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ELECTRIC VEHICLE/PHOTOVOLTAIC TEST
AND EVALUATION PROGRAM

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ABSTRACT

The University of South Florida (USF) in collaboration with Florida utilities and other organizations have executed a research and development program for the test and evaluation of Electric Vehicles. Its activity as one of 13 U.S. Department of Energy (DOE) Electric Vehicle Test Site Operators was funded by DOE and the Florida Energy Office (FEO). The purpose of this program was to determine the efficiency of electric vehicles under commuter and fleet conditions in Florida. An additional feature of this program was the development of a utility interconnected photovoltaic (PV) system for charging electric vehicles with solar energy.

USF developed an effective and economical automated on board Mobile Data Acquisition System (MDAS) that records vehicle operating data with minimum operator interface. Computer programs were written by the USF team to achieve processing and analysis of the vehicles' MDAS data, again minimizing human involvement, human effort and human error. A large number of passenger cars, vans and pickup trucks were studied. Procedures for monitoring them were developed to a point where the equipment is commercially available and its operation has become routine.

The nations first PV solar powered electric vehicle charging station and test facility was designed, developed and put into operation under this program.. The charging station is capable of direct DC-DC (PV to battery) or AC-DC (power grid to battery) charging and it routes unused PV power to the University's power grid for other use. The DC-DC charging system is more efficient, more dependable and safer than DC-AC-DC and traditional methods of DC-DC charging. A fortuitous correlation was observed between battery charging demand and solar power availability in commuter application of electric vehicles.

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Section 1

INTRODUCTION

The University of South Florida (USF) in collaboration with Florida utilities and other organizations have executed a research and development program for the test and evaluation of Electric Vehicles. Its activity as one of 13 U.S. Department of Energy (DOE) Electric Vehicle Test Site Operators was funded by DOE and the Florida Energy Office (FEO). The purpose of this program was to determine the efficiency of electric vehicles under commuter and fleet conditions in Florida. An additional feature of this program was the development of a utility interconnected photovoltaic system for charging electric vehicles with solar energy. This system consists of a twelve bay parking facility equipped with roof mounted photovoltaic panels. These panels not only provide power for charging, but also help protect vehicles from damage caused by solar heat and UV radiation.

OBJECTIVES

The main program objectives were:

1. Gather data relating to the performance of electric vehicles under actual commuter and fleet conditions.
2. Determine public acceptance of electric vehicles through questionnaires and personal interviews with the drivers.
3. Determine the specific regional vehicle maintenance requirements through the use of daily operation and maintenance logs.
4. Evaluate battery performance as a function of vehicle range and driving conditions.
5. Determine typical vehicle ranges for commercially available electric vehicles during commuter and fleet operations.
6. Evaluate the effect of an air conditioner on electric vehicle range and performance.
7. Determine the best role for photovoltaic systems in charging electric vehicles.
8. Determine the technical feasibility and economic advantages of returning the extra power generated by the photovoltaic system to the utility power grid.

VEHICLE INVENTORY

The vehicles under test consisted of commercially available electric cars, trucks, vans and a bus. These vehicles were located throughout Florida and used in varied driving and charging cycles.

MOBILE DATA ACQUISITION SYSTEM

USF developed an effective and economical automated on board Mobile Data Acquisition System (MDAS) that records vehicle operating data with minimum operator interface. The Mobile Data Acquisition System (MDAS) has been used in this project to measure the main battery pack voltage, current, and temperature as well as velocity and cab and ambient temperatures in twenty test electric vehicles.

SOFTWARE DEVELOPMENT

Computer programs were written by the USF team to achieve processing and analysis of the vehicles' MDAS data, again minimizing human involvement, human effort and human error..

Analysis of the data collected was performed using the electric vehicle analysis software program EV-SOFT and the new alternative fuel vehicle software AFV-SOFT. The software imports vehicles' binary data and converts them to the standard format. Once this is done, EV-SOFT/AFV-SOFT analyzes the data, provides both detailed and summary report outputs, displays data in graphical formats on the computer screen or prints it on the printer. Summaries can be generated over a range of the records thus giving the totals over a month, quarter or up to a year.

DATA COLLECTION AND ANALYSIS

Performance data for all the vehicles monitored since the development and deployment of MDAS systems were collected and analyzed.

Manually recorded data correlating speedometer with charge energy meter readings were collected throughout the program.

PHOTOVOLTAIC SOLAR POWER

A unique feature of this program is the use of photovoltaic arrays to charge the electric vehicles. The nations first PV solar powered electric vehicle charging station and test facility was designed, developed and put into operation under this program. Solar charging may be done directly or via the University's power grid with the choice depending on the time correlation of charging power need and solar power availability.

PROJECT PARTNERS

Federal: U.S. Department of Energy, National Renewable Energy Laboratory, Naval Weapons Center
State: Florida Energy Office, U. of South Florida (Electrical Engineering Department and Center for Urban Transportation Research)
City: City of Tampa
County: Hillsborough County Environmental Protection Commission
Private: Florida Power Corporation, Tampa Electric Co., GTE Mobilnet, Florida Power and Light Co.

