parasitic circuit elements to advantage in substantially reducing the switching losses. Reduced switching losses support operation at sufficiently high switching frequencies that capacitors and transformers can be reduced in physical size, thereby supporting lower cost and a more easily manufactured system. The reduced switching losses allow for operation with lower input voltage than inverters currently in the market. Operation at lower input voltage allows the solar PV array to be configured in a series-parallel configuration that is known to be more productive under conditions where the array is partially shaded.

The program has focused on commercialization issues that involve technical development, market planning, and working out manufacturing details. To the extent possible, simultaneous consideration of technology, market needs, and manufacturing planning has been used to create a product that meets unfulfilled need in the market with technological advantages that can be manufactured to allow for sustainable profitability.

Project Description

Original Project Goals and Objectives

The original objective of this project was to bring the AEC inverter technology from its pre-production state to a commercial product. Federal funds were to be used to build and test production-intent inverters, support the implementation of the commercialization plan and bring the product through UL certification. These objectives would be met by:

1. Completing the engineering design of the inverter.
2. Introducing the inverter to the market, developing a sound value proposition for the inverter along the way.
3. Arranging to cover the manufacturing details necessary to take the inverter into production.
4. Handling the regulatory issues of UL certification that are necessary before selling the inverter.

Our original commercialization plan for the AEC inverter is detailed below by project task. These tasks reflect an interleaving of the four objectives articulated above.

- Task 1:** Perform a detailed design of the isolation transformer within the inverter. This will involve magnetic design coupled with winding design to create an efficient transformer that can be manufactured reliably.
- Task 2:** Develop a marketing plan for the inverter. A specific objective is to gain access to system integrators that are able to specify the inverter, thereby serving a dual role as both customer and distributor.
- Task 3:** Develop a manufacturing plan for the inverter. This will involve selection of a manufacturing partner and resolution of issues surrounding the supply of components, fabrication of printed circuit boards, final assembly and testing.
- Task 4:** Use the test data from the engineering prototype to design the production intent AEC inverter. It is expected that changes will be focused on improving performance in some areas of the inverter while trying to drive down the manufactured cost of the inverter without sacrificing reliability. In addition, the housing for the inverter will be designed to create an attractive functional package that is consistent with manufacturability. Prospective manufacturing partners will participate in reviewing the design for manufacturability.
- Task 5:** Seek appropriate intellectual property protection. Given the competitive nature of the distributed generation industry, it will be important to protect our novel concepts with patent protection. It appears that the topology, maximum power point tracking concept and integrated magnetics concept may all be patentable.
- Task 6:** Fabricate the production intent AEC inverter according to the manufacturing plan to the extent possible.
- Task 7:** Fabricate a test facility as stipulated in IEEE Standard 929-2000. This will facilitate inverter evaluation relative to UL1741. It is expected that this test facility will form the basis of equipment that will be used for final testing of inverters according to the manufacturing plan.
- Task 8:** Experimentally evaluate the production intent AEC inverter. The experimental evaluation will include characterization of inverter performance over the specified input voltage range. The performance is taken to include inverter efficiency, utility power factor, power point tracking, and anti-islanding performance.

- Task 9:** Fabricate four manufacturing prototypes according to the manufacturing plan of Task 3. It is expected that this task will involve the fabrication of a number of fixtures that will reduce the amount of manual labor required for manufacture.
- Task 10:** Document the performance of the four manufacturing prototype inverters relative to competing technologies. Of interest are issues of consistency among the units. These four units will ultimately be used for acceptance testing at UL as well as market development by making them available to system integrators for examination and testing.
- Task 11:** Evaluate all manufacturing prototypes within AEC for compliance with UL1741.
- Task 12:** Prepare technical documentation for the AEC inverter, including installation, user and service manuals.
- Task 13:** Submit one inverter to Underwriters Laboratories for evaluation relative to UL1741 and the New York State interconnection requirements.
- Task 14:** Submit one inverter to each of two solar photovoltaics system integrators for field evaluation relative to competing inverters.
- Task 15:** Begin implementing the marketing plan with a press release of new product technology distributed to trade magazines with advertisements as appropriate.
- Task 16:** Implement the manufacturing plan and the marketing plan as the AEC inverter is launched.

Variance From Original Goals and Objectives

There were no variances from the original goals and objectives. However, there were variances between the work proposed and the work completed.

In particular, important market feedback indicated that the lower input voltage range would be of value in incorporating energy storage into the PV system. Accordingly, we modified the design of the inverter so that it is compatible with 48V battery backup as part of the original system design, or as an upgrade at some point in the future. This modification expanded the work associated with Task 4 and the subsequent technical tasks. This modification also had an impact on Task 2 and the associated marketing tasks.

We believe the market input to be extremely valuable in helping us to position the inverter for commercial success. While the change cost us time and money that was not budgeted, the cost is substantially less than it would have been if we had completed UL certification on a unit that would not sell well. Because of the additional engineering and marketing expenses incurred because of this change, we did not complete our original statement of work. However, AEC is continuing to put its own resources into the inverter, and it is expected that the inverter will be commercially available by the end of calendar year 2006.

The change in scope of each task is identified below.

- Task 1:** No change.
- Task 2:** This task was expanded based on market input. Substantial effort was put into sharpening the marketing message for the inverter into three succinct points:
1. A low input voltage inverter allows for greater energy capture under partial shade conditions, without sacrificing energy capture in full sun.
 2. A low input voltage inverter allows for easy integration of energy storage in the system, either as part of the original installation, or as part of a system upgrade in the future.

3. A low input voltage inverter supports an incremental system build because a smaller number of panels is needed to get up to the inverter input voltage. Additional panels can be added in parallel as needs change or additional capital becomes available.

Task 3: No change.

Task 4: This task was expanded to include the design of an integrated automatic transfer switch to support inverter operation in systems with battery backup. The automatic transfer switch operates to disconnect the inverter from the utility in the event of a utility outage, allowing power to continue to flow to a set of pre-selected loads. When the utility service returns to normal, the automatic transfer switch will automatically reconnect the inverter to the utility. In addition to the hardware design associated with the automatic transfer switch, there were significant software changes needed to support the new system configuration. When connected to the utility grid, the inverter behaves as a current source. When operating as a stand-alone unit, the inverter behaves as a voltage source.

