Summer 2016

Developing an idealistic model to characterize and optimize a photovoltaic battery systems

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Recommended Citation

Nalladimmu, Pavani Reddy, "Developing an idealistic model to characterize and optimize a photovoltaic battery systems" (2016). *Masters Theses*. 7563.
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DEVELOPING AN IDEALISTIC MODEL TO CHARACTERIZE AND OPTIMIZE A PHOTOVOLTAIC BATTERY SYSTEM

By

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A THESIS

Presented to the Faculty of the Graduate School of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTERS OF SCIENCE IN GEOLOGICAL ENGINEERING

2016

Approved by

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PUBLICATION THESIS OPTION

This thesis has been prepared in the style utilized by the International Journal of Green Energy. Pages 9-32 will be submitted for publication in that journal.

ABSTRACT

Solar energy is one of the most abundant and clean energy sources of renewable energy. Due to its unsteady nature, most photovoltaic systems require a solar storage system. Ultracapacitors have proven to be an effective solar energy storage component due to their wide range of input voltages and high power density. This research focuses on characterizing the performance of a PV/UCAP hybrid storage system to meet required household loads at various locations throughout the US as a backup energy source. A calibrated empirical model was developed to characterize system performance. A load profile was designed based on a typical 2 bedroom house with 1200 square feet. Loads were varied for different weather conditions (winter and summer) and different days (work days and weekends). The main reason in considering different weather conditions and days are the use of appliances are not same on every day and the most important thing to be considered is usage of loads will be more in weekends. Similarly, the usage of the loads will be more in winter as heating loads are accounted. So, for accurate load calculations the loads are separated based on the weather and also different days. These loads were identified on an hourly basis based on the type of appliance, hours of operation and watts required during operation. In addition to regular household loads. This model was then applied to meet required loads in multiple locations throughout the United States. This process allows characterization for how the system would perform as a backup power system during various intermittent periods throughout a typical meteorological year at different locations.

ACKNOWLEDGEMENTS

I would like to thank Dr. Joe Guggenberger, Dr. Curt Elmore and Dr. Mariesa Crow for their continued support and encouragement throughout my research experience at Missouri S & T. I would also thank Carlo Salvinelli, Zane Hellwig, and Travis Gardner for helping me with my research.

Lastly, but not the least I would like to thank my parents for letting me to go for a foreign country and encouraging me on every step.

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NOMENCLATURE

a	Ventilation rate
AC	Alternate current
A_{array}	The surface area of the panels
A_f	Net glazing area of the fenestration area
A_s	Area of the surface
b	Fixture types
C	Capacitance
CLF	Cooling Load Factor
C_{UCAP}	Capacitance of the UCAP
DC	Direct current
E_{UCAP}	Energy capacity
F	Farads
$HVAC$	Heating, ventilation and air conditioning
I_{solar}	Solar insolation (kW/m^2)
k	Principal during the particular year
L	Latitude with north being positive
$MPPT$	Maximum power point tracker
n	The efficiency of the inverter
$NOCT$	Normal operating conditions
$NREL$	National Renewable Energy Laboratories
n_m	The manufacturer’s rated panel efficiency

n_o	Ordinal date
n_{panels}	The number of PV panels connected to the system
^{0}	Degree
PV	Photovoltaic
P_{AC}	Available AC load power
$P_{Available}$	Total power available to the system prior to the MPPT
$P_{available\ with\ HL}$	The power that is available to the system after heat losses
P_{loads}	The loads that are utilized by the house (parasitic loads and HVAC)
P_{loss}	Power loss associated with increase in cell temperature
P_{peak}	Peak AC load power
$P_{Projected}$	The power that is generated from the PV panels without heat loss
P_{PVDC}	PV power available prior to storage
P_{UCAP}	The power from UCAP during charging and discharging
Q	The rate of air flow in (Cubic feet per minute) ft^3/min
R^2	Coefficient of determination
q_c	Cooling load
q_h	The sensible heat added or removed from the air, Btu/hr
q_r	Radiant and convective cooling load for the window
S	Shading Factor
SAM	System Advisor Model
SC	Shading coefficient
$SHGF$	Solar heat Gain per square feet
t	System lifetime

TMY	Typical meteorological year
T_1	Indoor temperature
T_2	Outdoor temperature
T_{amb}	Ambient temperature
T_C	Charging time
T_{cell}	Cell temperature
T_d	Discharge time
TS_{panel}	Temperature sensitivity of the panel
U	Overall heat transfer coefficient
UCAP	Ultracapacitor
US	United States
V	Volts
V_{Intial}	The battery voltage prior to each time step
V_{rated}	Rated system voltage
V_{UCAP}	UCAP voltage
W	Watts
y	Year
β	Solar altitude
δ	Solar declination angle
ω	Solar hour angle

SECTION

1. INTRODUCTION

The demand for energy is increasing, as the population and technology increases (Glavin et al., 2006). The limited availability and increasing prices of fossil fuels increased the need for renewable energy (Ghafoor et al., 2015). The sun provides the energy to sustain life. There are lot of research done to scavenge solar energy and supply it to the grid (Jayalakshmi et al., 2015, Galvin et al., 2009, Xu et al., 2011, Galvin et al., 2007, Zhou et al., 2010, and Mounir et al., 2014). Photovoltaic (PV) technology is used for the direct conversion of solar energy into electricity.