Section 2

VEHICLE INVENTORY

The vehicles under test consisted of commercially available electric cars, trucks and vans.

Eight electric vehicles were purchased with funds received from the Department of Energy, with cost sharing by Tampa Electric Company, Florida Power Corporation, the Florida Energy Office, Hillsborough County and the City of Tampa. Six of these electric vehicles were located at the University of South Florida and operated under the guidance of the Department of Electrical Engineering. Two were located in downtown Tampa and operated by Tampa Electric Company and the Hillsborough County Environmental Protection Commission respectively. These electric cars were tested in both "commuter" type and fleet type environments. Additional electric vehicles were acquired and operated by Florida Power Corporation and data from these operations were included in a common data base with those of the University of South Florida. These vehicles all operated in the Tampa-St. Petersburg metropolitan area. The map in Figure 2-1 shows the approximate locations of their stations.

Eight additional operators contributing to the data base in Florida were located in the Counties of Alachua, Volusia, Pinellas, Dade, Polk, Duval, Brevard and Orange. The map in figure 2-2 indicates the locations of these stations.

Table 2-1 lists the vehicles monitored, their location, model and status.

Arrows designate locations where Electric Vehicles are placed for testing in the Tampa Bay Area.

COUNTIES WHERE ELECTRIC VEHICLES
HAVE BEEN PLACED FOR TESTING IN FLORIDA

Figure 2-2

VEHICLE DOE# USF#		VEHICLE LOCATION AND MODEL	DATE MDAS INSTALLED	PRESENT STATUS OF VEHICLE
650	G01	UNIV. of SOUTH FLORIDA GMC PASSENGER VAN	FEB 1993	Vehicle not operational since end of 2nd quarter of 1996
651	G02	UNIV. of SOUTH FLORIDA GMC PASSENGER VAN	FEB 1993	Vehicle not operational due to motor failure, MDAS removed
652	S01	UNIV. of SOUTH FLORIDA CHEVROLET S10 PICKUP	FEB 1993	Vehicle operational Data being collected
653	S02	UNIV. of SOUTH FLORIDA CITY OF TAMPA	FEB 1993	Vehicle operational, MDAS working. Noisy charger is causing faulty charge readings.
654	M01	UNIV. of SOUTH FLORIDA MITSUBISHI MIRAGE	AUG 1994	Vehicle operational, Breaks modified, Testing continues, MDAS working
	SOL	UNIV. of SOUTH FLORIDA GEO FORCE by SOLECTRIA	AUG 1993	Vehicle totaled due to accident (October 23, 1994).
655	S3	CLEARWATER CHEVROLET S10 PICKUP	APR 1993	Vehicle totaled due to fire (October 22, 1993). Not to be repaired
656	S4	GAINSVILLE CHEVROLET S10 PICKUP	AUG 1993	Vehicle not operational Data not being collected
657	S5	JACKSONVILLE CHEVROLET S10 PICKUP	SEPT 1993	Vehicle operational, Data being collected, vehicle getting very little use.
658	S06	HILLSBOROUGH COUNTY CHEVROLET S10 PICKUP	MAY 1993	Vehicle operational, Data being collected, Received data for very few days.
659	S7	ORLANDO CHEVROLET S10 PICKUP	DEC 1993	Vehicle not operational Battery Pack status unknown, No immediate plans
660	S8	VOLUSIA COUNTY CHEVROLET S10 PICKUP	JAN 1994	Vehicle not operational due to bad battery pack
	S9	MIAMI CHEVROLET S10 PICKUP	AUG 1993	Vehicle not operational problem unknown
	S10	HAINES CITY CHEVROLET S10 PICKUP	DEC 1993	Vehicle lost due to controller failure. (Not to be repaired), Withdrew from program
	FP1	ST. PETERSBURG CHEVROLET S10 PICKUP		Vehicle operational, very little usage Data not being collected
	FP2	ST. PETERSBURG CHEVROLET S10 PICKUP		Vehicle operational, very little usage Data not being collected
	SL1	TAMPA CHEVROLET S10 PICKUP	DEC 1995	Vehicle operational, Data being collected, Received data for very few days.

Table 2-1. Inventory and Status of Vehicles Monitored by USF

Section 3

MOBILE DATA ACQUISITION SYSTEM (MDAS)

One of the tasks of the USF PV-EV project team was the collection of performance data from all participating electric vehicles (EV's). To this end, USF developed an effective and economical automated on board Mobile Data Acquisition System (MDAS) that records vehicle operating data with minimum operator interface.

The MDAS was specifically designed for installation in electric and alternative fuel vehicles. That is, the system was built to operate under harsh industrial environmental conditions with a broad range of users. Such a system must normally operate under conditions of high moisture, dirt, vibrations, temperature variations and electrical noise.

The human interface also played an important role in the design of the MDAS thus the system is as transparent to the user as possible; there is only one user input to the basic MDAS, the reset button.

The Mobile Data Acquisition System (MDAS) was used in this project to measure the main battery pack voltage, current, and temperature as well as velocity and cab and ambient temperatures in seventeen test electric vehicles.