Task 5: No change.

Task 6: No change.

Task 7: No change.

Task 8: This task was expanded to accommodate the changes in Task 4.

Task 9: This task was started but not completed because of lack of funds. AEC is presently completing the manufacturing prototypes using its own resources.

Task 10: This task was started but not completed because of lack of funds. AEC is presently completing the manufacturing prototypes using its own resources.

Task 11: This task was started but not completed because of lack of funds. AEC is presently completing the manufacturing prototypes using its own resources.

Task 12: No change.

Task 13: This task was started but not completed because of lack of funds. AEC is presently completing the manufacturing prototypes using its own resources.

Task 14: This task was started but not completed because of lack of funds. AEC is presently completing the manufacturing prototypes using its own resources.

Task 15: AEC began implementing the marketing plan for the inverter much earlier and much more aggressively than originally proposed. The inverter has been displayed at three trade shows (the Midwest Renewable Energy Fair, the Solar 2004 Conference, and the Mid-Atlantic Renewable Energy Conference) and one distributor conference (Energy Outfitters, Las Vegas, December 2004).

Task 16: This task was started but not completed because of lack of funds. AEC is presently completing the manufacturing prototypes using its own resources.

Discussion of Work Performed

Task 1: The isolation transformer is the heart of the inverter. It is used for stepping up the relatively low input voltage to a voltage compatible with interfacing to the utility. It is also used to provide galvanic isolation between the dc side (solar PV panels) and the ac side (utility). The use of an isolation transformer is a common method for preventing the injection of dc into the ac utility. This is an important issue for obtaining certification to UL1741.

Task 2: The marketing plan is comprised of strategy and tactics. The strategy was to coalesce the features of the inverter into a clearly articulated value proposition. As indicated above, using market feedback this has been achieved. Marketing tactics have been identified to include: a whitepaper to educate the state

agencies responsible for managing incentive programs; participation in conferences and tradeshow; identification of key installers that are able to make powerful recommendations within the industry; and, identification of promotional incentives to make sure that installers and distributors are going to recommend the AEC inverter.

- Task 3:** The central thrust of the manufacturing plan is to make use of contract manufacturers for the printed circuit boards (PCBs) within the inverter, the magnetics within the inverter, and the enclosure for the inverter. Suppliers for the PCBs, magnetics, and enclosures have been identified. The contract manufacturer for the PCBs was selected after conducting site visits with eleven different board houses. The balance of the manufacturing plan is to perform final assembly and test of the initial production units at AEC. This will allow for rigorous testing as the unit gets introduced to the market. In time as volumes grow the final assembly and test will be transitioned to a contract manufacturer. All of the board houses we considered are able to do assembly and test in addition to building PCBs.
- Task 4:** Significant effort went into the engineering design of the inverter. As described above, this design was modified to incorporate the automatic transfer switch to support stand-alone operation in the absence of the utility. The design of all PCBs was reviewed with multiple board houses to identify potential manufacturing issues; the feedback received was incorporated into the final design. In parallel with the inverter circuit design, packaging of the inverter was also considered to make sure that the electrical design would be manufacturable while being housed in an enclosure that would be easily accepted by the installers working in the solar industry. We solicited feedback from an array of installers and incorporated their insights into the enclosure design.
- Task 5:** We have two patents pending on the inverter. One patent is directed at the circuit topology. The second patent is directed at the control of the inverter. Both patents are in the process of being prosecuted. At this time we are optimistic that both patent applications will result in patents being issued.
- Task 6:** Prototype inverters have been built to the manufacturing plan to the extent possible. It is expected that there will be some evolution in the manufacturing plan as our initial run of twenty-five inverters is completed.
- Task 7:** A test facility was prepared as stipulated in IEEE Standard 929-2000 and UL1741. Prototype inverters were tested against this facility to refine the software algorithms that are used to detect an islanding condition.
- Task 8:** Prototype inverters have been experimentally evaluated. The experimental evaluation included characterization of inverter performance over the specified input voltage range. The performance analysis included inverter efficiency, utility power factor, power point tracking, anti-islanding performance, and operation as a stand-alone inverter.
- Task 9:** AEC is in the process of fabricating twenty-five inverters according to the manufacturing plan. Twenty of these inverters have been purchased, and the remaining five will be used for compliance testing and seeding the market.
- Task 10:** This task will be completed as part of checking out the inverters before they are delivered to our customer.
- Task 11:** This task will be completed as part of checking out the inverters before they are delivered to our customer.
- Task 12:** Technical documentation for the AEC inverter, including installation, user and service manuals, has been started. The technical documentation is expected to

evolve as we go through the experience of building, testing and installing our first production run of inverters.

Task 13: We have undergone a preliminary design review of the inverter with Intertec (ETL) to ensure that any UL1741 compliance issues were identified as early as possible. Based on this design review we are not expecting any issues to surface during final certification testing.

Task 14: This task will have to wait until the inverter clears UL1741 certification.

Task 15: Implementation of the marketing plan is well underway. As indicated above, the inverter has been shown at trade and distributor conferences and expositions. In addition, AEC has prepared a whitepaper on using the inverter to improve the productivity of the PV system. The whitepaper is attached to this report as Appendix E. In addition, application information for the inverter has been prepared; this information is attached as Appendix F.

Task 16: We expect this to be completed by the end of calendar year 2006.

Conclusions and Recommendations For Future Work

Through this program, the commercialization of the AEC inverter for distributed generation has progressed significantly. While the original tasks were not all completed as envisioned, the work carried out over the course of the program has:

1. Completed the engineering design of the inverter.
2. Supported sufficient testing of the inverter to pass a preliminary design review against UL1741.
3. Supported sufficient market interaction that we have been able to sharpen our marketing message.
4. Put in place the manufacturing details necessary to take the inverter into production.

