Energy Research and Development Division
FINAL PROJECT REPORT

DAVIS ENERGY GROUP PV INDIRECT-DIRECT EVAPORATIVE COOLING

Prepared for: California Energy Commission
Prepared by: Davis Energy Group

DECEMBER 2007
CEC-500-2013-071

DAVIS ENERGY GROUP
INCORPORATED

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ACKNOWLEDGEMENTS

Davis Energy Group expresses particular appreciation to Bruce Vincent of the Sacramento Municipal Utility District for his origination, support, and guidance of this project. Joe McCabe of the California Energy Commission and the PIER ReGen Advisory Committee also offered helpful guidance in early stages of the project. Special thanks are due to Steve Brennan, a Senior Engineer at the Davis Energy Group, whose tireless efforts to complete this project became more and more essential as unforeseen events kept extending the project schedule. Thanks are also due to the following individuals, without whose participation this project could not have proceeded to completion:

- Si Hyland and Covington Stanwick of the Speakman Co., CRS Division
- Bill Archer of the General Electric Company
- Kale Wisnia and Katherine Reon, site owners
- Cliff Murley and Hector Ortiz of SMUD
- Kerry Hartsough of Beutler Heating and Air
- Rick Lavezzo of Team Solar

Dick Bourne, Principal Investigator

Davis Energy Group

Please cite this report as follows:

Bourne, Dick. 2006. *PV Indirect-direct Evaporative Cooling*. California Energy Commission, PIER Renewable Energy Technologies Division. CEC-500-2013-071.

PREFACE

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PV Indirect-direct Evaporative Cooling is the final report for the SMUD ReGen project (Contract Number 500-00-034), conducted by Davis Energy Group. The information from this project contributes to Energy Research and Development Division's Renewable Energy Technologies program.

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ABSTRACT

Residential cooling systems contribute significantly to California's high electricity costs. Indirect-direct evaporative cooling systems can save energy, reduce peak demand for electricity, and can be powered by relatively small photovoltaic arrays. This project initiated the commercialization of a new method for cooling a home. The project installed, monitored, and evaluated two photovoltaic/indirect-direct evaporative cooling systems in Sacramento, California. One system inverted all photovoltaic output to alternating current power, with all indirect-direct evaporative cooling system power drawn from the house system. The intent of the other system was to allow indirect-direct evaporative cooling system operation from both alternating current and direct current power to eliminate inverter losses when photovoltaic output and cooling loads aligned. However, incorrect photovoltaic system implementation prevented direct current operation. Monitoring data showed that neither photovoltaic array was large enough to fully drive its associated indirect-direct evaporative cooling unit during peak cooling. Further, the indirect-direct evaporative cooling units provided marginally adequate cooling in the inefficient buildings used for the tests. This project created enhanced awareness of photovoltaic/evaporative cooling systems and identified how to configure them for maximum impact.

Keywords: Solar, photovoltaic, indirect-direct evaporative cooling systems, IDEC

EXECUTIVE SUMMARY

Introduction

Residential cooling systems contribute significantly to California's high electricity bills and peak demand shortages. Introducing a cost-effective, energy-efficient home cooling system that satisfies homeowner comfort requirements and removes cooling energy demand from the electrical grid would be a valuable contribution to California's energy efficiency goals. Indirect/direct evaporative cooling (IDEC) systems can provide adequate residential cooling with much lower energy consumption than conventional air conditioning systems. IDEC systems can operate from photovoltaic (PV) arrays with a rated capacity of one kilowatt (kW) or less and can be designed to use direct current (DC) power directly from a PV system without an inverter.

Project Purpose

This project applied PV power to the new "OASys" indirect-direct evaporative cooling system. The system was developed by the Davis Energy Group with California Energy Commission/PIER funding support, and was licensed to the Speakman Company of New Castle, Delaware. The OASys indirect-direct evaporative cooling system uses a General Electric (GE) electronically commutated motor to deliver up to 90 percent energy savings compared to conventional air conditioning**.** The two units in this project were the first two OASys field installations.

The overall project goal was to lay the groundwork for creating a new market for PVs and to explore the possibility of using air conditioning as a peak-load driver. Specific objectives included:

- Obtaining a direct current-operated indirect-direct evaporative cooler.
- Installing working alternating current (AC) and direct current (DC) PV/ indirect-direct evaporative cooling demonstration projects.
- Monitoring and evaluating the demonstration projects and reporting the results.

The first two objectives were modified early in the project. A DC-operated IDEC unit could not be obtained because a suitable DC motor was not commercially available and the necessary Underwriters Laboratories (UL) testing for the unit was beyond the scope and budget of the project. An all-dc system would not use the valuable excess PV power generated during non-cooling months and parts of many summer days. The cost savings associated with an all-DC PV/ indirect-direct evaporative cooling system were inadequate to justify the lost value of unused PV electrical generation.

Consequently, the project team decided on two new approaches, both of which allowed full indirect-direct evaporative cooling regardless of solar input, and also used all PV-generated electricity:

- A basic system with all PV output inverted to AC, and all indirect-direct evaporative cooling power drawn from the house AC system.

- A new category of AC system with an additional component that allowed the indirect-direct evaporative cooling electronically commutated motor to seamlessly merge "direct-dc" power from the PV array with AC power from the house grid when needed.

The second innovative approach facilitated a smaller PV array by eliminating inverter losses when PV output and cooling loads aligned. A smaller PV array had the advantage of being less expensive and easier to site on a house roof. Another project goal was to evaluate the performance and relative economics of these two alternatives.

Project Results

Key results from this project included:

- Evaluated various motor technologies and selected an efficient electronically commutated motor.
- Initiated the development work for an entirely new category of residential air conditioning systems.
- Designed and installed a first-of-its-kind DC-powered IDEC unit. Unfortunately, improper PV implementation and lack of UL-certification for a prototype component prevented operation of this unit in its direct-DC-powered mode.
- Designed, installed, and tested a prototype AC-powered IDEC unit.
- Developed and tested an AC/DC IDEC unit. Made significant enhancements to the unit, including improving the design to make it less susceptible to higher supply-air static pressures, improving the control features, and improving the water distribution system to reduce maintenance and increase system lifetime.
- Developed and tested a new concept with a diode combiner box.
- Tested and demonstrated air-distribution approaches for use with the new indirect-direct evaporative cooling units.
- Designed an IDEC unit with a GE electronically commutated motor that could deliver up to 90 percent energy savings compared to conventional air conditioning. Some of these units may be installed in future demonstration projects in Sacramento.
- Designed PV systems to power the evaporative coolers.
- Designed and demonstrated the first-ever coupling of PV and indirect-direct evaporative cooling.
- Developed installation criteria for the new IDEC units related to both mounting systems and the design of air-distribution systems.
- Installed a new standing-seam sheet metal roof that could accommodate photovoltaic systems with minimal installation difficulties.
- Evaluated a range of IDEC installation options to determine interior placement locations that generated effective performance yet hid the IDEC units from the building exterior

and occupied interior. This result was significant because it will help overcome the widely-held notion that evaporative coolers are oversized and difficult to integrate aesthetically.