The first MDAS with the custom designed chassis was installed in a Chevy S10 at the University of South Florida (USF) in December of 1992. Since then many improvements in software and hardware components of the system have been implemented so that the MDAS is now truly an integrated system tailored for use in electric and alternative fuel vehicles.

Sensors were designed to measure the high current and voltage of EV's with an emphasis on safety. Equally important in designing for electric vehicle data acquisition is non-interruption of vehicle operation; in no way can the properly installed MDAS impede normal vehicle operation, even under a catastrophic failure.

The MDAS has been developed to a point where it is now commercially available and its operation is routine. It is manufactured and marketed by Sigma TecSystems, Inc. of Tampa, FL under a license from USF.

Section 4

SOFTWARE DEVELOPMENT

A series of data analysis programs, defined analysis procedures, utility functions and network organization were developed. The heart of this system was the data analysis program. An analysis program named EV-SOFT was developed and efficiently used. Several versions of the program were released (major versions were 2.2, 2.3 released in 1993, and 2.5 released in 1994.) with every new version offering new analysis functions. EV-SOFT is DOS based. In 1995 we released a fully redesigned new program named AFV-SOFT. AFV-SOFT offered many new features and analysis functions, and was developed and operational under MS Windows. Since this initial version (ver. 1.0) several new versions have been developed. The current version is AFV-SOFT ver. 1.3. In the next few paragraphs an outline of the program development is given.

Constant upgrading of the data analysis and system software was needed to cope with the large amount of data analyzed, variations of sensor configurations, introduction of new or improved analysis functions and users suggestions. The expansion of the program to include alternative fuel vehicles placed an expanded demand on the analysis software requirements.

Alternative Fuel Vehicle Software (AFV-SOFT) development goals were to make the software (i) more powerful by introduction of new analysis functions or improvement of the old functions, (ii) more flexible by allowing the user to configure the tool based on the local configuration and (iii) more user friendly.

EV-SOFT

One of the tasks during the EV-SOFT development was to design an efficient, user friendly, standard interface for acquired and analyzed data presentation. There are several major requirements that were set by the USF EV-PV project team in order to make the presentation tool efficient and versatile. A variety of approaches have been considered and the decision was made to integrate the C language core of the existing programs developed at USF (EV-SOFT and others) with the interface capabilities of the National Instruments Lab Windows SW package to get the large inventory of analytical and presentation capabilities. A few examples of the functions added by Lab Windows are graphical presentation of periodic reports with up to four concurrent values presented on the graph, Printing/plotting functions for both graphs and individual user screens and high level help. EV-SOFT version 2.5 brought numerous changes compared to the previous version of the software (file import, reports display, daily and periodic reports,...). Since it would be impractical to list them all here the reader is referred to the detailed EV-SOFT 2.5 User's manual. This manual was carefully written to include all SW details and step-by-step examples of how to execute

analysis functions. Also, a Demo disk of EV-SOFT was developed.

AFV-SOFT

AFV-SOFT is a more powerful, user friendly and versatile data analysis program than EV_SOFT. It can be used for electric vehicle as well as solar energy and other data analysis applications. In AFV-SOFT every analysis step can be user programmable. Unlike EV-SOFT, that has fixed analysis functions, AFV-SOFT allows the user to define the exact algorithms (functions) that should be performed during the analysis. User algorithms can be defined using the output configuration functions that include math operations, conditional statements, threshold and bound functions, average, min and max functions and others. It also offers three analysis levels (basic, daily and periodic) and a complete set of printing, previewing, drawing and exporting functions. After its introduction, USF team members focused their efforts on fine tuning the program's execution and performance. One of the procedures that was thoroughly revised was the installation procedure. A new version of this procedure allows that AFV SOFT automatically replaces any existing (old) version of the program and updates the MS Windows AFV group. Also, AFV SOFT looks for certain common programs in the AFVFILES subdirectory of the main directory. The new installation procedure eliminated the need for user interaction during creation and contents update of this directory. With this change AFV installation became fully automated. Another significant change was made on the graph module within AFV SOFT. To allow more efficient selection of the parameters displayed on the graph, a new selection window was designed. Using this window, a user can select a field to be displayed by a simple mouse click. Several other functions were added to the graph module: trip time and date information, zoom in, zoom out and zoom full functions and time base functions. Trip time and date information is now clearly displayed on the bottom of the graph. Zoom functions allow users to view data from the database with a choice of resolution. This is especially important during troubleshooting or performance analysis processes. Time base functions belong to the same group of functions designed for easy troubleshooting and performance analysis. Wide acceptance of 32 bit operating systems for PC platforms set a development goal to upgrade the existing analysis programs for the new environment. During the last two quarters the major software development activity was to upgrade the existing software tools for the new, 32 bit operating system environment (Microsoft Windows 95 and Microsoft Windows NT). The new 32 bit environment allows better resource usage, higher efficiency, faster analysis and introduction of new features. Since it is impossible to list and explain all new features of the AFV-SOFT, more detailed information can be obtained by requesting the AFV-SOFT User's Manual from USF.