Tracking the maximum power has become the main alarm for a PV system, due to the unpredictable nature of solar insolation and ambient temperature (Jayalakshmi et al., 2015). All stand-alone PV systems require an energy buffer to bridge the gap between available power (during daylight hours) and electrical load requirements (during night time hours) for which a storage element is required (Glavin et al., 2006). It is difficult to store the solar energy generated in order to utilize it for future purpose. In order to overcome this problem a lot of studies have been conducted on the concept of energy devices (Jayalakshmi et al., 2015, Galvin et al., 2007, and Mounir et al., 2014).

There are three main types of conventional storage batteries that are used extensively today: the lead–acid batteries, the nickel-based batteries, lithium-based batteries and ultracapacitor (UCAP). Characteristics of different types of batteries are provided in the Table 1.1 (Smith et al., 2010, Albright et al., 2012, McCluer et al., 2008, Yang, 2013, and Chen, 2009). Based on the characteristics, UCAP as energy storage

Table 1.1 Different types and characteristics of a battery

Characteristics	**Lead-Acid**	**Nickel based**	**Lithium based**	**UCAP**
Energy Efficiency	85-90%	65-70%	90-100%	98%
Self-discharge Rate	3-20% of rated capacity per month	10-15% rated capacity per month	5% per month	17-19% per month
Cycle life	1200-1800 life cycles	1500-3000 life cycles	More than 1500 life cycles	1,000,000 life cycles
Energy Density (Wh/kg)	30-50	50-75	100-275	3-5
Specific Power (W/kg)	180	150	250-340	3300
Operational life time	5-15 years	10-20 years	3-5 years	10 years
Effect on temperature levels	Tolerates 25^0C. Every 8°C rise in temperature will cut the battery life in half.	It can tolerate up to 70^0C	Degrades significantly above 45^0C	They can tolerate to high temperatures. -40^0C to 70^0C

device have high power density, high efficiency, life cycle, and wide range of voltage (Bruke, 2000). UCAPs have a high power density, which is suitable for charging the battery and supply the peak power to the load in the system (Galvin, 2007). Limitations to using UCAPs include high leakage rate and low energy storage (Lukic et al., 2006).

Burke (2000) focuses on the science and technology of UCAPs, which stated that the design of high capacity batteries came into market due to the increase in power requirements in a number of applications. Research concluded that UCAPs has high power density, high efficiency, and long shelf and cycle life. Also UCAPs being recharged in very short times compared to the batteries.

Power from one source will not satisfy the need of modern energy loads. So, the research of hybrid powers becomes more and more popular (Xu et al., 2011). The PV/UCAP hybrid storage system approach incorporates PV panels, maximum power point tracker (MPPT), regulator, and load to form an autonomous PV system (Glavin et al., 2009). Therefore, PV/UCAP hybrid systems has marked signification to extend life.

For a given solar insolation and load profile, Glavin et al. (2012) designs the system with the combination of PV panels, batteries, and UCAPs using Matlab software. In order to design and size renewable energy systems and energy storage, it is important to forecast a typical household daily consumption (Rodrigues et al., 2014). Load data is important to plan the electricity distribution, accurate load forecasting and optimizing the generation capacity (Asare et al., 2014). According to the type of weather (solar insolation and ambient temperature), seasons (summer, winter) and customer load types (residential, commercial and industrial) the daily load consummation in the house may vary (Asare et al., 2014). In order to study the load management, published work focused on physical-based load models, especially on heating, ventilation, and air conditioning (HVAC) loads and water heating loads (Shengnan et al., 2012).

The daily electricity consumption on a yearly basis is dependent on external variables such as outside temperature and daily daylight hours that typical follow similar patterns over successive years (Jukka et al., 2005). The hourly fluctuations of domestic loads results from the combined effect of consumer availability and activity level (Capasso et al., 2004). Thus, the mean daytime consumption during workdays is typically lower than that in weekends, and in the evening the consumption is somewhat higher compared to the weekend evenings (Jukka et al., 2005).

2. EXPERIMENTAL DESIGN

The preliminary phase of the study was to calibrate the equipment and collect the data in the field. The system was mounted in small wagon to be transported to and from the field location daily. It is operated September 2015 to November 2015 (a total of 42 days) only during daylight hours and when there is no precipitation. The following steps are taken in collecting the data:

- As defined in the PC200 wiring diagram, voltage and current sensors are connected to the CR1000 datalogger.
- Connect the computer to the datalogger to make sure the wiring has been properly recorded.
- After proper connection, datalogger records and stores the data. Now, make sure that all the sensors are functional and records the data.