- Implemented the first two AC/DC IDEC units in two demonstration projects.
- Operated and monitored the PV/ IDEC units in AC mode for an entire summer.
- Developed a knowledge base that will facilitate the correct sizing of future PV/ IDEC installations.
- Transferred the technology to the Speakman Corporation, which will explore commercial possibilities for PV/ IDEC systems.
- Evaluated the ability of PV/ indirect-direct evaporative cooling systems to eliminate AC loads from the grid, although further work on maintaining comfort conditions is needed.

The project team believed that PV/IDEC technology is an option for fully removing residential cooling loads from the electrical grid based on the experience gained in this project. The results of this project laid the groundwork for developing a fully commercialized system capable of eliminating residential cooling loads on the grid. Speakman was taking the first step in this direction by beginning manufacturing of the OASsy units. A key lesson learned in this project was that typical residential cooling loads extended into the evening beyond PV power availability even with west-facing PV arrays. Few homeowners will be satisfied with cooling systems that cannot deliver cooling after 7:00 p.m.

IDEC units can significantly reduce residential cooling energy use and demand even without a PV power source. IDEC systems can reduce peak demand and energy consumption by more than 85 percent[1] when installed in appropriate configurations in new California homes. In addition, an IDEC unit costing $3,000 to $3,500 (including installation costs) was less expensive than a PV system sized to supply it, which cost $3,500 to $5,000 (including installation costs, and after rebates were applied).

PV has proven to be marketable despite longer paybacks compared to energy efficiency measures. The project team believes that an affordable PV/IDEC system might resonate with buyers who are interested in making an environmental statement while at the same time reducing their cooling bills. “Bragging rights” deriving from a “zero energy cooling” label might help drive both IDEC system and PV sales.

The size of the market has not been determined. Integrated PV/ IDEC systems are not commercially available, comparative economics have not been developed, and neither reliability nor first costs have been projected or compared. Additional studies are necessary to compare the system versions before supporting further technical development work.

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[1]. Final Report, “Development of an Improved Two-Stage Evaporative Cooling System,” DEG to the Energy Commission, March 2004.

The project team's recommendations include:

- Continue development of a PV/ IDEC system to create a reliable, cost-effective system that will be attractive to homeowners.
- Complete, monitor, and evaluate prototype installations of the new designs.
- Determine the market potential for the new technology in the residential retrofit and new construction market sectors based on the results of the evaluation process.
- Evaluate and compare alternate PV/ IDEC cooling versions.
- Solicit further development of promising PV/ indirect-direct evaporative cooling systems.

Project Benefits

The potential benefits of PV/IDEC implementation are significant. A cost-effective PV/IDEC system that delivers homeowner comfort and exerts no draw on the electrical grid could eliminate the need for a large new power plant every year if applied to all new California homes. Savings on new generation and distribution equipment could cover the added cost of PV/IDEC systems compared to conventional air conditioning.

Chapter 1: Introduction

1.1 Background and Overview

Residential cooling systems contribute significantly to California's high electricity bills and peak demand shortages. Residential cooling loads, with a 7 percent load factor (Brown and Koomey), are among the worst loads imaginable from the electric utility perspective. Up to 200,000 new housing units are completed in California each year and, in the hotter climate zones, almost all are equipped with compressor-based air conditioning systems with air-cooled condensing. With respect to electrical demand, this is the largest appliance in the home. Many existing, older homes that were originally built without compressor-based air conditioning add such systems every year. Clearly, the introduction of a cost-effective home cooling system that provides adequate indoor comfort and exerts little demand on the electrical grid would be extremely valuable to California's energy future.

Indirect-direct evaporative cooling (IDEC) systems have demonstrated their ability to satisfy residential comfort requirements with much lower energy consumption than comparable conventional cooling systems. They add less moisture to indoor air than direct evaporative coolers and their low energy usage suggests the possibility of completely removing cooling loads from the electrical grid by powering them with photovoltaic (PV) arrays. They can create opportunities for using PV-generated electricity in a more efficient manner by directly applying DC power. This efficiency gain is valuable as the PV array is relatively expensive compared to other system components. The primary energy consumer in an IDEC unit is the blower motor. While all available IDEC units use AC motors, use of a DC motor could eliminate the inverter for the PV system, with DC power from the PV array sent directly to the IDEC unit.

This project, with partial funding from the California Energy Commission and the Sacramento Municipal Utility District (SMUD), began the development of a new market for PV and IDEC by investigating the coupling of small photovoltaic systems to a new generation of IDEC designs. The project completed preliminary work on products for a new PV market that will eliminate peak-period air conditioning loads from the utility grid. The project began the evaluation of systems that can fully or partially remove cooling loads from the grid with relatively small PV arrays. The project applied a new cooling system called OASys, developed by the Davis Energy Group (DEG) and produced by the Speakman Company of New Castle, Delaware. This IDEC technology uses an efficient, variable-speed motor to deliver cooling at up to 90 percent energy savings compared to a conventional air conditioner. The reduction in peak electrical demand is expected to be similar. The two units in this project were the first two OASys field installations. Others have been installed since, and the reference list at the end of this report includes several other reports on OASys field performance. The endnotes also include other sources of information about past and current IDEC designs.

Since cooling loads may not perfectly align with PV power output, the consequences of expected misalignments were carefully considered in project design. Design Issues included the following:

- When PV output exceeds the power draw required by IDEC cooling operation, should the excess PV output be used elsewhere, and if so, how?

- When PV output cannot fully satisfy IDEC needs, should AC power be used as well, and if so, how?

This project evaluated blower motors for the OASys units and selected a General Electric (GE) variable-speed electronically commutated motor (ECM). All other motors failed to meet the needed performance criteria. Concurrent with the start of this project, Speakman CRS and GE worked together to develop a simple "diode combiner box" that enables the ECM motor to accept either un-inverted DC power directly from a PV array, or AC power that is rectified in the diode box. With this box, the IDEC can seamlessly blend DC and AC power as necessary. For this project, DEG and SMUD designed and implemented installations for two PV-coupled OASys units in adjacent houses on a single-owner lot in Sacramento. One was equipped with the diode box and an inverter, and the other had only an inverter. These units were monitored to evaluate the performance and relative economics of coupling PV to low energy cooling systems that run on either AC power alone or AC and DC power.

1.2 Project Objectives

The project contract[2] references SMUD's Request for Proposals (RFP) to define objectives and the statement of work. SMUD's "RFP 2511.DL" stated the project goal to be **"Lay the groundwork for creating a new market for PV and begin to address air conditioning as a peak-load driver."** The RFP listed the following five objectives:

- Obtain a DC-operated indirect-direct evaporative cooling unit.
- Complete a demonstration project with 115 Vac PV and a 115 Vac evaporative cooling unit.
- Complete a demonstration project with 115 Vac/48 Vdc PV and a 48 Vdc evaporative cooling unit.
- Monitor and evaluate the demonstration projects.
- Prepare a final report.

During the project several objectives changed slightly because it was not possible to obtain a DC-operated IDEC unit. An exhaustive search failed to locate a suitable blower motor and, at the time of project initiation, one may not have existed. Instead, both IDEC units in the project used the General Electric ECM motor. It can be driven from both 115 Vac and 300 Vdc power sources and has several other advantages that have made it the motor of choice for the

[2]. SMUD Professional Services Contract No. 4500016527, October 31, 2002.

subsequent prototype units produced by Speakman. The selection of the GE motor affected the first objective and the third objective.