DATA COMPRESSION

One of the first activities during this project was the statistical analysis of the data obtained from different vehicles, under different driving conditions, different state of charges and at different times of year. The aim of this analysis was to find the optimal data compression algorithm for reducing redundant information within the file. Data compression introduced several advantages. First, recording media (MDAS memory, floppy disks, hard disks and other) were able to store larger

amounts of data. Second, the file transmission time over the cellular and land-line phones was shorter. Both of these reduced the costs for retrieving and analyzing the EV-PV data. After comparing the algorithms one algorithm was selected and functions for performing data compression and decompression were written in C programming language. The functions were extensively tested with numerous worst-case input patterns to avoid possible errors during real time operation. Following these tests, memory requirement reduction procedures were applied to the source code and tests repeated. The data compression was later included in the AFV SOFT data analysis program.

ADRS

Data collected at other sites was forwarded to USF by mail on floppy disks or electronically using the automatic data retrieval system (ADRS). ADRS transmits data from remotely located vehicles via a telephone network. Depending on the local system configuration data was either transmitted directly to a USF host computer or to the local Internet node and then to USF using the Internet network.

HFORMAT

Since vehicle data files were also of interest to other institutions, during the first quarter of 1995 a new program, named HFORMAT, was developed. The program reads MDAS data files and additional user inputs. The additional inputs include driver identification, number of passengers, cargo weight and odometer readings. The result of the conversion is the spreadsheet file formatted according to the EV-NDC specifications. EV-NDC confirmed the full compatibility of the data files output by HFORMAT and EV-NDC databases. Since the initial version several improvements were added. A vehicle database was introduced to allow definition of all nonstandard parameters that are important for evaluating vehicle performance. These parameters are: Vehicle identification number (VIN), Personal identification number (PIN), Battery ID, Motor ID, Power acc. ID.

INTERNET COMMUNICATION

During the 2nd quarter 1994, the USF EV-PV team introduced an INTERNET network configuration that has been used for collection of data from remote sites. The communication software that can upload data files to the USF INTERNET node has been developed and sent to site operators. Users have successfully transmitted data files and stored it on a USF mainframe running under a UNIX operating system. This opened new data transfer possibilities.

Another important task for the USF team was efficient information and data distribution. In order to provide 24 h/day 7 days/week information access USF EV/PV Mosaic pages were designed. Mosaic pages can be accessed at:

<http://www.eng.usf.edu:80/EE/evprogram.html>.

Along with the pages an automated e-mail server was started. The purpose of the mail server was to enable on-line access to vehicle files, software upgrades, frequently asked questions and answers, tips and other information. The mail server can be accessed at:

cevinfo@rasip.fer.hr

Both Mosaic pages and mail server were constantly updated.

Section 5

DATA COLLECTION AND ANALYSIS

USF collected electric and natural gas vehicle data, evaluated the vehicles' performance using analysis tools developed at USF, and distributed the results to interested parties.

MDAS DATA

The University of South Florida installed Mobile Data Acquisition Systems (MDAS) in seventeen vehicles under its monitoring program. These vehicles include both electric and natural gas vehicles. For the electric vehicles the parameters monitored were battery voltage, battery current, battery temperature, cabin temperature, ambient temperature, and vehicle speed. In the case of the natural gas and hybrid vehicles, the parameters monitored were vehicle speed, engine water temp, cabin temperature, natural gas pressure, gasoline level, oil pressure, natural gas mass flow, and battery voltage. Analysis of the MDAS data collected was performed using the electric vehicle data analysis software EV-SOFT.

Table 5-1 gives a summary of the performance derived from MDAS data of all the vehicles monitored by the USF EV-PV team since the start of MDAS data collection during the fourth quarter of 1993. Quarterly breakdowns of this data are given in the Quarterly Reports.

DRIVER LOG DATA

Vehicle driving and charge summaries for G01, S01, S02, and M01 as derived from driver logs are shown in figures 5-1 to 5-4. These figures were obtained for the periods in which the vehicles were operational. The period of data availability extended from the second quarter of 1993 to the second quarter of 1996. Driving cycles for G01 and S01 are shown in figure 5-1, and those for S02 and M01 are shown in figure 5-2. They are shown in pie-chart form, and give the percentage of the total miles driven for three different categories of usage (commuter, fleet, other). The charge summaries for all the vehicles are shown in figures 5-3 and 5-4. Figure 5-3 shows the total miles driven and the total AC energy in kilowatt hours. Figure 5-4 shows the efficiency in kWh(AC)/mi and the inverse efficiency mi/kWh(AC). The AC figures were derived by using the chargers average efficiency as specified by the manufacturer. Monthly breakdowns of this data are given in the Quarterly Reports.