Additional work remains. Currently AEC is undertaking the following steps using internal resources:

1. Building twenty-five inverters according to the manufacturing plan. These inverters will be used to support UL certification testing.
2. After we have completed certification testing, the twenty-five inverters will be used to seed the market. Twenty of the inverters have already been purchased by a company with presence on both the east and west coasts. They are moving into residential systems and have selected the AEC inverter for its feature set over the other inverters currently in the market. The remaining five inverters will be used for getting other installers and distributors interested in the product.
3. Establishing a sales and marketing organization to push the inverter into the market.

Appendices

- Appendix A. Final Task Schedule
- Appendix B. Final Spending Schedule
- Appendix C. Final Cost Share Contributions
- Appendix D. Energy Savings Metrics

Supplemental Information

- Appendix E. AEC's Whitepaper "Increasing the Productivity of Solar Photovoltaic Systems," Proceedings of the Solar 2006 Conference, Denver, CO, July 8-13, 2006.
- Appendix F. AEC's Application Information for the ecoJoule2800 Inverter

Appendix A

Final Task Schedule

Final Task Schedule

Task Number	Task Description	Task Completion Date				Progress Notes
		Original Planned	Revised Planned	Actual	Percent Complete	
1	Transformer Design	11/1/2003	1/31/2004	1/31/2004	100%	Completed.
2	Marketing Plan	9/30/2004	9/30/2004	9/30/2004	100%	Completed.
3	Manufacturing Plan	12/1/2003	5/31/2004	9/30/2004	100%	Completed.
4	Prototype Intent Design	12/31/2003	1/31/2004	1/31/2004	100%	Completed.
5	Intellectual Property	12/31/2003	4/30/2004	2/28/2004	100%	Completed.
6	Production Intent Prototypes	1/31/2004	4/30/2004	4/30/2004	100%	Completed.
7	UL1741 Test Facility	1/31/2004	3/31/2004	3/31/2004	100%	Completed.
8	Prototype Evaluation	2/28/2004	5/31/2004	6/15/2004	100%	Completed.
9	Manufacturing Prototypes	3/31/2004	6/30/2006		60%	In process.
10	Prototype Evaluation	4/30/2004	7/31/2006		0%	Not started yet.
11	Internal UL1741 Compliance Testing	5/31/2004	8/31/2006		0%	Not started yet.
12	Technical Documentation	5/31/2004	8/31/2006		80%	Installer, user, and service manuals in preparation
13	UL Testing	7/31/2004	9/30/2006		0%	Not started yet.
14	Field Evaluation by System Integrators	8/31/2004	12/31/2006		0%	Not started yet.
15	Implement Marketing Plan	9/30/2004	11/30/2006		75%	In process.
16	Implement Manufacturing Plan	12/31/2004	12/31/2006		0%	Not started yet.

Appendix B

Final Spending Schedule

Final Spending Schedule **Project Period:** 10/1/2003 to 2/28/2006

Task	Approved Budget	Final Project Expenditures
Task 1 Transformer Design	21,550	24,664.74
Task 2 Marketing Plan	20,241	35,000.00
Task 3 Manufacturing Plan	24,907	37,556.73
Task 4 Prototype Intent Design	41,901	133,000.00
Task 5 Intellectual Property	18,043	18,992.18
Task 6 Production Intent Prototypes	18,894	62,941.37
Task 7 UL1741 Test Facility	30,634	34,070.29
Task 8 Prototype Evaluation	16,552	39,900.00
Task 9 Manufacturing Prototypes	33,292	56,343.89
Task 10 Prototype Evaluation	18,292	10,000.00
Task 11 Internal UL1741 Compliance Testing	18,292	22,000.00
Task 12 Technical Documentation	20,950	34,500.00
Task 13 UL Testing	27,577	10,000.00
Task 14 Field Evaluation by System Integrators	8,514	0.00
Task 15 Implement Marketing Plan	13,356	27,000.00
Task 16 Implement Manufacturing Plan	22,630	0.00
Total	355,625	545,969.20
DOE Share	250,000	250,000
Cost Share	155,625	295,969.20

Appendix C

Final Cost Share Contributions

Final Cost Share Contributions

Funding Source	Approved Cost Share		Final Contributions	
	Cash	In-Kind	Cash	In-Kind
Department of Energy	250,000		250,000	
Advanced Energy Conversion, LLC		155,625		295,969.20
Total	250,000	155,625	250,000	295,969.20
Cumulative Cost Share Contributions				295,969.20

Appendix D

Energy Savings Metrics

One Unit of Proposed Technology:

One unit is taken to be a 2.8kW (peak) solar photovoltaic (PV) system installed on a house in New York State.

One Unit of Current Technology:

There are two ways to define the current technology. The first way is to consider the house to be without the solar PV system. This approach is reasonable on the basis that solar PV has such small penetration.

The second way to define the current technology is by comparison with a comparably-rated PV system that uses a competing inverter technology.

Energy savings are calculated both ways. Table 1 states the assumptions that form the basis for the comparison. The energy savings is calculated because experimental data for this specific comparison do not exist.

Table 1: Assumptions underlying benefit calculations based on data from the New York State Energy Research and Development Authority.