To switch on and off the inverter and PV units, the system should be manually operated. Approximately 1 month is spent on the troubleshooting the system. In troubleshooting, connected all the voltage and current sensors, calibrated and make sure that all the sensors are collecting the data properly. The power from PV panels is supplied to Outback Flexmax-60 charge Controller. The MPPT can reduce the high voltage into the lower voltage to recharge the battery. The MPPT is programmed to float when the UCAP, with the capacity of 165Farads (F)/48Volts (V), reaches 48 VDC. DC power produced from the UCAP is supplied to the inverter through a buck-boost converter. The inverter converts the DC current to AC current which powers the required loads. The data collected from the datalogger is stored in the excel sheet by the end of the day. This entire description is represented in circuit diagram in Figure 2.1. The PV system was characterized separately during charging and discharging. In the charging phase, power from PV panels is used to charge the battery. In discharging phase, power produced from the UCAP is discharged using different loads.

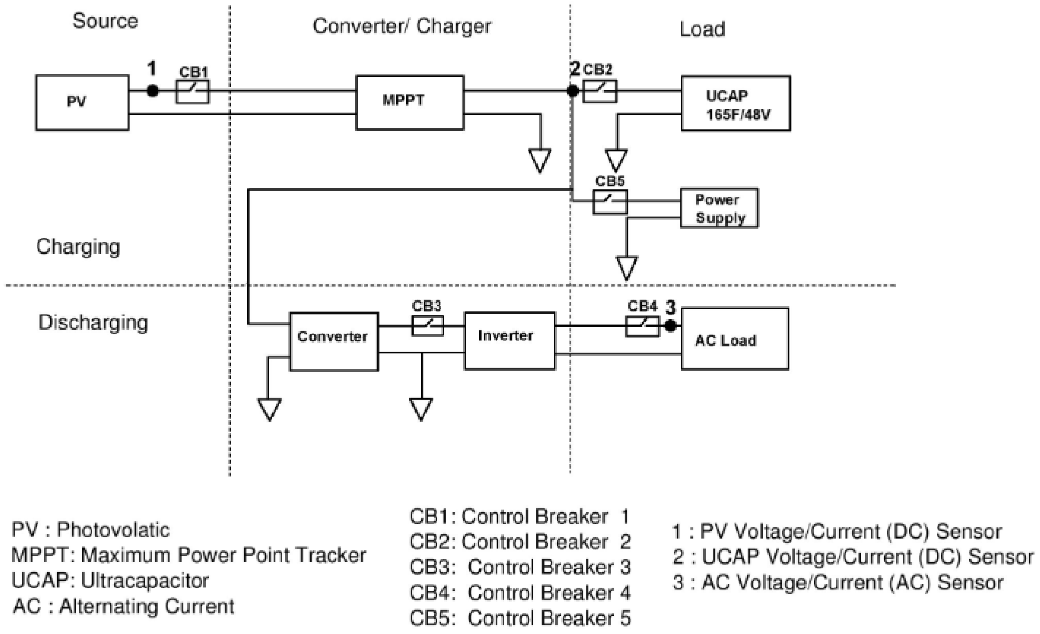

Figure 2.1 Circuit diagram

The second phase of the research is in analyzing the data. The data is collected from the weather station every five seconds, and averaged and recorded every two minutes. A Campbell Scientific model CR 1000 data logger was used for continuous collection of data during testing. Apogee CS300 Pyranometer is used to collect solar insolation. One Campbell scientific 107-L temperature probe is used to calculate ambient temperature. But the data from the Pyranometer and ambient temperature sensors are collected for every five seconds and averaged every 15 minutes. This 15 minutes interval was converted to two minute interval using Microsoft excel. To retrieve the collected data from CR 1000 data logger, PC200W software is used. The data collected from the software used to calibrate the system. The calibrated data is used to calculate the power from the PV panels and also power into and out the battery.

3. OBJECTIVES AND GOALS

This paper focuses on characterizing the performance of a PV/UCAP hybrid system to meet required household loads at various locations in the US as a backup energy source. To do this, a model was developed to characterize the PV/UCAP hybrid system, calibrated the model. An appropriate load profile was developed, applied the model using typical meteorological year 3 (TMY3) data from various locations, and characterized how the system would perform as a backup power system for various intermittent periods during a given year. Characterized the charging and discharging time for the UCAP and also characterized when the system should be powered.

PAPER

I. DEVELOPING AN IDEALISTIC MODEL TO CHARACTERIZE AND OPTIMIZE A PHOTOVOLTAIC BATTERY SYSTEM

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ABSTRACT

Due to its unsteady nature, most PV systems require an energy storage system. Because of their large range of input voltages and high power density, UCAP's have proven to be an effective storage system for PV systems. This research mainly on characterizing the performance of a PV/UCAP hybrid storage system to meet required household loads at various locations throughout the US as a backup energy source. An empirical model was developed to characterize the PV/UCAP system. A household load profile was developed, which stimulated the typical meteorological year 3 data for locations throughout the United States. UCAP discharge and charging time during in emergency power conditions were calculated.