VEHICLE TRIP SUMMARY					
PARAMETERS	UNITS	G01	S01	S02	M01
# of days in use	days	372	408	149	139
Total # of trip cycles		1526	1274	429	445
Total trip time	hours	222.3	204.4	55.6	81.2
Total time at rest	hours	66.5	78.3	15.9	38.8
Total distance	miles	4142.6	3580.7	1075.1	1098.5
Avg. speed	mph	22.2	21.72	19.6	18.1
Max. batt. temp.	°C	64.5	57.8	98.8	98.8
Avg. batt. temp.	°C	34.9	30.9	36.1	36.9
Total Regen Braking	kWh	73.5	14.7	2.5	NA
Total A/C energy	kWh	100.5	30.3	7.6	NA
Total discharge	kWh	2367.9	1183	365.7	417.2
Net DC energy eff.	mi/kWh	1.8	2.6	3	2.9
VEHICLE CHARGE SUMMARY					
PARAMETERS	UNITS	G01	S01	S02	M01
Total # of charges		264	424	136	117
Total charge time	hours	1540	2735.6	558.6	537
Max. charge current	A	184.6	33.8	136.4	39.3
Avg. charge current	A	18.3	8.7	9.31	9.6
Max. batt. temp.	°C	51.5	75.4	43.5	36.4
Avg. batt. temp.	°C	26.7	29.4	26.5	19.6
Total charge energy	kWh	6883	2961.6	747.5	623.4
Gross DC eff.	mi/kWh	0.6	1.8	1.2	1.4
Battery pack eff.	%	33.3	69.2	40	48.3

Table 5-1. Summary of parameters monitored by USF

VEHICLE TRIP SUMMARY					
PARAMETERS	UNITS	S3	S4	S5	S6
# of days in use	days	10	86	108	114
Total # of trip cycles		15	247	425	450
Total trip time	hours	3	49.2	53.6	57.8
Total time at rest	hours	0.9	13.1	18.3	15.5
Total distance	miles	74.1	630	1005.6	1208.2
Avg. speed	mph	24	21.5	18	21.8
Max. batt. temp.	°C	45	60.2	42.3	98.8
Avg. batt. temp.	°C	40	35.4	25.7	41.6
Total Regen Braking	kWh	0.039	1.8	9.3	4.3
Total A/C energy	kWh	2.8	27.8	17	7
Total discharge	kWh	25.5	133.3	304.3	409.5
Net DC energy eff.	mi/kWh	2.9	4.7	3.3	2.9
VEHICLE CHARGE SUMMARY					
PARAMETERS	UNITS	S3	S4	S5	S6
Total # of charges		7	66	108	110
Total charge time	hours	62	658.7	590.9	911.1
Max. charge current	A	41	53.2	26.4	36
Avg. charge current	A	5.2	6.8	5.9	12.6
Max. batt. temp.	°C	52	44.2	44.6	45.2
Avg. batt. temp.	°C	33.6	26.3	26.5	26.9
Total charge energy	kWh	47.3	408.6	413.8	1047.6
Gross DC eff.	mi/kWh	1.6	1.5	2.4	1.2
Battery pack eff.	%	53.9	32.1	72.7	41.4

Table 5-1. (Contd.) Summary of parameters monitored by USF

VEHICLE TRIP SUMMARY					
PARAMETERS	UNITS	S7	S10	SOL	VLC
# of days in use	days	7	45	12	95
Total # of trip cycles		9	261	55	116
Total trip time	hours	6	31	8.2	16.9
Total time at rest	hours	2	7.5	1.7	3.1
Total distance	miles	71.2	706.6	80.9	505.7
Avg. speed	mph	16.5	26.4	11.1	35.6
Max. batt. temp.	°C	33.9	98.8	46.9	48.9
Avg. batt. temp.	°C	29.7	38.8	32.5	33.2
Total Regen Braking	kWh	1.7	4.9	5.2	8.6
Total A/C energy	kWh	0.4	NA	NA	2.9
Total discharge	kWh	3.9	178.3	19.7	118.8
Net DC energy eff.	mi/kWh	2.4	3.9	4.1	4.3
VEHICLE CHARGE SUMMARY					
PARAMETERS	UNITS	S7	S10	SOL	VLC
Total # of charges		3	67	21	102
Total charge time	hours	4.8	270	97.9	770.5
Max. charge current	A	15.8	23.2	19.5	75.3
Avg. charge current	A	2	11.7	3.6	8.2
Max. batt. temp.	°C	31.1	38.4	51.9	48.3
Avg. batt. temp.	°C	27.4	25.2	29.8	26.8
Total charge energy	kWh	1.7	258.1	43.6	329.2
Gross DC eff.	mi/kWh	5.4	2.7	1.9	1.5
Battery pack eff.	%	225	69.2	45.2	34.9

Table 5-1. (Contd.) Summary of parameters monitored by USF

ELECTRIC VEHICLE DRIVING CYCLE

Figure 5-1

ELECTRIC VEHICLE DRIVING CYCLE

S02

M01

Figure 5-2

ELECTRIC VEHICLE CHARGE SUMMARY

5-8

Figure 5-3

ELECTRIC VEHICLE CHARGE SUMMARY

Figure 5-4

AIR CONDITIONING

Sensors to monitor air conditioning power requirements were installed in the G01 G-van in the second quarter of 1995. Data was recorded on the MDAS. Results obtained through the second quarter of 1996 were as follows:

Total Battery Discharge Energy	1161kWh
Energy Consumed by Air Conditioner	56kWh
Percentage of Battery Discharge Consumed by Air Conditioner	4.8%

SUMMARY/CONCLUSIONS

The USF EV-PV team collected and analyzed data for electric vehicles. A large number of passenger cars, vans and pickup trucks have now been studied and procedures for monitoring them have become routine.