Description	Value	Units
Annual Residential Electricity Consumption in New York State	42.239×10^9	kWhr
Number of Households	6,766,000	
Residential Electricity Price	0.134	\$/kWhr
CO ₂ Emissions	1.2687×10^{-4}	ton/kWhr
Energy Production Per Barrel Petroleum	498	kWhr/barrel
Energy Production Per Ton of Coal	2087	kWhr/ton
Average Daily Length of Useable Daylight	10	hr
Average Percentage of Sunshine	50	%
Incremental Energy Capture Due to Partial Shading	7.5	%

Energy Savings Metrics – Comparison to No PV

Type of Energy Used	A	B	C=A-B	D	E=CxD
	Current Technology (Btu / yr / unit)	Proposed Technology (Btu / yr / unit)	Energy Savings (Btu / yr / unit)	Estimated Number of Units in U.S. by 2010 (units)	Energy Savings by 2010 (Btu / yr)
Oil / Gasoline					
Natural Gas					
Coal					
Electricity (@ 10,500 Btu / kWh)	63.536×10^6	9.881×10^6	53.655×10^6	66,100	3.547×10^{12}
Other Energy 1 (Explain)					
Other Energy 2 (Explain)					
Other Energy ...n (Explain)					
Total Per Unit	63.536×10^6	9.881×10^6	53.655×10^6	66,100	3.547×10^{12}

Energy Savings Metrics – Comparison Against A Competitive Inverter

Type of Energy Used	A	B	C=A-B	D	E=CxD
	Current Technology (Btu / yr / unit)	Proposed Technology (Btu / yr / unit)	Energy Savings (Btu / yr / unit)	Estimated Number of Units in U.S. by 2010 (units)	Energy Savings by 2010 (Btu / yr)
Oil / Gasoline					
Natural Gas					
Coal					
Electricity (@ 10,500 Btu / kWh)	51.509×10^6	53.655×10^6	2.146×10^6	66,100	1.419×10^{11}
Other Energy 1 (Explain)					
Other Energy 2 (Explain)					
Other Energy ...n (Explain)					
Total Per Unit	51.509×10^6	53.655×10^6	2.146×10^6	66,100	1.419×10^{11}

Discussion of Energy Savings:

To begin, using New York state as an example, the daily electrical energy consumed per household is 17.1kWhr. Output of the competing string inverter for an average day is $2.8\text{kW} \times 10\text{hr} \times 50\% \times 96\% = 13.44\text{kWhr}$, amounting to 4,906kWhr/year or 51.509×10^6 Btu/year. The energy output of the AEC inverter is taken to be 7.5% higher because of the increased productivity under partial shade. However, the efficiency of the AEC inverter is expected to be slightly below the 96% efficiency of the string inverter. This makes the daily output of the AEC inverter $2.8\text{kW} \times 10\text{hr} \times 50\% \times 93\% \times 107.5\% = 14.00\text{kWhr}$, amounting to 5,110kWhr/year or 53.655×10^6 Btu/year.

If a home does not have solar PV and installs a system using the AEC inverter, the total energy savings over a year is 53.655×10^6 Btu/year. If a home that already has PV replaces the string inverter with the AEC inverter, the total annual energy savings is $(53.655 \times 10^6 - 51.509 \times 10^6) = 2.146 \times 10^6$ Btu/year.

AEC's business plan for the inverter is that through 2010 cumulative sales will reach 66,100 units.

Appendix E

Proceedings of Solar 2006
American Solar Energy Society
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INCREASING THE PRODUCTIVITY OF SOLAR PHOTOVOLTAIC SYSTEMS

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ABSTRACT

State-sponsored incentives have played a significant role in driving the demand for residential and small commercial photovoltaic (PV) systems. All state incentive programs are tied to the power rating of the system, though some states also offer energy production incentives. Unfortunately, there is a disconnect between the power rating of a PV system and the energy that system produces over its lifetime. It is extremely important to consider system productivity, which goes well beyond the efficiency of the components. System productivity is tied directly to the structure of the array, not just the efficiency of the components and the quality of the installation. This paper examines the issues associated with improving solar PV system productivity. The focus is on comparing a series-parallel array configuration to a series-string array configuration and the impact on energy production. Partial shade is used to highlight substantial differences between the operation of the two array configurations.

NOMENCLATURE

T_0 Test temperature at which the parameters are obtained.
 V_{OC} Open circuit voltage (at T_0).
 I_{SC} Short circuit current (at T_0).
 k_C Temperature coefficient for short circuit current.
 k_V Temperature coefficient for open circuit voltage.
 G_0 Standard light irradiance value.
 I_L Solar cell photocurrent.
 I_D Solar cell forward diode current.
 I Terminal current provided by the solar cell.

R_S Series resistance in the solar cell model.

R_{SH} Shunt resistance in the solar cell model.

v_D Forward voltage across the diode in the solar cell model.

v_T Solar cell terminal voltage.

INTRODUCTION

State-sponsored incentives have played a significant role in driving the demand for residential and small commercial photovoltaic (PV) systems. All state incentive programs are tied to the power rating of the system, though some states also offer energy production incentives [1]. Unfortunately, there is a disconnect between the power rating of a PV system and the energy that system produces over its lifetime. This has led to a migration in system design that de-emphasizes effective energy production. Since it is the energy captured by the system that drives system payback and value to society, increasing the energy capture by a few percentage points can have a substantial positive impact.

Consideration of system productivity is extremely important. A more productive system is able to pay for itself more quickly, bringing greater economic benefit to the homeowner and better value to the agency that provided the installation incentives. System productivity goes well beyond component efficiency. It is tied directly to the structure of the array, not just the efficiency of the components and the quality of the installation.

This paper examines issues associated with improving the productivity of solar PV systems. The following section discusses different approaches to system configuration. Subsequent sections address the issues that require attention to maximize PV

Figure 1: THE SERIES-STRING ARRAY CONFIGURATION THAT LEADS TO A HIGH-VOLTAGE SYSTEM.

Figure 2: THE SERIES-PARALLEL ARRAY CONFIGURATION THAT LEADS TO A LOW-VOLTAGE SYSTEM.

system output.

SOLAR PV SYSTEM CONFIGURATION

A PV array is configured to match the voltage generated by the panels to the voltage input range of the inverter, taking into consideration multiplication factors for temperature extremes. Virtually all inverters on the market for grid tie systems accept input voltages in the range of 250 V to 600 V, though some input voltages may go lower. In the early grid tie market there were inverters that accepted much lower input voltages, in the range of 50 V to 90 V. The transition from the lower voltage range to the higher voltage range was promoted as a way of simplifying system installation. While this is true for installation only, it discounts the impact array configuration has on energy production.

A low-voltage array is created by installing many short series strings of panels in parallel. A high-voltage array would use much longer series strings of panels. Figures 1 and 2 show the differences in configuration between the high-voltage and low-voltage installations, respectively.