1.3 Report Organization

Section 2 discusses strategies used to complete this project and Section 3 discusses project outcomes. Section 4 presents our conclusions and recommendations based on the completed work. Section 4 also summarizes our views on the commercialization potential of PV/IDEC technologies, and the benefits to California, both directly from this work and, over time, from successful commercialization of these technologies.

Chapter 2:
Project Approach

2.1 Project Organization

Davis Energy Group (DEG) was the prime contractor for the project, and was responsible for all project activities, except that SMUD was responsible for the PV design and installations. Speakman CRS, a division of the Speakman Company of New Castle, Delaware, provided two beta-version "OASys" IDEC units for the project. A GE division in Fort Wayne, Indiana, provided assistance with development of the diode box that allows seamless merging of DC and AC power to operate the OASys motor. Beutler Heating and Air of Sacramento installed the two IDEC units at the project site. SMUD contracted with Team Solar of Sacramento for installation of the PV arrays.

The project schedule was extended largely due to delays with the PV installations. The two IDEC units were installed in the spring 2004, but as the first field-installed units of the OASys design, they also went through a "shakedown period" at the site. DEG installed IDEC monitoring components by mid-2004 and commissioned the PV monitoring components in early August 2005.

2.2 System Design and Installation

2.2.1 Site Descriptions

Both IDEC units are located at a single residential site in Sacramento, California. The front or "large" house (Figure 1) is an older two-story unit and the back or "small" house (Figure 2) is a newer carriage house with a large garage and a smaller two-story apartment with a living room, kitchen, and bath downstairs, and a large sleeping room upstairs.

Figure 1: Front (main house) referred to as the "large" house

Photo Credit: Davis Energy Group

Figure 2: Back or "small" house before placement of PV arrays

Photo Credit: Davis Energy Group

2.2.2 IDEC systems

The cooling system featured in this project is the two-stage IDEC designed by Davis Energy Group and built under the "OASys" trade name by the Speakman CRS Division of the Speakman Company of New Castle, Delaware. The original design for this product was developed by DEG beginning in 1991. Previous iterations of the design used a sheet metal enclosure with the blower and electronics mounted below the sump and evaporative stages. These older units often suffered failures when water migrated into the motor electronics and controls. The new units feature a one-piece rotationally-molded plastic enclosure, sump and blower housing, with the blower and electronics mounted at the top of the unit (see Figures 3 and 4) and carefully sealed to prevent moisture migration. Many features, including all control strategies, were retained and further developed for the current design. The resulting product is a high-efficiency, two-stage, indirect-direct evaporative cooler with advanced control algorithms to minimize mineral buildup. Appendix A provides OASys specifications and lab test data. The project OASys units used ¾ and 1 hp motors for the small and large houses, respectively.

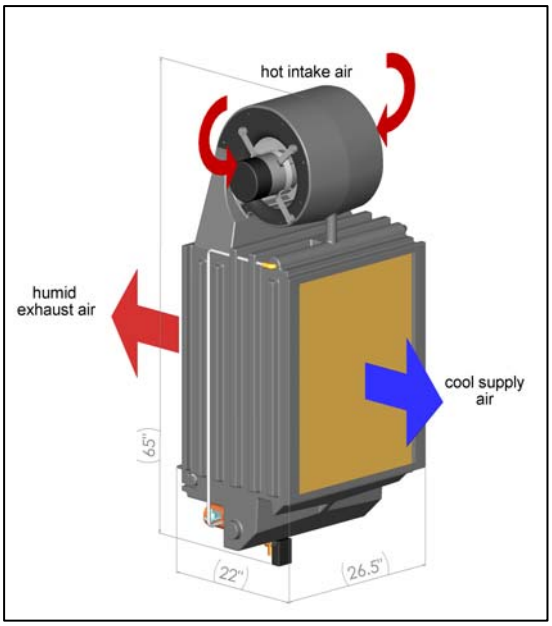

Figure 3: OASys airflow schematic

Photo Credit: Davis Energy Group

Figure 4: OASys unit for interior mounting

Photo Credit: Davis Energy Group

To overcome the widely-held notion that evaporative coolers are oversized and difficult to integrate aesthetically, the project team evaluated a range of IDEC installation options and found interior placement locations that generate effective performance yet hide the IDEC units from both the building exterior and occupied interior.

The "large house" IDEC unit is located in an upstairs closet (Figure 5) and delivers unducted air into the major stairwell. When the IDEC unit is operating it pressurizes the house; exhaust air leaves the house through open windows controlled by the owners. The second IDEC unit is located in what was the garage area of the small house (Figure 6), with supply air delivered through ductwork to both floors. House exhaust air leaves through open upstairs windows. Figures 5 and 6 show the units in their "most visible" condition, before final plenum and duct connections were made.

Since the large house is uninsulated and has large single-glazed windows, DEG warned the owners at the outset of the project that the IDEC on that house might not maintain comfort in hot-weather conditions. Neither house is equipped with conventional air conditioning.

Figure 5: Large house IDEC in closet

Photo Credit: Davis Energy Group

Figure 6: Small house IDEC in garage

Photo Credit: Davis Energy Group

2.2.3 Direct-DC Design

In the context of this project, the term "direct-DC" meant delivering photovoltaic (PV) power directly to a DC motor in an IDEC unit. The project considered the following two potential paths for direct-DC viability:

- An IDEC unit with a DC motor and pump, not connected to the grid, and a PV system without inverter or battery. With this design approach:
    - The IDEC can only deliver as much cooling as PV output allows.
    - Installed cost is lower than that of the second path (immediately below).
- An IDEC unit with an electronically commutated motor (ECM), connected directly to the PV system and to a household AC circuit, and a PV system installed with an inverter for grid connection. With this design approach:
    - The IDEC cooling unit can draw whatever power is necessary, combining available DC power from the PV array with additional AC power if necessary to satisfy cooling loads.
    - PV power in excess of any needed to satisfy cooling loads can be delivered into the building and utility grid to maximize the value derived from the expensive PV system.
    - The system cannot guarantee fully "off-grid" cooling.

The work statement suggested only the first of these two paths but after much effort early in the project, it became apparent that no advanced IDEC unit could be obtained or modified with a suitable DC motor. The early "OASys" IDEC units developed by Speakman CRS used an ECM from GE. As part of this project, Speakman demonstrated that, with the addition of a custom-designed diode box, the selected ECM could seamlessly merge AC and DC power if the DC power was supplied in the 300 to 400 volt (V) range. This success facilitated both of the two direct-DC project paths described above. Speakman decided that they would not pursue UL-listing of the diode box in the immediate future due to cost considerations. As a result, the project team decided:

1. To pursue the second path instead of the first because it would leave the owner of the two demonstration projects with a code-approved system after project completion, and
2. To evaluate direct-DC operation based on a one-day test with the diode box in place. Conclusions regarding viability of the direct-DC mode could then be extrapolated with the short-term test data.

2.2.4 PV Systems

To maintain the original appearance of the south-facing street-front of the large house, both PV systems were installed on the small house. The owners worked with SMUD to have a standing-seam metal roof installed on the small house prior to PV placement. The metal roof allowed selection and demonstration of a UniSolar building-integrated PV (BIPV) array to serve the large house. The UniSolar PV strips were bonded directly to the south-facing metal roof between the standing seams, as shown in Figure 7.