Section 6

PHOTOVOLTAIC SOLAR POWER

The Electric Vehicle/Photovoltaic Demonstration and Evaluation Program being conducted at the *University of South Florida (USF)* includes a 20 kW (peak) photovoltaic (PV) system in which PV panels form the roof of a 12 bay carport. This was the nations first PV solar powered electric vehicle charging station. A 6 kW (peak) segment of the PV system can be simultaneously distributed between computer controlled direct DC-DC charging and power grid interconnection.

The DC-DC charger (DC-DAS) controls the charging current of a battery pack with minimal power waste, by computer control of current flow direction of each of four source circuits. It demonstrates superior efficiency, dependability and safety for DC-DC charging over DC-AC-DC charging and has greater control over the last 20% of charge than traditional PV DC-DC chargers.

PV SYSTEM CONFIGURATION

The 12 bay photovoltaic carport utilizes *Siemens Solar M55* high efficiency power PV modules that can achieve a peak output of 53 Watts ($V_{mpp}=17.4V$ & $I_{mpp}=3.05A$ @ $75^{\circ}F$ & $1000W/m^2$) each. Refer to figure 6-1. A total of 377 M55 modules are used which provides a peak power of 19,981 Watts. By properly connecting the modules in series and in parallel, the modules can be interfaced with the EV's directly or through the utility grid. AC-DC chargers are available for charging when solar power is unavailable or insufficient.

The photovoltaic panels are tilted south at three different angles. An individual array consists of all the panels mounted at a specific angle. Array #1 has 117 modules angled at 25° , Array #2 has 130 modules angled at 15° , and Array #3 has 130 modules angled at 25° .

All the electric power produced by Arrays #2 and #3 is directed to the power grid via microprocessor controlled inverters, which load the PV circuits at their maximum power voltage by constantly varying the load and monitoring the power.

DC-DC CHARGER CONFIGURATION

Array #1 was configured for both direct DC-DC charging and utility grid interconnection and is capable of delivering a 41.6A maximum current. The segment consists of four source circuits which in turn are comprised of series circuits. A series circuit consists of nine PV modules wired in series to provide a peak power voltage of 130V-156V (depending upon the PV module temperature) and a current of about 3.2A at $1000W/m^2$. A source circuit is formed by connecting a number of series

circuits in parallel. Source circuit #1 (SC#1) has one series circuit, SC#2 has two series circuits, SC#3 has three series circuits, and SC#4 has seven series circuits. The DC-DAS configuration is shown in (Figure 6-2). The source circuits are switched between the charging vehicle and the power grid (via two 3kW inverters) by computer controlled relays. The 124V to 156V charging voltage range of the electric vehicle battery pack is within the power knee of these source circuits (Figure 6-1).

DC-DC CHARGING (DC-DAS) PROCEDURE

The DC-DAS is able to control the charging current of a battery pack with minimal power waste and can achieve an efficient 100% state of charge (SOC). This is made possible by properly utilizing the 4 source circuits (SC#1-SC#4) of the PV array (Figure 6-2). With source circuits of 1, 2, 3 and 7 series circuits, any number of series circuits from 1 to 13 can be employed. Each source circuit can provide 3.2A at 148.5V and 75°F. This will allow any integral multiple of 3.2A from 3.2 A to 41.6A. DC-DC charging is accomplished using USF developed software, which monitors the battery temperature, voltage, and charging current along with the array irradiance. The DC-DAS analyzes these parameters to determine the current required for safe and efficient charging. For the initial 70%-80% battery state of charge, all PV power is utilized for charging without any interruptions. The DC-DAS provides this power by connecting all four SC's for DC/DC charging. The DC-DAS provides current control during the final 20% - 30% of charge by switching the SC's between the charging vehicle and the power grid. With the ability to control the charging current in steps of 3.2A, a fairly smooth charging curve can be maintained and fluctuations in irradiance will not have a drastic effect on the last 20%-30% of charge, when the battery can not safely accept all of the PV power. The power that is not used for charging is routed to the power grid to insure that no PV power is wasted. This power is routed to the grid on the customer side of the meter to maximize its economic value.

To determine the proper charging current during the last 20%-30% of charge, the DC-DAS constantly monitors the charging current and determines if this value can be increased for expeditious charging or if it should be decreased for charging safety. This is accomplished by maintaining the charging current within a window determined by a calculated upper and a lower control current. To help define these control currents the DC-DAS maintains a 1 minute running average of the charging current. When the battery begins to gas, which is indicated by a temperature based algorithm, the DC-DAS uses the 1 minute average current value to calculate the new upper and lower control currents. The upper control current is one current increment less than the previous 1 minute running average and is a fixed value until the next gassing. However, the lower control current will constantly change depending upon the number of series circuits being used. If the charging current drifts a certain percentage below or slightly above the control currents, due to more/less cloud obstruction or to sun intensity reduction/strengthening, the DC-DAS will switch the required number of SC's between the battery pack and the inverters to remain within the control current window. Every time a gassing voltage is reached, new upper and lower control currents are determined from the preceding 1 minute average current.