Keywords: PV, UCAP, Load profile, Solar Insolation, Ambient Temperature

INTRODUCTION

Global fossil fuel reserves of fossil fuels are decreasing constantly (Glavin et al., 2006). At the same time, awareness of the importance of the global environment is growing. Searching for a pollution-free replacer of fossil resources is becoming more and more urgent (Ghafoor et al., 2015). Electricity is the most universally available energy source (Galvin et al., 2006). Renewable energy sources are becoming more important contributions to the total energy consumed throughout the world (Jayalakshmi et al., 2015). There are lot of research done to scavenge solar energy and supply it to the grid (Jayalakshmi et al., 2015, Galvin et al., 2009, Xu et al., 2011, Galvin et al., 2007, Zhou et al., 2010, and Mounir et al., 2014). For the direct conversion of solar energy into electricity, PV technology is used.

It is difficult to store solar energy generated in order to utilize it for future purposes. All stand-alone PV systems require an energy buffer to bridge the gap between available power (during daylight hours) and electrical load requirements (during night time hours) for which a storage element is required (Glavin et al., 2006). In order to overcome this problem, multiple studies have been conducted on the concept of energy devices (Jayalakshmi et al., 2015, Galvin et al., 2007, and Mounir et al., 2014).

There are four main types of conventional storage batteries that are used extensively today: lead–acid batteries, nickel-based batteries, lithium-based batteries, and, UCAPs. Characteristics of different battery types are listed in the Table 1 (Smith et al., 2010, Albright et al., 2012, McCluer et al., 2008, Yang, 2013, and Chen, 2009). Based on these characteristics, UCAPs are proven to have high power densities, high efficiencies, life cycles and a wide range of input voltages (Bruke, 2000), which allows them to effectively be used as buffer power during power outages (Galvin, 2007). Limitations in UCAP applications include high leakage rate and low energy storage density (Lukic et al., 2006).

Table 1 Different types and characteristics of a battery

Characteristics	**Lead-Acid**	**Nickel based**	**Lithium based**	**UCAP**
Energy Efficiency	85-90%	65-70%	90-100%	98%
Self-discharge Rate	3-20% of rated capacity per month	10-15% rated capacity per month	5% per month	17-19% per month
Cycle life	1200-1800 life cycles	1500-3000 life cycles	> 1500 life cycles	1,000,000 life cycles
Energy Density (Wh/kg)	30-50	50-75	100-275	3-5
Specific Power (W/kg)	180	150	250-340	3300
Operational life time	5-15 years	10-20 years	3-5 years	10 years
Effect on temperature levels	Tolerates 25^0C. After 8°C rise in temperature will cut the battery life in half.	It can tolerate up to 70^0C	Degrades significantly above 45^0C	They can tolerate to high temperatures. -40^0C to 70^0C

For a given solar insolation and load profile, Glavin et al. (2012) designs the system with the combination of PV panels, batteries, and UCAPs using Matlab software. In order to design and size renewable energy systems, it is important to forecast a typical household daily energy consumption (Rodrigues et al., 2014). Load data is important to plan the electricity distribution, accurate load forecasting and optimizing the generation capacity (Asare et al., 2014). According to weather conditions and customer load types (residential, commercial and industrial), a load profile may vary (Asare et al., 2014). In order to study the load management, previous research focused on physical-based load models, especially on HVAC loads and water heating loads (Shengnan et al., 2012).

This paper focuses on characterizing the performance of a PV/UCAP hybrid storage system to meet required household loads at various locations in the US as a backup energy source. To accomplish this, a model was developed to characterize a PV/UCAP hybrid system. This model was calibrated, and an appropriate load profile was generated to represent a target household throughout the United States. Tests were then performed using Typical Meteorological Year 3 (TMY3) data to determine load supply time and UCAP charging time at various locations throughout the United States. An economic analysis was performed to determine the cost-effectiveness of a PV/hybrid system in comparison to a diesel generator to meet the required loads at various locations during intermittent power periods during a given year.

SYSTEM DESCRIPTION

A PV/UCAP hybrid system was installed at latitude 37.9 north and longitude 91.8 west in Rolla, Missouri. This system was operated during September 2015 to November 2015 (a total of 42 days) only during daylight hours when there is no precipitation. The PV array consisted of four Sharp ND solar module model ND-216U2 panels mounted facing due south at a tilt angle of 38 degrees to maximize the annual energy output. A cart-based renewable power system was constructed on the campus of Missouri University of Science and Technology in Rolla, Missouri. The circuit diagram of this cart-based system is presented as Figure1. PV panels are connected in two parallel series to a PV combiner box. Through an Outback Flexmax-60 MPPT charge controller to optimize battery charging efficiency. The MPPT is programmed to float when the Maxwell technologies, model number BMOD0165P04801 UCAP 165F/48V reaches its maximum rating of 48Volts. DC power produced from the UCAP is supplied to the inverter through a Zahn Electronics Inc., model number CH63120F-SU with series number 092926 buck-boost converter. The inverter converts the DC current to AC current to powers the required loads. The PV system was characterized separately during charging and discharging. During charging periods, all PV power generated was directed at charging the UCAP. During discharge periods, power produced from the UCAP was discharged using different loads. The data was collected during September 2015 to November 2015 (a total of 42 days) from 9:00AM to 4:00PM, excluding weekends. Voltage and current sensors were installed to characterize system performance. DC voltage and current sensors were installed prior to the MPPT, as well as prior to the

UCAP. AC Voltage and current sensors were installed to effectively monitor the load during discharging. An Apogee CS300 Pyranometer was mounted at panel tilt to characterize total solar insolation striking the collector. One Campbell scientific 107-L temperature probe is used to monitor ambient temperature.