Figure 7: Uni-Solar PV array serving large house

Photo Credit: Davis Energy Group

The project also located, analyzed and demonstrated a mounting system for conventional PV modules on a standing-seam sheet metal roof. The "First Solar" PV array for the small house

was placed on the upper, west-facing roof section, in part because inadequate south roof remained after dedication of the lower south roof for the Uni-Solar array. In addition, since the small house system was chosen for the direct-DC experiment, the time lag between solar input and resulting cooling loads suggested a greater opportunity for direct PV delivery with a west-facing array. Figure 8 diagrams the "First Solar" PV panel design, and Figure 9 is an edge-on view of the panels mounted on the standing seams. First Solar panels were chosen because they were used by Speakman in their testing of the "seamless transfer" diode box (see Section 1.1), and because they were stocked by SMUD.

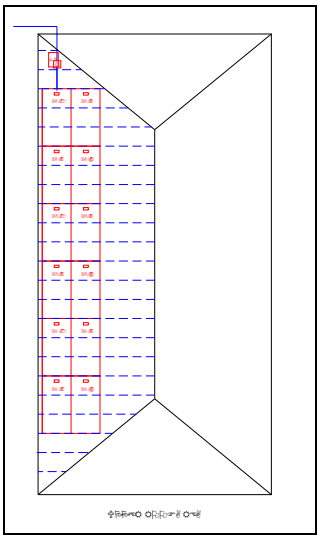

Figure 8: Diagram of first solar PV panels on upper west-facing roof

Photo Credit: Davis Energy Group

Figure 9: First solar PV array on upper west roof serving small house

Photo Credit: Davis Energy Groupv

The UniSolar array for the large house was coupled with a Xantrex 1500 inverter with internal hardware that controls output from parallel PV strings. The First Solar panels for the small house were installed with a SMA Sunnyboy 1100 inverter and accessory SMA "Combi-box" that controls the parallel strings. Because the experimental diode box is not a UL-listed component, it was not left in operation. The First Solar panels were disconnected at the Combi-box and connected directly to the diode box for one set of tests to evaluate direct-DC operation. Figure 10 shows both inverters and Table 1 provides comparative data on the two PV systems.

Figure 10: Switches and Inverters

Photo Credit: Davis Energy Group

Table 1: PV Systems

Feature	Large House	Small House
Location	Lower roof	Upper roof
Orientation	South	West
Supplied to IDEC	AC only	AC and DC
PV Brand	Uni-Solar	First Solar
PV Type	Amorphous Si	CdTe thin film
Surface Area, sq. ft.	144	96
Rated Watts	744	600
Inverter	Xantrex 1500	SMA 1100

Data collected by Dick Bourne

2.3 Project Monitoring

DEG developed a monitoring protocol for the project that tracked the performance of both IDEC and PV systems. The detailed monitoring plan was included with the Interim Monitoring Report[3] for this project. Since the IDEC units were installed well in advance of the PV systems, the IDEC monitoring components were used for more than a year before completion of the PV monitoring components.

2.3.1 IDEC Monitoring

The IDEC monitoring system was installed in March 2004. Each IDEC was equipped with a panel that contained a DT50 datalogger and a US Robotics modem. The following data points were recorded for each IDEC:

- Date and time.
- Outdoor dry bulb temperature and relative humidity.
- Indoor dry bulb temperature and relative humidity.
- Supply air dry bulb temperature.
- Sump water temperature.
- Energy and water consumption.
- Fan motor RPM (small house only).

[3]. "PV/IDEC Interim Monitoring Report," DEG deliverable No. 3.7.2.3 for this project.

Both modems were connected to a line-switching device at the phone box and a single business line was installed for downloading monitoring data.

2.3.2 PV Monitoring

DEG modified the IDEC monitoring systems to capture PV performance when the PV systems were installed. These modifications included the addition of power meters between the inverters and the disconnect boxes to record the energy generated by each array. DEG engineers also installed current transducers and voltage reference taps in the disconnect box. The meters were installed in a separate enclosure with the transducer and voltage tap wires run through flex conduit. Another power meter was added at the main panel to monitor power consumed in the big house.

Data Analysis Approach

DEG computers automatically downloaded data after midnight each night via modems connected to the DEG database reserved for this project. The data were stored and subsequently compiled and downloaded into an Excel spreadsheet for later analysis.

2.4 Project Schedule and Operational Issues

The original project schedule called for completion of all tasks by the end of 2004, but delays in the delivery and installation of the PV systems caused the project to extend through summer 2005.

2.4.1 IDEC Operational Issues

Although the IDEC units had been thoroughly lab-tested, several operational issues arose after the units were installed and commissioned in spring 2004. These issues did not surface until the cooling season began, as the units sat idle for several months of mild spring weather in 2004. The systems went through several weeks of troubleshooting to resolve water delivery and control problems. The original water distribution manifolds developed problems with uneven distribution and, in midsummer 2004, DEG replaced them with a new "permeable tube" design from Speakman. This design ultimately clogged from hardness minerals and DEG engineered a new manifold design in early 2005, replacing the manifolds at the PV/IDEC project again in May.

The new manifolds have worked well, but the circulating pumps also needed to be changed with the manifolds to maintain proper flow rates. Accomplishing the changes was particularly difficult at the large house where the IDEC unit's placement in an upstairs closet allows very limited access for service.

One control issue was associated with a new float switch used to maintain sump water level. DEG replaced the switches with an alternate design when it became clear that failures could occur due to impurities in the water and misalignment during installation. DEG also modified the sump overflows to prevent routine loss of water. Further control problems arose with apparent malfunctioning of the thermostats. DEG ultimately found that the installers had run staples through the thermostat wires for the big house, and that the "quick-connect" head on the thermostat wire for the small house was not crimped correctly.

The customer ultimately reported that both IDECs were working well, although the unit in the big house has proven to be undersized for the peak cooling loads.

2.4.2 PV Installation Issues

Between April 2004 and June 2005, the IDEC units were operating but the PV arrays were not yet installed due to a United States shortage of the specified UniSolar panels. PV shortages are currently widespread in the United States due to high demands for PV in Germany and Japan. Many American and foreign PV manufacturers have sold large portions of their production to Germany to fulfill the demand created by the 70 percent cost sharing offered by the German government.

2.4.3 Integrated System Operational Issues

Despite considerable care with the specification of the PV array for the small house, where DEG planned to test the direct-DC approach, the installed PV system did not deliver adequate voltage to drive the IDEC unit in a direct-DC mode. As a result, power to the diode box from the AC connection always overrode the DC supply from the PV. DEG was forced to draw conclusions about the direct-DC option based on performance data from product data sheets rather than field data. (See Section 3.4 for a discussion of direct-DC viability.)

Chapter 3:
Project Outcomes

3.1 General Outcome Overview

Summary of outcomes, successes, and innovations:

- Designed an IDEC unit with the GE ECM to deliver up to 90 percent energy savings compared to conventional air conditioning. This unit is now in prototype production by the Speakman Corporation and some of these IDEC units will be installed in demonstration projects in Sacramento in 2006.
- Completed the installation of PV systems and prototype IDEC units at a site in Sacramento.
- Demonstrated a BIPV system for standing-seam metal roofs.
- Demonstrated a mounting process for conventional PV modules on a standing-seam metal roof.
- Operated and monitored the units for an entire summer.
- Developed a knowledge base that will allow future PV/IDEC installations to be correctly sized.
- Developed installation criteria for the new IDEC units, related to both mounting systems and the design of air-distribution systems.
- Accomplished technology transfer to the Speakman Corporation. Speakman sees commercial possibilities for PV/IDEC systems and is evaluating the further development of this technology.