When the upper current control is reduced to 8A, the gassing algorithm is no longer used, since this current signifies a safe 1/20th of the battery ampere hour rating. The battery pack is permitted to charge up to 156V (2.6V per cell), then the upper control current is deincremented by a series circuit and allowed to charge up to 156V again. This process of deincrementing by one series circuit every time 156V is reached is repeated until only one series circuit is required for charging.

DC-DC CHARGED VEHICLES

Three electric vehicles with nominal 120V battery packs were employed in comparative studies of DC-DC and DC-AC-DC charger performance. These were 2 Chevy S10 pickup trucks and a Mitsubishi Mirage compact sedan. The vehicles were charged under a variety of circumstances while real time operating parameters were monitored for the batteries, PV arrays, insolation and inverters.

MEASUREMENTS

PV Operation:

The PV data acquisition system (PV DAS) monitored and recorded the plane of array solar pyranometer signals, DC output voltages and currents of the PV source circuits, and AC kWh outputs of the inverters. It also monitors array panel and ambient temperatures.

Battery Charger:

The PV DAS monitored and recorded DC output voltages and currents of the DC-DC charger unit. Input energy to the AC-DC chargers was monitored by kWh meters and recorded manually for each charge.

Vehicle:

Each test electric vehicle was equipped with a Mobile Data Acquisition System (MDAS) that monitored and recorded battery voltage, current and temperature as well as other operating parameters of the vehicle. The battery voltage and current was used in the calculation of AC-DC charger efficiency. The battery temperature sensor provided this parameter for DC-DC charger control.

SOLAR ENERGY CONVERSION

The PV data collected was sampled every 15 seconds and was comprised of 3600 daily data points per parameter (voltage, current, temperature, irradiance, etc.) The gathered data was analyzed using an analysis program called PV Soft, which was developed at USF. With this program each profile can be graphed with respect to time and the user has the ability to obtain a profile for an individual source circuit (SC), for each array (5°, 15° and 25° tilt angles) and for the entire PV system.

PV Soft is operated through a menu format and can be controlled by either a mouse or a keyboard. This is made possible by interfacing *LabWindows* (National Instruments) to facilitate graphical presentation. We performed 16 mathematical analyses on the PV data for the individual arrays and the entire system, to determine the performance of the PV carport:

PV kWh A1	Inv kWh A1
PV kWh A2	Inv kWh A2
PV kWh A3	Inv kWh A3
Total PV kWh for the day	Total INV kWh for the day
PV 1 % efficiency	Inv 1 % efficiency
PV 2 % efficiency	Inv 2 % efficiency
PV 3 % efficiency	Inv 3 % efficiency
Overall PV % efficiency	Overall Inv % efficiency

Figure 6-1 I-V characteristics of Siemen's M55 solar module

Figure 6-2 DC-DAS configuration at USF

The Overall average PV efficiency was found to be about 10.8 % and overall average inverter efficiency of 88 % was recorded for the USF installation. The outputs from Arrays 1, 2 and 3 in 4 quarters are plotted in figure 6-3. The total AC energy production for Array 1, Array 2 and Array 3 in the 4 quarters as shown in figure 6-3 was 8171 kWh, 7711 kWh and 7686 kWh respectively.

Array 1 production has been multiplied by 1.11 in the figure to adjust for its smaller size and provide a proper comparison of the configuration

Figure 6-3 Comparison of AC kWh from A1, A2 and A3 at USF.

Potential of the USF PV Carport for DC-DC Charging.

The average energy production per day was been 70 kWh. On a good day the energy production was 90 DC kWh. On an exceptionally good day the energy production reached as high as 110 DC kWh. Array 1 has direct DC-DC charging capability. If the entire carport were to have the direct DC charging capability then the DC charging potential can be evaluated. The Chevy S-10 with 17 kWh battery pack is the most common EV in the USF program. The USF carport has 12

charging bays. Considering an S-10 as the vehicle to be charged we can estimate the charging potential of the USF PV installation.

Average day solar energy production correlation:

1: *Topping Up* (35 % of full charge) charge requirements

12 electric vehicles can be topped up with approximately a 6 kWh charge per day.

2: 70 % of full charge requirements.

6 electric vehicles can be charged to 100 % if the state of charge were initially about 30 % or requiring 12 kWh of energy.

3: 100 % charging requirements

4 electric vehicles can be charged fully in a day. It would be very rare that we would encounter a totally discharged battery pack which would require this.

4: Opportunity charging

The number of vehicles that can be charged would vary depending on the extra vehicles and their state of charge, that could return to the bay for a charge.

On an average day, a full charge can be provided for the 73 kWh battery pack of one 31-foot transit bus whereas about 88 % of full charge can be provided for the 84 kWh battery pack of one 22-foot transit electric bus. For the 56 kWh battery pack of the G-Van, 100 % charge can be provided per day and at the same time a surplus could be delivered to the grid or another vehicle.