A low-voltage system will raise the installation cost by 1.9% for a 3 kW (dc) system to cover the cost of additional wire, a slightly more expensive disconnect, the combiner box, and the associated labor. However, this additional installation cost is more than offset by improved system productivity, as discussed in the section on productivity considerations.

Installation Issues

Some installers would prefer to install a high-voltage string array rather than a low-voltage series-parallel array. This preference is based on installation preferences that do not take into consideration energy production issues:

1. High-voltage arrays require fewer parallel connections than low-voltage arrays.
2. High-voltage arrays are marginally less expensive to install than low-voltage arrays.
3. High-voltage arrays use less wire.

Looking at these separately, the relative ease of installation is a direct result of the array voltage and required panel wiring. Since power is the product of voltage and current, a low-voltage system will need to supply more current than a comparably power-rated high-voltage array. As a result, more conductors will be needed for the low-voltage system. In addition, instead of simply daisy-chaining the panels in a series configuration, the low-voltage installer is left with a number of sub-arrays that all need to be connected in parallel. This requires the use of a separate junction or combiner box that is not needed in a high-voltage system.

The difference in installation expense between the two systems is an artifact of four clear points:

1. There are more conductors required for the series-parallel array configuration.
2. The combiner box is additional hardware not needed in the high-voltage system.
3. The dc disconnect required by the National Electric Code needs to carry a higher current rating in the low-voltage system, though it does not need to support as high a voltage.
4. The time required to pull more conductors and make more cable terminations translates into slightly higher installation labor costs.

Table 1 summarizes the incremental installation cost increase of \$544 for a 3 kW (dc) PV series-parallel array relative to a series-string array. The installed cost of the series-string array is \$29,400, so the series-parallel array is

$$\frac{\$29,400 + \$544}{\$29,400} = 1.0185$$

giving a 1.85% cost increase.

Table 1. INCREMENTAL INSTALLATION COST ADDITIONS FOR A SERIES-PARALLEL ARRAY.

Combiner Box:	\$139
Breakers for Combiner Box:	\$60
Increased Conduit Size:	\$68
Additional Wire:	\$147
Miscellaneous Fittings:	\$50
Labor:	\$80
Total:	\$544

Flexibility of Design

High-voltage strings are somewhat limiting to the designer/installer. Greater emphasis must be placed on the voltage of the series-string under all conceivable operating conditions, as open-circuit voltages go up in the colder climates. In addition, since the modules behave effectively as current sources, care must be taken to ensure that each panel in the string sees the same lighting conditions. Partial shading of a single panel will reduce the output of the entire array, a significant issue that is unavoidable for most arrays for various reasons:

1. The sun rises in the east and sets in the west, thus creating a creeping shade effect.
2. Trees tend to grow over time.
3. Birds and other animals are unpredictable.
4. Snow does not immediately or uniformly clear from panels.
5. Subsequent structures tend to be erected without regard to existing arrays.
6. Panels dispersed over multiple roof surfaces exist in a permanent condition of partial shade.

In other words, shade happens!

The inability of a series-string array to accommodate shading also makes installations on multiple roof pitches problematic as all modules do not see the same levels of irradiance, a condition akin to partial shading.

The low-voltage array is much less sensitive to shading, as non-uniform irradiance will result in a smaller percentage of panels being current limited by the offending shade. This provides more energy per rated watt over the lifetime of the system – a benefit that can easily surpass the added cost of a low-voltage system in certain installations. Following this logic, the following circumstances may indicate that a low-voltage system would be a better design choice:

1. Flat-roof installations where roof projections may present

even the slightest level of shading during the day.

2. Installations that have wires overhead, particularly if those wires attract birds.
3. Installations where rapidly growing vegetation may occasionally shade panels or shed leaves that limit panel output.
4. Installation in the proximity of future construction that may block panels.
5. Installations that must occur on east- or west-facing roof pitches instead of a south-facing pitch.
6. Installations that are spread over multiple roof surfaces.
7. Installations that experience snow.

Another aspect of design flexibility is the ability to build a system incrementally. Even with incentives, a PV system is expensive. A series-parallel array allows the system to be built with a smaller number of panels initially, thereby making PV accessible to more people. It may be possible to add panels incrementally to a series-string array, but only after a large number of panels have been used in the initial installation.

Energy Storage

A series-parallel array is more directly compatible with back-up energy storage than a series-string array. Work by others has shown that integration of energy storage can help to maximize the value of PV systems [2]. Frequently, the consumer is surprised to discover that the utility-interactive PV installation that they purchased does not provide electricity when the utility grid is interrupted.

Because a series-parallel array outputs a lower voltage than a series-string array, a series-parallel array can be configured to support the input of a charge controller that is used to regulate the voltage on a battery bank. The output of a series-string array is generally too high to efficiently convert down to the 48 V of a battery bank. An inverter with an input voltage range comparable to that of a charge controller would support the addition of battery backup in the future.

PRODUCTIVITY CONSIDERATIONS

To appreciate the significance of productivity, it is useful to understand why people choose to buy solar systems. Strictly on the basis of current-day economics, solar PV is still difficult to justify. Payback periods, without government incentives and tax credits, would be on the order of 30 years with today's equipment and electric prices. The modules would need replacing just as the system would finish paying for itself.

Even with incentives, the payback periods are still more than 10 years, a time longer than most people will remain in their current residences. So what motivates people to purchase these systems for their homes? Although a fool and his money soon part, it would take a lot of fools to drive module manufacturers to increase production capacity and support annual growth rates

in excess of 30%. There are a number of factors the typical PV consumer considers when deciding to buy:

1. Energy prices: Purchasing a PV system is a hedge against increases in fossil-fuel costs.
2. Cash flow: A \$20,000 vacation home or boat will not pay monthly dividends, however, the equivalent investment in a PV system will.
3. Home improvement: An investment in PV will increase the resale value of the home.
4. Green power: "If my electric bill is reduced each month, I am generating some of the electricity that I use. This is all green power and that makes me feel good."