Summary of Innovations and Technology Development:

- Exhaustively evaluated existing DC motors for use in a possible all-DC IDEC.
- Further designed and developed the AC/DC IDEC.
- Implemented the first two AC/DC IDEC units in two demonstration projects.
- Debugged IDEC design and made significant improvements in 2004 and 2005.
- Developed and tested an innovative design diode combiner box.
- Developed and tested the AC/DC IDEC unit. Improved the design to make it less susceptible to higher supply-air static pressures. Improved the unit's control features. Improved water distribution and pumping system in the unit.
- Tested and demonstrated air-distribution approaches for use with the new IDEC units.
- First-ever coupling of PV and IDEC-design and demonstration.

- Evaluated the ability of PV/IDEC systems to eliminate AC loads from the grid (further work on maintaining comfort conditions may be needed.)

3.2 Indirect-Direct Evaporative Coolers

As the first beta installations of a new product, the two advanced IDEC units underwent an extensive in-the-field "shakedown" period to sort out operational problems. This was necessary given the significant differences between the field installations and the laboratory test configuration used in the only prior OASys operational testing. The field-test experience was useful in identifying design flaws and opportunities for improving the OASys product which is slated for a 200-unit prototype production run in 2006. The most valuable data for IDEC performance were collected between June and mid-September 2005 when the IDEC units operated with the final water manifold design.

Despite some operating problems, the new OASys unit clearly overcame many problems experienced by the prior IDEC units of a similar design. Placing the blower and electronics above the evaporative heat exchangers eliminated the potential for water leakage to damage expensive system components, and the rotationally-molded polymeric cabinet eliminated cabinet leakage and corrosion. The rear exhaust-air location has eliminated the opportunity for debris to enter the top when the unit is not operating, but this new feature was not of value in these "interior-mount" installations.

The final monitoring report[4] provides detailed data and monthly summaries for IDEC operation. Table 2 provides summary operating data for both systems for July 2005.

[4]. "PV/IDEC Final Monitoring Report," DEG deliverable No. 3.7.2.4 for this project.

Table 2: IDEC summary data—July

Parameter	House	
	Large	Small
Avg outdoor air temp °F	79.1	77.0
Avg. indoor air °F (at t'stat)	77.1	74.9
Avg. indoor RH (%)	65.0	62.1
Avg. supply air temp °F	66.3	66.3
Avg. hr/day operation	13.9	21.3
Total cooling kBtu	NA	7214
IDEC energy use, kWh	310	418
Avg. IDEC EER	NA	17.3
Total water use, gal	2133	2381
Avg. water use, gal/hr	4.96	3.60

Data collected by Dick Bourne

The occupants operated the two systems quite differently. The tenant in the small house operated the IDEC sporadically through June and early July, when he began operating the unit in Auto mode all day and in Fan mode at night. This near-continuous operation resulted in an average of 21.3 hr/day in July (as seen in Table 2) and 19.3 hr/day in August. By comparison, the owners (occupying the large house) averaged 13.9 hr/day IDEC operation in July and 12.4 hr/day in August. Even these lower totals are much higher than seen in prior IDEC monitoring. For example, the 1994 results from two similar IDEC units in Sacramento showed an average 3.5 hr/day operation,[5] though the monitoring period was later, spanning August and September. Two factors influencing the high IDEC usage were:

1. Poor building shells in both houses.
2. A July weather pattern featuring unusually warm nights and the highest number of cooling degree days ever recorded for a July in Sacramento.

The extended operating hours for this project indicate either high cooling loads or lower-than-expected IDEC performance at these homes. The longest operating cycles at the small house reflect its lower average indoor temperatures as seen in Table 2, in comparison to those of the large house. The tenant in the small house set the thermostat in the mid-70s, causing long IDEC operating times. The property owners, living in the large house operated the unit in Auto mode

[5]. *IDEC Development Project Final Report,* from DEG to the Energy Commission, Appendix B p. 17, May 18, 1995.

during the day and occasionally in Fan mode at night. Despite the fact that the IDEC unit was too small to meet the peak cooling load, they operated it many fewer hours compared to the small house, and thus used less energy. The large house IDEC unit also used less water compared to the small house IDEC unit in all months monitored.

A calculated average EER is only available for the small house.[6] The 17.3 Btu/Wh monitored average EER (see Table 2) for July is lower than expected and only about twice the typical average EER for conventional air conditioning, when duct losses are included, as they already are for the IDEC system. By comparison, two 1994 IDECs averaged 47 Btu/Wh,[7] and lab tests of the OASys unit showed a 41 EER in the "ducted, high speed" configuration.[8] A check of the small house IDEC unit in August indicated that high supply-duct pressure drop was causing too much exhaust air, so DEG constricted exhaust flow to increase the supply flow. This adjustment did improve performance and likely increased the EER in subsequent operation. It is probable that the average EER was higher at the large house, where the average indoor temperature was higher and supply air pressures were lower, increasing the cooling rate and cooling capacity of the IDEC unit.

Both IDEC motors drew more electrical power than expected. In the laboratory tests completed prior to the installations for this project, power at high blower speed was 498 watts (W). The ¾ hp IDEC motor at the small house was identical to that used in the lab test, yet the monitoring system recorded IDEC unit demand at almost 800 W at high speed. At the large house, where the motor size was 1 hp, peak blower demand reached almost 1 kW. At an installation in Magna, Utah, similar to the (¾ hp) small house in this project, the peak IDEC demand on high speed did not exceed 450 W. Unreported OASys test results at the National Renewable Energy Laboratory (NREL) suggest that high downstream pressure drop can significantly increase blower energy use and peak power demand. The production OASys version will use an improved blower design and dampered exhaust path that should be less susceptible to severe flow reduction with increased supply side pressure drop.

3.3 PV Array Output vs IDEC Energy Demand

Neither PV array installed at the site proved to be large enough to fully drive its associated IDEC unit during peak cooling operation. Based on monitoring performed by DEG, SMUD initiated an evaluation of the PV systems and identified several problems which are being corrected. In particular, a careful site inspection showed that two trees were partially shading the PV arrays. Figures 11 and 12 show graphs of IDEC power consumption and PV output on a late summer day (September 1, 2005), with outdoor high temperature of 95°F, in the big and

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[6]. The narrow stairway prevented measurement of supply airflow and calculation of EERs for the large house IDEC unit

[7]. *IDEC Development Project Final Report.*

[8]. Final Report, "Development of an Improved Two-Stage Evaporative Cooling System", DEG to the Energy Commission, March 2004.

small houses, respectively. Note that in both cases, the energy consumed by the IDEC units is much greater than the energy generated by the PV systems.