CHARGER EFFICIENCIES

The two main sources of loss that are incurred from DC-DAS charging are IR losses and V_{mpp} deviation losses. The IR losses of about 2% are due to the switching relays, the blocking diodes and the wiring interconnections. The V_{mpp} deviation losses are a result of an imperfect match between the PV series circuit V_{mpp} and the voltage of the battery being charged. Figure 6-1 demonstrates that as the PV panel temperature increases the V_{mpp} decreases. This results in the V_{mpp} lying between 130V and 160V. The charging EV battery voltage lies between 124V and 156V. Because the majority of the charge remains within the knee of the I-V curve, V_{mpp} losses are small.

The AC-DC chargers which were used for comparison came as standard items with the Chevy S10 electric vehicles. One was an on-board charger with about a 10A capacity. The other larger one was used off- board.

The following results were obtained for tests of the two charging systems used on the same vehicle (S01) on the same day (January 12, 1995).

On board charger

Charger Input : 13kWh AC (kWh meter)
Battery Input: 8.76 kWh DC (MDAS)
AC-DC Efficiency: 67%
PV Efficiency: 11.5% (PV DAS)
Inverter Efficiency: 88% (PV DAS)
% (Light-DC-AC-DC Efficiency)=
 $0.67 \times 0.115 \times 0.88 = 6.8\%$.

Off Board Charger

Charger Input: 21kWh AC (kWh meter)
Battery Input: 18.795 kWh DC (MDAS)
AC-DC Efficiency = 89%
PV Efficiency = 11.5% (PV DAS)
Inverter Efficiency = 88% (PV DAS)
% (Light-DC-AC-DC Efficiency) =
 $0.895 \times 0.115 \times 0.88 = 9\%$.

The charger losses added to the inverter losses during the DC-AC-DC charging can total as high as 35% while for the DC-DAS the losses remain under 10%.

Potential of USF Carport for DC-AC-DC Charging

Since essentially the DC-AC-DC losses could be as high as 35%, the capacity of the carport is reduced to $\frac{2}{3}$ of the capacity using DC-DC charging.

1: *Topping Up* charge requirements

8 EVs could be topped up with a charge of 6 kWh.

2: 70 % of full charge requirements

4 EVs could receive 12 kWh or 70 % of their full charge.

3: 100 % charging requirements

3 EVs can receive about 100 % charge.

On a good day and exceptionally good day, the available charging energy will increase in proportions of 1.3 and 1.8 p.u energy respectively.

By utilizing the DC-AC-DC mode of operation of the USF PV installation on an average day, a 31-foot electric bus can receive 70 % charge and a 22-foot electric bus can receive 62 % charge. For the 56 kWh battery pack of the G-Van, 100 % charge can be provided per day with no surplus.

Relative Value of PV and EV Charging Energy

For charging vehicles in the daytime, DC-DC charging is obviously preferable because of its greater efficiency. However, nighttime charging (which involves the DC-AC-DC) has a benefit in that

power is less valuable to the utility at night when it has surplus capacity. If the PV system delivers its power to the utility in the daytime when the utility needs it most, its value may be greater than nighttime power drawn from the utility for charging. This can be true even though the amount withdrawn is larger than the amount delivered (the difference being due to the inefficiency of DC-AC-DC charging).

INSOLATION AND CHARGING POWER TRACKING

There is a fortuitous correlation of battery charging demand and solar power availability in commuter application of electric vehicles. If a commuter plugs an electric vehicle into a solar charger in mid-morning at a work-place parking lot, the charging power tends to track the insolation. This tracking is illustrated in Figure 6-4 which shows insolation (upper curve) and DC-DC charging power (lower curve) as a function of time after the charge was started the morning of November 3, 1994. The battery uses all the available solar power initially as well as in the early afternoon when the insolation peaks. Whenever clouds reduce the insolation, the battery charging power is reduced. About 5 hours into the charge, however, the battery approaches gassing voltage and the DC DAS starts diverting source circuits away from the battery to the inverters. By about 6 hours there is a substantial amount of solar power available in excess of what the batteries can safely accept. At this time the charging power is less sensitive to small changes in insolation because the DC DAS responds to reduced insolation by directing more source circuits to the battery to keep charging at the maximum possible safe rate. Spikes introduced into the power curve trace by switch transients when source circuit connections are transferred between the DC-DC charger and the inverter should not be confused with power variations. Later in the day insolation starts to decrease faster than charge rate so that all the available solar power is again used for charging. There is only a limited period between the 5 and 8 hour marks when some solar power must be directed to the less efficient DC-AC application.

CONCLUSIONS

The University of South Florida designed, developed and is currently operating a solar powered (20kW) electric vehicle charging station and test facility. The charging station is capable of direct DC-DC charging which provides effective current control and is capable of routing unused PV power to the University's power grid for other use. The charging station is also capable of providing utility interconnected charging. DC-DC charging is more efficient, more dependable and safer than DC-AC-DC and traditional methods of DC-DC charging. There is a fortuitous correlation of battery charging demand and solar power availability in commuter application of electric vehicles.

Insolation and Charging Power

Figure 6-4