The value of a PV system to the consumer is a direct result of its ability to produce electricity during daylight hours. The more energy it captures, the faster it pays for itself, and the owner's satisfaction is maximized when energy production is maximized. Until now, little effort has been made to ensure that the solar PV industry supplies systems that maximize energy production and, therefore, customer happiness. This should be corrected. The following sections discuss several performance issues that affect lifetime energy production.

Shading Issues

It might seem counterintuitive to suggest that two PV systems of comparable wattage-rating can have significantly different capacities for energy production. The confusion arises from the physical difference between power and energy. We speak of the power company, but we do not buy power, we buy energy. Energy results from power being produced over time. In that regard, it makes more sense to evaluate systems based on their total energy output, since this is the best measure of a system's usefulness.

Under shaded conditions, a PV array is not able to produce its rated power. However, confining the impact of shade to only a small section of the array will minimize the drop in array output. Shading effects are difficult to quantify because shading rarely happens under textbook conditions. Shading effects also are complicated by the maximum power-tracking algorithms used in inverters. Attempts to characterize shade are given in [3, 4].

Figures 3 through 5 show situations that are indicative of shade [5]. Figure 3 shows a PV array that is comprised of panels on multiple roof faces. This will generate an effect that is similar to shade since the panels do not see the sun from the same orientation. Figure 4 shows a similar situation where the PV array is used to form a building entry. Figure 5 shows an array that has many tall trees in close proximity that will provide diffuse shading during some portion of the day. From these three examples, it is clear that shading effects are introduced in any number of ways.

There is also significant anecdotal information about the influence of shading. Consider:

"There is a large eucalyptus tree on the neighbor's property that shades any given panel in the array for about an hour each day during the "winter." The first panels start to get shade around solar noon and shade leaves the last panels around 3 pm. The panels continue to produce power even while shaded, but only 1/3 to 1/2 the amount that they do when under direct sunlight. From about two weeks after spring equinox until about two weeks before the fall equinox, the panels were no longer shaded at any time.

The panels are arranged in a 6×6 (physical) array, with nine (series) panels in each of four (parallel) strings. When shading occurs, it first takes out 2/3 of the first string, then the remainder of the first string and 1/3 of the second string, then all of the second string. Shade overtakes the third and fourth strings in similar fashion. At the height of the shading, the entire array is in the shade. Shade clears from the panels in the same manner." [6]

While the array is completely shaded there is nothing that can be done to increase productivity (short of cutting down the neighbor's tree). However, as the array is moving in and out of shade, there is some energy that is being missed because of the long strings.

Less extreme examples are far more common: shade from trees or roof projections that nibble away at the irradiance along the outside edges of the array. This is particularly common as the sun gets lower in the sky during winter months. On our own series-string array shading 0.28% of the array caused the inverter output to drop 7.5%.

A model was used to compare the performance of two arrays under various lighting conditions. Since there are many ways shade can manifest itself, we have developed our model to apply shade to two arrays, a 20×1 series-string array and a 4×5 series-parallel array (5 paralleled strings of 4 panels in series). Each array is formed by four rows of five panels each. As a baseline comparison, Figs. 6 and 7 show the array output voltage, current, and power without shading. As expected, peak array power is the same for both array configurations. The data of Figs. 6 and 7 were generated by self-consistently solving the panel voltage-current terminal characteristics for a voltage imposed on the array. Sweeping the voltage imposed to the array simultaneously generates array currents that correspond to array voltage. Array power is the product of array current and voltage. For the simulations, the Kyocera KC158G panel is used, making the nominal rating of each array 2.5 kW. The details of the panel model are given in Appendix A.

Shading is difficult to predict and quantify. Here we consider a number of scenarios under which some panels are shaded, i.e.,

Figure 3. A SOLAR PV ARRAY CONSTRUCTED ON MULTIPLE ROOF FACES, GIVING AN EFFECT SIMILAR TO THAT OF DIFFUSE SHADING.

Figure 4. A SOLAR PV ARRAY CONSTRUCTED AS A BUILDING ENTRY, GIVING AN EFFECT SIMILAR TO THAT OF DIFFUSE SHADING.

they do not receive full irradiance. These scenarios are not intended to represent the full range of possible shading conditions. Rather, they are intended to illustrate some situations that are easy to envision and to identify the difference in potential output power between a series-string array and a series-parallel array.

The shading is assumed to be diffuse, rather than complete. Diffuse shading effectively reduces the irradiance seen by the panel, whereas complete shading would drop the irradiance to zero. Diffuse shading is by far the most common type of shading seen by PV panels; it is rare to block all of the light to the panel.

Table 2 summarizes a number of shading scenarios along with the power available from the two arrays and the percentage improvement offered by the series-parallel array. The percentage improvement is based on the global maximum of output power for each array configuration. The results show that relatively little shading can have significant impact on power production

for the PV array. Figures 8 and 9 show the output of the string and series-parallel arrays for the first shading scenario given in Table 2, respectively, and provide an example of how shading impacts the output characteristics of the array. The array characteristics are shown as the array voltage as a function of array current, along with array output power as a function of array voltage and array current. The outputs for other shading scenarios is similar in nature to those shown in Figs. 8 and 9.

It is worthy of note that partial shade creates multiple peaks in the output power as a function of voltage in the output of the series-string array. These peaks do not have the same value, so shade increases the difficulty in performing maximum power-point tracking since there are now local maxima that can trap the algorithm and prevent it from getting to the global maximum. The series-parallel array output is also impacted by shade, but not nearly to the same degree and in the same way. Figures 8 and

Figure 5. A SOLAR PV ARRAY SURROUNDED BY MANY TALL TREES THAT CREATE SHADE ON THE ARRAY DURING THE DAY.

Figure 6. MODELED OUTPUT PERFORMANCE FOR THE SERIES-STRING ARRAY UNDER UNIFORM LIGHT INTENSITY.

9 show robust maximum power-point tracking is easier with the series-parallel array than the series-string array.