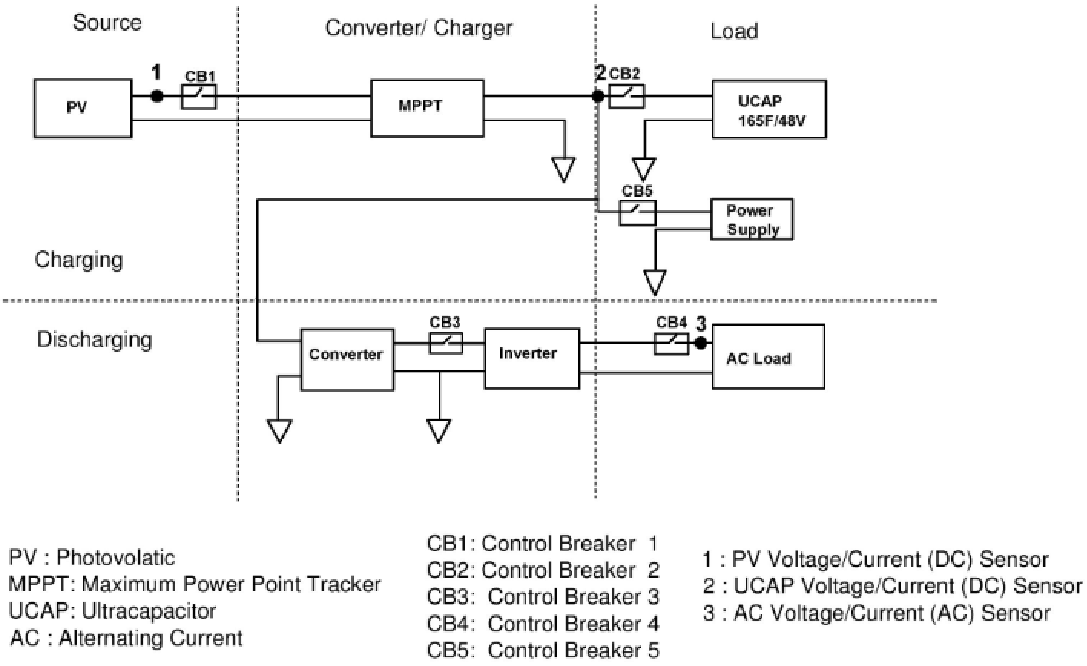

Figure 1 Circuit diagram

Each sensor was connected to a Campbell Scientific model CR 1000 data logger for continuous collection of data during testing. Data from each sensor was collected every five seconds during operation and averaged every two-minute interval. These two-minute intervals are downloaded and used during system characterization. Ambient temperature sensor readings were collected for every five seconds during operation and averaged in 15 minute intervals. Each 15 minute interval was converted to 2 minute intervals using Microsoft Excel. To retrieve the collected data from CR 1000 data logger, PC200W software was used.

DATA ANALYSIS

Empirical data analysis was performed to determine efficiencies and associated losses for each system components, which includes the available PV power to the system, MPPT losses, inverter losses and wring losses. The power balance equation for microgrid system is shown in equation (1),

$$P_{available\ with\ HL} + P_{UCAP} = \frac{P_{loads}}{n} \tag{1}$$

Where $P_{\text{available with HL}}$ is the power that is available to the system after heat losses, P_{UCAP} is the power from UCAP during charging and discharging, P_{load} is the loads that are utilized by the house (which includes parasitic loads and HVAC), n is the efficiency of the inverter.

Available power. Projected Power is the power generated from the PV panels prior to adjustment for heat losses (Gilbert, 2013) are calculated by equation (2),

$$P_{Projected} = I_{solar} \times n_{panels} \times n_m \times A_{array} \tag{2}$$

where $P_{Projected}$ is the power that is generated from the PV panels without heat loss, I_{solar} is solar insolation (kW/m^2), n_{panels} is the number of PV panels connected to the system, n_m is the manufacturer's rated panel efficiency, A_{array} is the surface area of the panels.