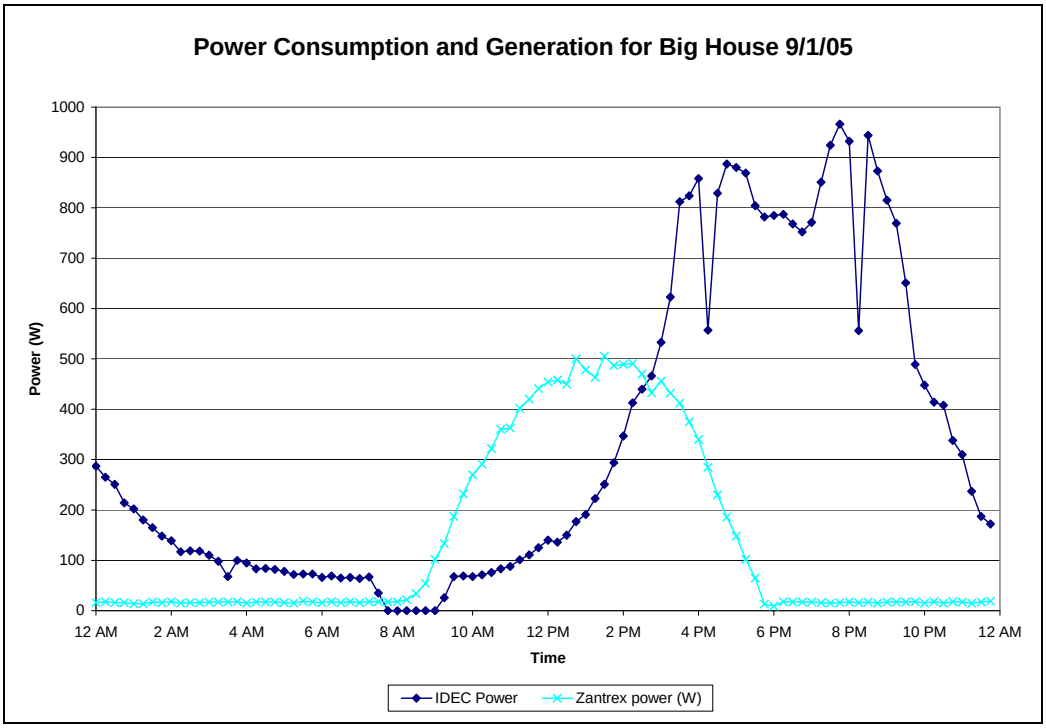

Figure 11: Big house energy comparison

Photo Credit: Davis Energy Group

For the day shown, the PV array generated 81 percent of the daily cooling power requirement, but generated zero output concurrent with the 8 p.m. peak cooling load. The key question is, what is the appropriate PV sizing for a given house? To fully offset the peak cooling load is not possible for the large house, with its delayed cooling load pattern. See Section 3.5 for further discussion of the sizing question.

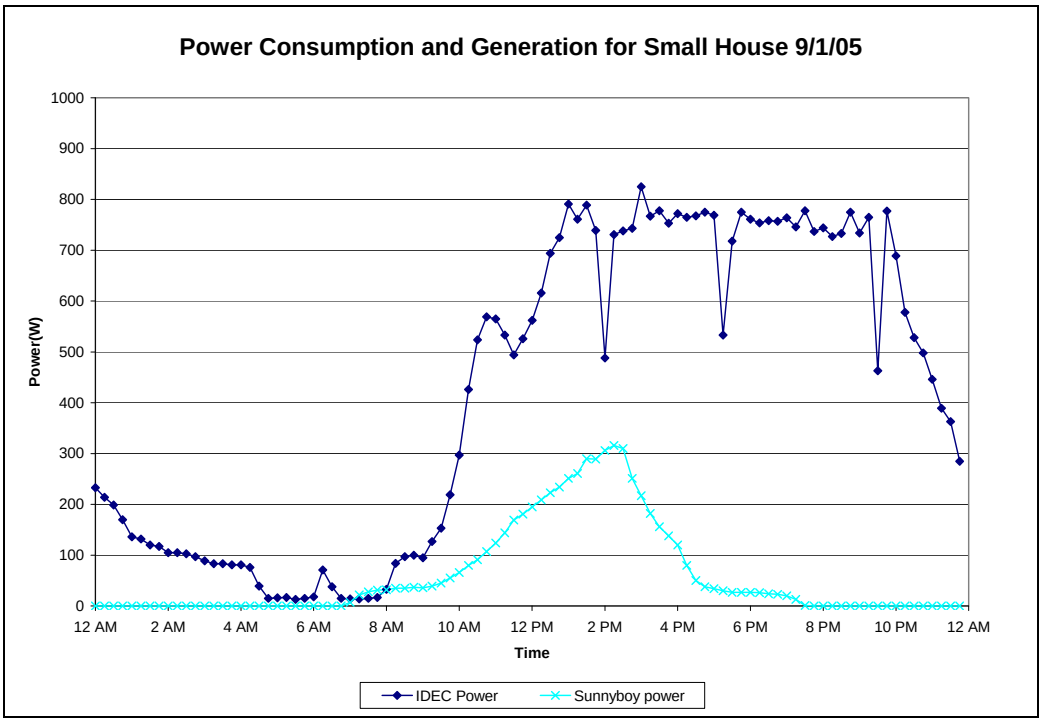

Figure 12: Small house energy comparison

Photo Credit: Davis Energy Group

As the figures show, the difference between IDEC energy used and PV energy supplied is greater in the small house than in the large house. Table 3 provides quantitative data supporting this outcome. For the one-month comparison period shown, the large house derived more than 80 percent of its IDEC energy use from PV, compared to less than 20 percent for the small house. This significant difference is likely due to a combination of the following:

- The output of the west-facing PV array serving the small house was much lower than expected due to module problems and local tree shading.
- The large house has unducted IDEC supply, while the small house has ducted supply. The supply ductwork appears to be reducing the airflow rate and therefore the IDEC cooling capacity, and at the same time increasing IDEC energy use.
- The occupant of the small house ran the unit at a relatively high speed as a fan on most nights, apparently not understanding that it can deliver a significant amount of air at much lower energy consumption at a lower fan speed setting.
- The occupant of the small house maintained a much lower thermostat setting than did the owners occupying the large house.

Table 3: PV/IDEC summary data

Parameter	House	
	Large	Small
PV brand	Uni-Solar	First Solar
Inverter brand	Xantrex	Sunnyboy
Monthly totals (8/9 thru 9/7)		
PV kWh output	100.2	42.9
IDEC kWh consumption	124.3	223.2
% from PV	81%	19%
Daily peak comparison (9/1)		
PV Watts output	505	316
IDEC Watts consumption	966	825
% from PV	52%	38%
Daily balance comparison (9/1)		
PV kWh output	3.33	1.43
IDEC kWh consumption	8.1	10.1
% from PV	41%	14%

Data collected by Dick Bourne

3.4 Direct-DC Viability

The "small house" PV array supplying the temporary GE/Speakman diode box at the project site did not supply adequate voltage to override the rectified power from the grid. The PV array consists of three 360 V strings at "open circuit" rating but, under load, the output only reaches 195 V, which can directly drive the motor by itself, but will always be overridden if the rectified AC power is connected to the diode box at the same time. Rewiring the strings for higher voltage was not justified because the non-UL diode box could not be left in permanent operation.