Inverter Efficiency

The input voltage of the inverter can have an effect on some metrics of inverter efficiency. This is an artifact of higher input currents at the lower voltage translating into higher conduction losses. But the reality is that two different well designed invert-

ers should not vary more than 1 or 2% in efficiency. Is a 95% efficient inverter better than a 93% inverter? To the unwary consumer, the answer is "yes." To the savvy purchaser, the more likely answer is "it depends."

The difficulty in assessing inverter efficiency is that it has multiple dependencies. The most prominent system parameters that affect the inverter efficiency over its operating spectrum are inverter input voltage, inverter temperature, and operating power level. Ideally one would prefer an inverter that provides > 90%

Table 2. A COMPARISON OF POWER OUTPUTS OF SERIES-PARALLEL (4 × 5) AND STRING (20 × 1) ARRAYS UNDER VARIOUS SHADING SCENARIOS. EACH MATRIX UNDER "SHADING SCENARIO" PROVIDES THE ASSUMED IRRADIANCE FOR EACH PANEL IN THE ARRAY. THE VALUES GIVEN FOR EACH SHADING SCENARIO REPRESENT THE IRRADIANCE IN W/m^2 THAT IS ASSUMED TO BE HITTING THE PANELS. VALUES OF LESS THAN $1000 W/m^2$ ARE PANELS SUBJECTED TO DIFFUSE SHADE.

Shading Scenario						String Output (kW)	Series-Parallel Output (kW)	Series-Parallel Performance Advantage
1000	1000	1000	1000	1000		2.439	2.636	8.07%
1000	1000	1000	1000	800				
1000	1000	1000	1000	800				
1000	1000	1000	800	700				
1000	1000	1000	1000	1000		2.148	2.278	6.06%
1000	1000	800	1000	1000				
1000	800	700	800	1000				
800	700	600	700	800				
1000	800	1000	1000	1000		2.542	2.578	1.42%
1000	1000	800	1000	1000				
1000	1000	1000	800	1000				
1000	1000	1000	1000	800				
1000	1000	1000	1000	1000		2.142	2.142	0.00%
1000	1000	1000	1000	1000				
1000	1000	1000	1000	1000				
600	600	600	600	600				
1000	1000	1000	1000	600		2.285	2.624	14.83%
1000	1000	1000	1000	600				
1000	1000	1000	1000	600				
1000	1000	1000	1000	600				
1000	900	800	900	1000		1.841	1.957	6.33%
900	800	700	800	900				
800	700	600	700	800				
700	600	500	600	700				
1000	1000	1000	800	700		2.254	2.567	13.90%
1000	1000	1000	800	700				
1000	1000	1000	800	700				
1000	1000	1000	800	700

Figure 7. MODELED OUTPUT PERFORMANCE FOR THE SERIES-PARALLEL ARRAY UNDER UNIFORM LIGHT INTENSITY.

Figure 8. THE AVAILABLE OUTPUT FROM THE SERIES-STRING ARRAY FOR THE FIRST SHADING SCENARIO OF TABLE 2.

efficiency over all operating powers and operating temperatures. Unfortunately, most inverter manufacturers specify efficiency as the highest value they can measure. While the California Energy Commission requires a weighted average of inverter efficiency,

there is no guarantee that the consumer will see that efficiency. A 95% efficient inverter might only provide 88% of the available power from the array over most of its typical operating spectrum of input voltage and power. Therefore, more emphasis must

Figure 9. THE AVAILABLE OUTPUT FROM THE SERIES-PARALLEL ARRAY FOR THE FIRST SHADING SCENARIO OF TABLE 2.

be placed on the efficiency spectrum associated with variations in input voltage and power rather than the manufacturer's rated peak efficiency. To put it in perspective, a 96% efficient 2500 W inverter generates 100 W of heat losses. This value is comparable to an incandescent light bulb. So if losses are limited to 100 W over the entire operating range, why did the manufacturer put such a large finned heat sink on the enclosure?

The consumer can make better choices if inverter manufacturers provided efficiency curves that characterize performance across a spectrum of usage. Just as automobiles rarely live up to their EPA mileage rating, every inverter should carry the caveat "Your efficiency may vary." Further, an inverter with a higher peak-efficiency rating than another inverter may not necessarily always provide higher efficiency under similar conditions. In other words, just because the efficiency is higher at one set of operating conditions does not imply that the efficiency is always higher.

Beyond the issue of inverter efficiency are all of the other factors of system design and implementation that affect energy capture. There are a number of places beyond the inverter where power can be lost. A list of these factors is given at [8], where the default derating factors for conversion from dc into ac give a 16.3% reduction in power *before* the inverter efficiency is even considered. Clearly there is a lot of room for improvement in system performance beyond that of the inverter.

SUMMARY

Our industry has gravitated toward solar PV systems based on high-voltage series-string arrays, due in large part to limitations in technology available in the past. Over the past several years, a number of competitors have entered the market with similar products, likely motivated by a rapidly expanding market. This paper shows that there are inherent limitations to high-voltage series-string arrays that make them less-than-ideal in a variety of installation scenarios. The effects of random shading and inverter efficiency on lifetime energy production have been shown, suggesting that the current emphasis on inverter efficiency, while valid, is perhaps a much less important issue than shading and lifetime energy production. If the goal of the solar PV industry is to maximize the return on investment for solar energy, it is critical to look more closely at the effects of shading and non-ideal system siting. Low-voltage PV systems based on series-parallel arrays offer greater productivity in diffuse partial shade, as well as providing other positive attributes, such as compatibility with battery back-up and a smaller initial number of panels for systems built incrementally.

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Figure 10 A STANDARD ELECTRICAL CIRCUIT MODEL OF A SOLAR CELL. THE STRUCTURE OF THE PANEL MODEL IS THE SAME.

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Appendix A: A Solar Panel Model

A circuit model for a solar cell is shown in Fig. 10, where I_L represents the current generated by exciting the cell with light. The other circuit components model the losses and nonlinearities of the cell. More information about modeling solar cells and panels is given in [7].