Power produced from the panels reduces due to the increase in the cell temperature above nominal operating cell temperature (NOCT). Gilbert (2013) calculated cell temperature (T_{cell}) using equation (3),

$$T_{cell} = T_{amb} + \left(\frac{NOCT - 25^0C}{1} \times I_{solar}\right) \tag{3}$$

where T_{amb}ambient temperature and NOCT is the temperature the cells reach when operated at an open circuit at an ambient temperature of 25^0 C, which was assumed to be approximately 40^0C. The wind speed must be assumed to be 1 m/s to meet this criterion (Sharp Electronics Corporation, 2008).

Power loss (P_{loss}) associated with increase in cell temperature, when $T_{cell} > 25^0$C (Gilbert, 2013) is calculated using equation (4)

$$P_{loss} = (T_{cell} - 25^0C) \times (TS_{panel}) \times P_{Projected} \tag{4}$$

where TS_{panel} is temperature sensitivity of the panel (Sharp Electronics Corporation, 2008). At high temperatures, efficiency loss can be noticeable because high temperatures of solar panels are recorded at 70^0C (Notten et al 2005). Total power available to the system prior to the MPPT ($P_{Available}$) can then be calculated using equation (5),

$$P_{Available} = P_{Projected} - P_{loss} \tag{5}$$

These calculations are performed for solar insolation data collected during system operation from September through November 2015. Empirical analysis of voltage and current data during operation was used to calculate system losses during operation, calculated available power after heat loss and measured PV power available after the MPPT/charge controller is plotted in Figure 2 during system operation. A linear correlation between available power and PV power had a coefficient of determination

(R^2) of 0.97. Therefore, the PV power available prior to storage (P_{PVDC}) can be calculated using (6),

$$P_{PVDC} = 0.77 \times P_{Available} - 27.028 \quad (6)$$

Finally, AC inversion losses were characterized during system operation by plotting measured PV power after storage (P_{UCAP}) and available AC load power (P_{AC}). These results are shown on Figure 3. A linear correlation between available DC load power (P_{UCAP}) and available AC load power (P_{AC}) had a coefficient of determination (R^2) value of 0.92. Therefore, P_{AC} can be calculated using (8),