However, calculations support the value of the direct-DC connection. Relative efficiencies of the AC and DC options depend on relative losses in the inverter and the diode box. The 93 percent inverter efficiency on this project means 7 percent inverter losses. By comparison, the measured diode box losses are less than 0.5 percent, so direct-DC operation facilitates at least a 6 percent efficiency improvement. On average, the PV array can thus be 6 percent smaller for equal output. In this context, the best way to assess the value of the diode box is to compare its

installed cost to that of the saved PV area. For a 1 kW peak array that supplies 800 W through the early afternoon, 6 percent of the array is 60 W; at $5/W incremental installed cost for the array, the diode box is justified if its installed cost is less than $300. A $300 price is clearly achievable, particularly if integrated with other electronics and the inverter in the IDEC unit.

3.5 Displacing Cooling Load

One primary project goal was to demonstrate a combined PV and IDEC system that removes cooling loads from the grid. This desirable result was not achieved in this project, largely because on both houses, significant cooling loads occur after daily solar input has ended. Even on the small house with its west-facing PV array, PV output peaks in the early afternoon and ends by 7 p.m. (clock time) on the longest summer day (June 21). On a 90°F September 1, the IDEC units drew at least 400 W until 10:30 p.m. in the big house and 11:30 p.m. in the small house. For these homes, it is not possible to fully displace the cooling loads using the PV/IDEC combination unless batteries are used to store daytime PV output for later use. The PV array and batteries could be adequately sized to satisfy the peak daily cooling load.

While this project did not fully displace cooling loads from the electrical grid, it may be possible to do so without batteries on other buildings in other climates. Figure 13 below shows a more typical expected case than either of the two houses from this project. This plot combines a more typical house cooling load pattern with an unducted IDEC unit that performs according to the laboratory results, supplied by a PV array that actually achieves 700 W peak output. In this case, the PV supplies more than enough power to cover the total daily cooling load, although the load is delayed several hours later than the PV output profile.

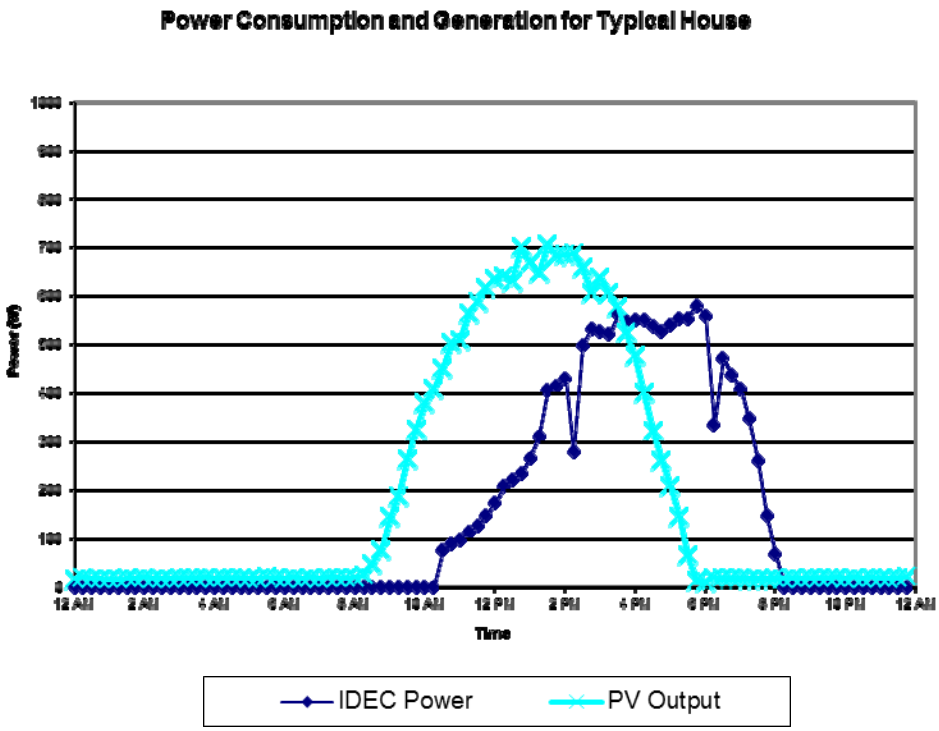

Figure 13: Typical house energy comparison

Photo Credit: Davis Energy Group

But how could such a system be configured to guarantee a "zero grid impact" cooling system? Only the direct-DC option, without an AC connection to the IDEC unit, can promise the desired result. The cooling unit could be operated only when PV power is available to pre-cool the house, coasting through the end of the cooling load period with a slight increase in indoor temperature.

Is there a large potential market for such a system? Perhaps- it depends on the flexibility of the occupants. But there is the danger that most buyers willing to pay for a PV installation will want to have cooling available whenever there are cooling loads. Typical homes are low in mass and thus may experience noticeable temperature rises during summer conditions when the cooling unit turns off. For such homes, the third (and preferred) path to fully removing cooling loads from the electrical grid appears to be an "all dc" PV/IDEC system that incorporates batteries. Further evaluation of this option appears valuable, but is beyond the scope of the current project.

Residential construction using insulated concrete walls or other massive building components could conceivably eliminate the need for batteries in the direct-DC approach. The added mass would substantially reduce the temperature rise after cooling operation ends. Dow's "T-Mass" pre-cast wall system is gaining attention for its range of benefits; an R&D project that considers the potential combination of PV, IDEC, and T-Mass to eliminate residential cooling loads could generate valuable data. One such project is underway as an element of the Building America Program,[9] but the Borrego Springs, California, project location experiences such hot summers that vapor compression cooling is also being provided for the test home.

[9]. The project by Clarum Homes includes four test houses, slated for completion in 2006; two homes have cooled floors and IDEC units. Contact Davis Energy Group for additional details.

Chapter 4:
Conclusions and Recommendations

4.1 Conclusions

The authors have drawn the following key conclusions related to the original project objectives:

- Obtain a DC-operated indirect-direct evaporative cooling (IDEC) unit:

  This objective was achieved by purchasing an IDEC unit with a variable speed, electronically commutated motor that can, in conjunction with an experimental "diode box," accept both AC and DC power. Since the diode box was not a "listed" component, it could not be left in operation at the project site. The project team's conclusion with respect to this objective is that a useful DC-powered IDEC unit is not yet available, but can be in the near future.

- Complete a demonstration project with 115 volt (V) AC PV and evaporative cooling components:

  This objective was achieved by installing a Speakman CRS "OASys" IDEC unit in conjunction with a south facing roof-integrated "UniSolar" PV array. However, the PV array did not fully displace the cooling loads because cooling loads extend into the evening beyond the availability of PV output.

- Complete a demonstration project with 48 volt DC PV system with 115 volt AC inverter and a 48 volt DC evaporative cooling unit:

  This objective was not achieved for reasons enumerated in this report. The project did install a Speakman CRS "OASys" IDEC unit with an experimental diode box in conjunction with a west-facing roof-mounted "First Solar" PV array. Our conclusion regarding this DC combination is that, if such a system is to be marketed, it is crucial that the PV array be properly designed for the site and for compatibility with the IDEC motor. Hopefully, a limited number of PV/IDEC kits could be organized for applicability to all roof configurations.

- Monitor and evaluate the demonstration projects:

  This objective was achieved by monitoring the IDEC units at both demonstration sites through most of the 2004 and 2005 summers, and by monitoring the full systems including PV components through the 2005 summer. Monitoring indicated that the new IDEC unit is clearly superior to prior models, but additional work is required to better define how it should be applied in ducted systems. Our significant conclusions based on the monitoring results are conveyed in Section 4.2 below.