A panel is comprised of an array of solar cells. Aggregating

Table 3 PARAMETERS OF THE KYOCERA KC158G SOLAR PANEL.

V_{OC}	28.9 V
I_{SC}	7.58 A
k_C	6.08 mA/C
k_v	-0.11 V/C
G_0	1000 W/m ²
T_0	47 C

Table 4 CALCULATED MODEL PARAMETERS FOR THE KC158G PANEL.

R_S	424 m Ω
I_S	15.843 nA
I_L	7.7137 A

the behavior of cells is rather complex, particularly when bypass diodes are taken into consideration. We can expect through aggregation that the model will retain a similar structure, with a few changes. For example, the effective diode $v-i$ characteristic will change substantially because there are now a large number of diodes connected in series and parallel. The current sources also will add to create a larger current, and the series resistances will add in series and parallel as the panel model is formed.

For the simulations, the Kyocera KC158G panel is used. The panel parameters, taken from the KC158G data sheet, are given in Table 3.

Due to the nonlinear nature of the panel model, the panel parameters are solved numerically. Table 4 summarizes the results.

The data of Table 2 was generated by using the panel model for each of the 20 panels in the array. Each panel had its own irradiance as given in the table. The outputs of each panel were aggregated according to the array structure to determine the peak available output power. In the model, we assume each panel is uniformly illuminated even when shaded. This approach is justified since very little shading is required to affect panel output. The data given in Table 2 assume that each panel is at a temperature of 25 C.

Appendix F

Advanced Energy Conversion
Putting Power to Work

ecoJoule 2800

Overview

The ecoJoule inverter from Advanced Energy Conversion, LLC (AEC) is designed to provide an easy interactive interface to the electric utility for solar photovoltaic systems.

The ecoJoule is designed to take the direct current (DC) provided by the photovoltaic panels, and deliver the energy to the alternating current (AC) utility. Using patent pending technology, the ecoJoule maximizes the energy output of the solar panels (MPPT). It does this while making use of a high frequency isolation transformer that helps to keep the ecoJoule compact and lightweight.

The ecoJoule is designed to provide maximum system flexibility because of its low input voltage and internal transfer switch. Low input voltage inverters extract more energy from partially shaded arrays than string inverters do, thereby providing increased energy output every day. Because of the internal transfer switch, the ecoJoule can be configured to support:

- Utility-interactive systems.
- Utility-interactive systems with battery backup for critical loads. Battery charging is handled with a (separate) charge controller.
- Grid independent systems that may be tied to the grid at some point in the future.
- System expansion in the future, through the addition of more panels or battery backup.

An LCD display on the unit allows you to monitor the performance of the inverter. With optional temperature, wind and solar power sensors, you can also monitor the performance of an entire solar photovoltaic system. All of the data collected by the inverter can be downloaded to a computer through a network port.

Designed and built in the USA, the ecoJoule is both ecological and economic, helping you make the most of renewable energy.

System Configurations

Standard Grid-Tie:

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Grid-Tie with Battery Backup:

Off-Grid:

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Specifications

Parameter	2800UI Value
Output Power	2.8kW
Output AC Voltage	240V (RMS) single phase; split phase with autotransformer; 208V
Output AC Current	11.7A (RMS)
Output Frequency Range	59.5-60.5Hz
Input DC Voltage Range (Peak Power Tracking)	60-90V
Maximum Input DC Voltage	130V
Maximum Input DC Current	55A
Warranty	10 years
Operating Temperature Range	-20C—50C (-4F—122F)
Enclosure	NEMA 3R (IP22)
Ease of Installation	2 keyed holes, 2 round holes, all visible from the front
Display on Inverter	Display Standard
Communications and Data Collection Options	Network Computer Interface Standard Inputs for pyranometer, cell temperature sensor, ambient temperature sensor and wind speed indicator.
Flash Memory	Remotely upgradeable
Certifications	UL1741, FCC
Other Standards	IEEE 1547
Efficiency	93%
Cooling	Internal Fan (runs only when needed)
THD	<3%
Size	14" x 24" x 4.5" (Width x Height x Depth)
Weight	12.71kg (28lb)
Ground Fault Protection	Standard
Surge Protection (AC Side)	Standard
Surge Protection (DC Side)	Standard
Product Lifetime	25 years
Price	\$2800 MSRP

Specifications are subject to change without notice.

Features

Inverter features include:

- 2.8kW of output power.
- High frequency transformer isolation.
- Low weight.
- High efficiency.
- Temperature activated cooling system.
- Surge protection for both AC and DC with indication.
- Integral display and keypad reporting 13 standard (plus 5 optional) indicators of inverter (system) performance.

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ecoJoule 2800

- Integral network data interface to a computer reporting 14 standard (plus 6 optional) indicators of inverter (system) performance.
- Certified to UL1741, FCC.
- Compliant with IEEE 1547.
- NEMA 3R rain proof enclosure.
- 10-year limited warranty.

System information available from the display and computer interface includes:

- Output power (kilowatts)
- Output AC current (Amps)
- Output AC voltage (Volts)
- Inverter input power (kilowatts)
- Inverter input DC current (Amps)
- Inverter input DC voltage (Volts)
- Inverter efficiency (%)
- Time of Day (12 Hour, AM/PM format)
- Energy (kWh) captured to date
- Energy (kWh) captured today
- Energy (kWh) captured yesterday
- Incident input solar power (Watts/meter²: requires optional pyranometer)
- Ambient temperature (°C or °F: requires optional temperature sensor)
- Solar panel temperature (°C or °F: requires optional panel temperature sensor)
- Avoided CO2 emissions to date (kg: 115g/kWh)
- Total Savings (\$)
- Wind Speed (requires optional anemometer)
- Wind Direction (requires optional wind vane)
- Energy (kWh) captured each day for the last month (through Ethernet interface only)
- Solar PV panel efficiency (%: through Ethernet interface only, requires optional pyranometer and panel temperature sensor)

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Output Waveforms

Inverter output
waveforms at
2.5kW.

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Pictures

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