$$P_{AC} = -0.6827 \times P_{UCAP} - 19.171 \quad (8)$$

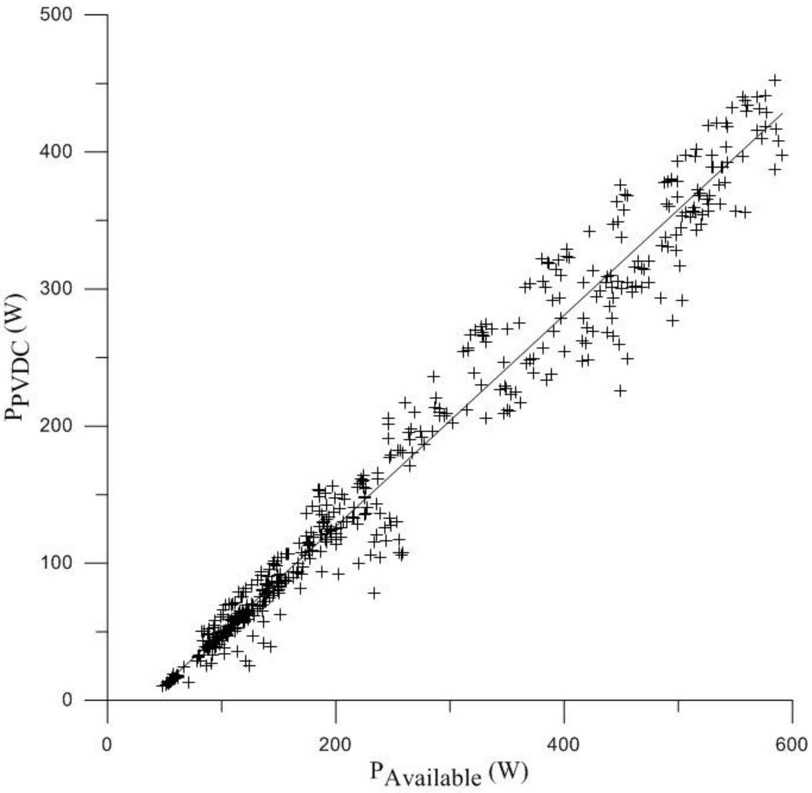

Figure 2 PV power Vs Available power

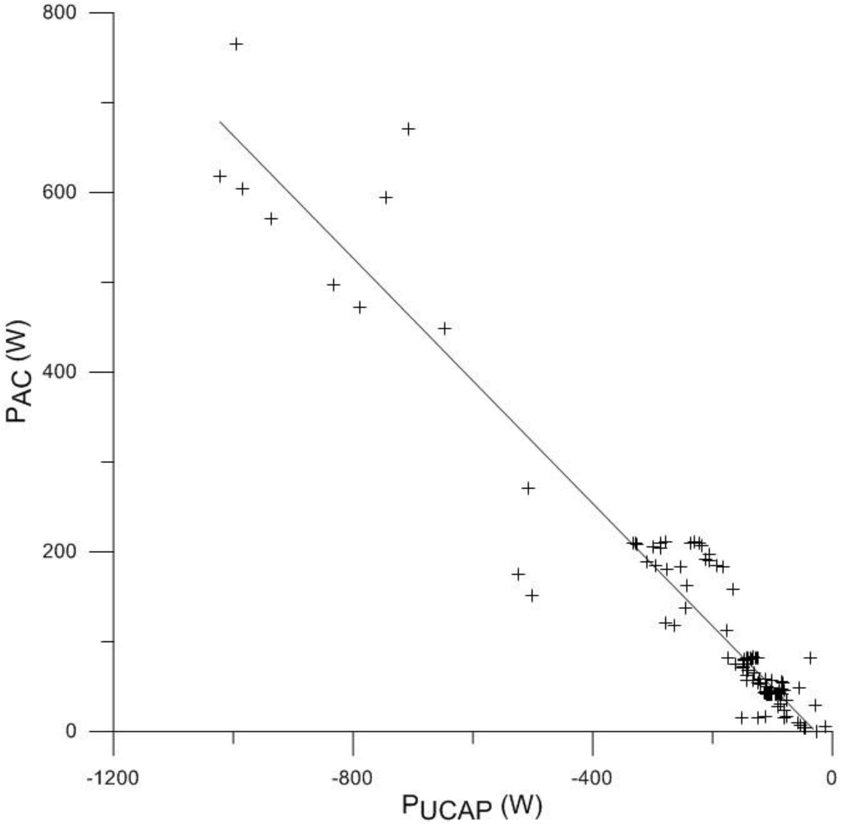

Figure 3 AC power Vs UCAP power

Model. An empirical model was developed using correlations previously stated in Section A. Inputs into the model include the time step, solar insolation, ambient temperature, and load profile. The output of the model calculated the effectiveness of the simulated system to meet the required load profile during a given time period. Input variables into the model were obtained from TMY3 data sets from various locations.

UCAPs have a very wide range of voltage. UCAPs store charge as electric potential energy (Burke et al, 2000). UCAP energy capacity (E_{UCAP}) is calculated by using (6),

$$E_{UCAP} = \frac{1}{2} \times C_{UCAP} \times {V_{UCAP}}^2 \tag{6}$$

where C_{UCAP} is the capacitance of the UCAP and, V_{UCAP} is UCAP voltage.

From battery capacity, the UCAP voltage is then calculated based on the linear correlation between battery capacity and voltage established by the sharp electronics cooperation 2008.

The minimum and maximum battery voltage set points of the UCAP were based on manufacturer specifications, and were 28V and 48V respectively (Sharp Electronics Cooperation 2008). A comparison of the modeled results and actual results during system operation are shown in Table 2. The percent difference of total energy production between actual and modeled results totaled 22.2% (adding percent difference of Available, PV and AC efficiency losses).

Table 2 Comparison of actual and modeled data in terms of energy

Description	**Available (kWh)**	**PV (kWh)**	**AC Efficiency Losses (kWh)**
Actual	14.5	3.4	-2.3
Modeled	14.5	3.9	-2.1
Percent Difference (%)	0.0	14.8	7.4

Calculations of load profile. A load profile was designed considering a typical two bedroom house with 1200 square feet of living area. It is assumed that two adults and two children reside in the house. Loads were varied for different weather conditions (winter and summer) and different days (regular work days and weekends). Analysis of the household load profile is presented in Table 3. Load requirements, are identified on an hourly basis based on the type of appliance, hours of operation and power required during operation (Wiles, 2003).

Table 3 Load profile analysis

Appliances (Wiles, 2003)	**Watts (W)**	**Summer**				**Winter**			
		Weekend		**Week Day**		**Weekend**		**Week Day**	
		Time (hours)	**Total Watts**	**Time (hours)**	**Total watts**	**Time (hours)**	**Total watts**	**Time (hours)**	**Total watts**
Refrigerator	110	24	2640	24	2640	24	2640	24	2640
Smoke Alarms	50	24	1200	24	1200	24	1200	24	1200
Ground fault circuit interrupt	10	24	240	24	240	24	240	24	240
Radio clocks (2)	14	24	336	24	336	24	336	24	336
Water heater	479	1	488	0.7	321	1.34	642	0.8	397
Domestic water Pump	240	1	244	0.7	161	1.34	322	0.7	160
Linear tube lightning	104	6	624	5	520	7	728	6	624
Phone charger	4	1	4	1	4	1	4	1	4
Compact fluorescent light	28	5	140	5	140	5	140	4	112
Vented Range hood	150	0.5	75	0.7	112	1	150	0.7	112
Dishwasher	1200	0.3	408	0.3	408	0.3	408	0.3	408

Table 3 Load Profile Analysis (cont.)