- Prepare a final report:

  This objective is achieved through submittal of this report.

4.2 Commercialization Potential

Based on experience gained in this project, PV/IDEC technology is an option for fully removing residential cooling loads from the electrical grid. The results of this project lay the groundwork for developing a fully commercialized system capable of eliminating residential cooling loads on the grid. Speakman is taking the first step in this direction by beginning manufacture of the OASys units. A key lesson learned in this project is that even with west-facing PV arrays, residential cooling loads often extend into the evening beyond PV power availability. Some homeowners will not be satisfied with cooling systems that cannot deliver cooling after 7 p.m. Therefore, we see the following as the most promising PV/IDEC versions for commercialization:

- Version 1: An "off-grid" version that combines a DC-driven IDEC with a PV array and batteries. The IDEC would be sized to satisfy the maximum cooling load, and the PV+battery set would be sized to satisfy the daily load on the peak day.
- Version 2: An integrated version that includes an IDEC powered by an electronically commutated motor (ECM), an onboard electronics package that includes an inverter and can seamlessly merge AC and DC power, and a compatible PV array that can directly deliver power to the IDEC motor when solar energy is available.
- Version 3: Version 2 plus batteries and utility-controlled switching devices that select "off-grid" battery mode during peak summer weather sequences, and return to "normal" inverter mode for all other operating conditions.

Versions 1 and 3 are most attractive to electric utilities because they clearly remove the cooling load from the electrical grid. From the customer standpoint, Version 1 has the liability that it cannot use or sell PV electricity generated in excess of amounts needed to satisfy cooling loads. A liability for Versions 1 and 3 is that the batteries are costly, have energy losses, and require periodic replacement. Version 2 does not guarantee removal of cooling loads from the grid; in fact, it uses the grid as a battery. However, in this version, the PV would counter cooling loads during summer midday hours that extend well into peak load periods. Demand-responsive rates will affect economics, but until PV captures a significant portion of the residential market, the bottom line may favor Version 2, especially as inverter efficiencies improve. However, the combined value to utilities and homeowners of Version 3 may justify its added costs for batteries and switching controls.

A key observation is the extent to which IDEC units can reduce residential cooling energy use and demand even without a PV power source. Installed in appropriate configurations in new California homes, IDEC systems can reduce peak demand and energy consumption by more than 85 percent.[10] An IDEC unit (at $3,000 to $3,500 installed) is less expensive than a PV system sized to supply it (at $3,500 to $5,000 installed).

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[10]. Final Report, "Development of an Improved Two-Stage Evaporative Cooling System," DEG to the Energy Commission, March 2004.

While logic suggests that an investment in PV to further reduce cooling load impacts might better be placed in another IDEC unit, PV has proven to be marketable despite longer paybacks compared to energy efficiency measures. Thus, an affordable PV/IDEC system might resonate with buyers looking to make an environmental statement while reducing their cooling bills. "Bragging rights" deriving from a zero energy cooling label might help drive both IDEC and PV sales.

But how large is the market? Additional research is warranted in response to this question. And if the market is sizable, which of the three PV/IDEC versions should it be? No integrated PV/IDEC system is yet available; comparative economics have not been developed, and neither reliability nor first costs have been projected or compared. Potential utility support is another unknown. All versions have potential appeal to a zero energy cooling market; two have more immediate appeal to electric utilities, and the other offers greater overall energy savings. Additional studies are warranted to compare the system versions before supporting further technical development work.

4.3 Recommendations

Based on the conclusions above, we recommend the following further research activities regarding PV/IDEC systems:

- Complete a professional market research study to assess whether the availability of PV/IDEC systems would increase sales of both PV and IDEC equipment (time: 3-6 months).
- If market research shows favorable prospects, engage a contractor to evaluate and compare the three PV/IDEC versions (time: six to nine months). Results should compare the relative losses of inverters and storage batteries respectively and the relative economics of the three versions.
- Based on comparisons of the three versions, decide whether and how to solicit further development of promising PV/IDEC systems that can significantly reduce the impact of residential cooling systems on California's electricity supply systems.
- If "high mass" construction techniques such as concrete walls gain a foothold in the new residential marketplace, evaluate the potential for direct-DC PV/IDEC systems to satisfy full cooling loads without batteries.

4.4 Benefits to California

4.4.1 Benefits from the Project

The key immediate benefit from this project is enhanced awareness of a new way to cool a home using PV/IDEC systems. A secondary benefit is how a PV/IDEC system must be configured for maximum favorable impact. The potential benefits of PV/IDEC implementation are significant. A cost-effective PV/IDEC cooling system that delivers homeowner comfort and exerts no draw on the electrical grid, if applied to all new California homes, could eliminate the need for a new large power plant every year, and savings on new generation and distribution

equipment could cover the added cost of PV/IDEC system as compared to conventional air conditioning.

This project also clarified that these PV/IDEC systems cannot fully remove residential cooling loads from the electrical grid unless batteries are used to bridge the time gap between the end of daily PV power availability and evening cooling loads. Purely "off-grid" PV/IDEC cooling, even with batteries, has the liability that it cannot use the valuable PV output available in excess of that needed for cooling loads. However, a "hybrid" PV/IDEC system could include both batteries and an inverter, thereby offering the benefits of both off-grid and grid-connected systems. Without batteries, there is substantial potential for zero energy cooling systems that achieve a balance between PV output and cooling energy consumption on a peak day, peak month, or annual basis.

4.4.2 Benefits from Successful PV/IDEC Technology

Residential cooling loads, at a 7 percent load factor (Brown and Koomey), are one of the worst loads imaginable from the electrical utility perspective. A cost-effective cooling system that satisfies homeowner comfort requirements and exerts no draw on the electrical grid would be extremely valuable to California's future. If the state continues to average 200,000 new homes per year, each typically requiring 3 to 4 kW in a peak cooling event, full PV/IDEC coverage on new homes could eliminate the need for a 500 MW power plant every year, with associated savings in air pollution. And, if new generation and distribution equipment (considering diversity) costs $1,000/kW, the $4,000 savings per home might substantially pay the incremental cost of the PV/IDEC system. Thus, the potential benefits of widespread PVC/IDEC implementation are quite significant.

Broad implementation of PV/IDEC systems will:

- Reduce peak demand growth.
- Reduce the need for capital investment in new generation equipment.
- Increase electricity distribution reliability by reducing peak day loads.
- Reduce dependence on non-renewable energy sources, thereby stabilizing energy prices and increasing statewide energy security.
- Reduce energy costs for ratepayers by eliminating cooling expenses from monthly energy bills.
- Improve indoor air quality during the summer months.

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GLOSSARY

AC	Alternating current
BIPV	Building Integrated PV
DC	Direct current
DEG	Davis Energy Group
ECM	Electronically commutated motor
EER	Energy Efficiency Rating
GE	General Electric
kW	Kilowatt (1000 Watts)
IDEC	Indirect-direct evaporative cooling
NREL	National Renewable Energy Laboratory
PIER	Public Interest Energy Research
PV	Photovoltaic
RD&D	Research, development, and demonstration
RFP	Request for proposals
SMUD	Sacramento Municipal Utility District
W	Watt
V	Volt