Toaster	1100	0.1	88	0.1	88	0.1	88	0.1	88
Coffee Machine	1500	0.1	75	0.3	510	0.1	120	0.1	124
Blender	300	0.1	24	0.1	24	0.1	24	0.1	24
Electric Stove	3000	0.7	2250	0.4	1248	0.9	2730	0.6	1740
Energy star Microwave	1100	0.2	275	0.1	147	0.4	451	0.2	750
Standard TV	188	2.3	439	1.3	251.9	2.3	440	1.3	251
Cable box	20	2.3	47	1.3	27	2.3	47	1.3	27
Energy Star Washer	165	0.7	123	0	0	0.7	110	0	0
Dryer	3400	1.5	5100	0	0	2	6800	0	0
Iron	1100	0.1	91	0	0	0.2	184	0	0
Vacuum Machine	500	0.3	170	0	0	0.3	170	0	0
Desktop Computer	40	1	40	0	0	1	40	0	0
Laptop	40	2	80	2.2	87	2	80	2.2	87
Bathroom fan	20	0.5	10	0.7	13.4	0.7	13.4	0.7	13.4
Total (W)			**15214**		**8478**		**18107**		**9340**

HVAC load requirements were also characterized as a function of variable ambient temperatures based on information obtained in Mull (1998). HVAC loads were calculated based on the geographic location of the house that is the house is located in Rolla, MO. Total HVAC load characterization was determined by independently calculating the required heating loads, external cooling loads, internal cooling and total cooling loads.

Heating loads were calculated based the location and usage of the building. Indoor temperature is set to be constant. Later, heat transfer coefficients for each heat transfer surface were determined. The net heat transfer area of each exterior surface, the surface adjacent to an unheated space and transmission heat losses were then determined based on the rate of infiltration for a space and the building. Heat losses are calculated for grade surfaces, such as floors, basement surface based on information obtained from Mull, 1998. Heat losses due to infiltration and outdoor ventilation (Mull, 1998) are calculated using (8),

$$q_h = (1.08) \times Q \times (T_2 - T_1) \qquad (8)$$

where q_h is the sensible heat added or removed from the air in Btu/hr, Q is the rate of air flow in ft^3/min, T_1, T_2 are indoor and outdoor temperatures respectively.

The total heat load of the building is obtained by summing up individual heat loss due to infiltration and outdoor ventilation.

Based on these procedures, a total heating load 1673.4W was obtained.

External cooling loads were calculated based on outdoor weather conditions for appropriate building type and location. The net surface area of each exterior surface such as walls and roofs are calculated. The values for the differences between cooling load temperatures were selected based on the time of the day Table 7.2 and 7.3 in Mull (1998). Solar altitude (β) and solar declination (δ) were calculated (Mull, 1998) based on the n value and latitude of the location as shown in (9) and (10), respectively,

$$\delta = 23.45 \times Sin\left(\frac{360^0(284+n_o)}{365}\right) \qquad (9)$$

where n_o is the ordinal date.

$$\beta = \sin^{-1}(sin\delta \sin L + \cos\delta \cos L \cos\omega) \qquad (10)$$

where L is the latitude with north being positive, and ω is the solar hour angle.

Cooling loads for each opaque surface (Mull, 1998) during each hour reading can be calculated using (11).

$$q_c = U \times A_s \times (CLTD) \tag{11}$$

where q_c is the cooling load in (British per hour) Btu/hr, A_s is the area of the surface in ft^2, U is the overall heat transfer coefficient in (British per hour. Square feet. degree Fahrenheit) Btu/hr. ft^2. ^{0}F, and CLTD is the temperature difference which gives the cooling load at designated time for the given surface type. Shading Factor (S), Window Shaded Area, Solar heat Gain (SHGF) (Btu/hr.sq ft), West Fenestration (Btu/hr), Maximum solar heat gain (SHGF) (Btu/hr.sq ft), cooling load factor (CLF), and cooling load for direct radiation are obtained from Tables 7.2 and 7.3 in Mull, 1998. The total radiant and convective cooling load for the window (q_r) can be calculated using (12),

$$q_r = A_f \times (SC) \times (SHGF) \times (CLF) \tag{12}$$

where A_f is the net glazing area of the fenestration area in ft^2, SC is the shading coefficient. The total radiant and convective cooling load was calculated to be 509.46 Btu/hr.

Internal and total cooling loads were calculated based on the information obtained from Mull (1998). The types of lighting and electrical power inputs were identified. The instantaneous heat gain for lights is calculated by multiplying the total wattage (obtained by adding watts of each appliance in the house) by 3.413. The total hours lights were used in the house was calculated based on the loads for lighting. Based on the type of the construction, ventilation rate (a) from Table 8.3 and fixture types (b) from Table 8.4 in Mull, 1998 cooling load factor is selected. Sensible and latent heat gain for each activity was calculated from Table 8.1 in Mull (1998). Lighting cooling load was then calculated by multiply the heat gain and cooling load factor. The total internal cooling loads are obtained by the sum of lighting cooling loads, instantaneous heat gain for lights and total cooling loads of occupants.

Heating loads were calculated from 7:00AM to 6:00PM, while cooling loads were calculated from 8:00AM – 6:00PM during each day of operation (Wang, 2001). Figure 4 shows the time of shut down and conditioning of cooling loads.

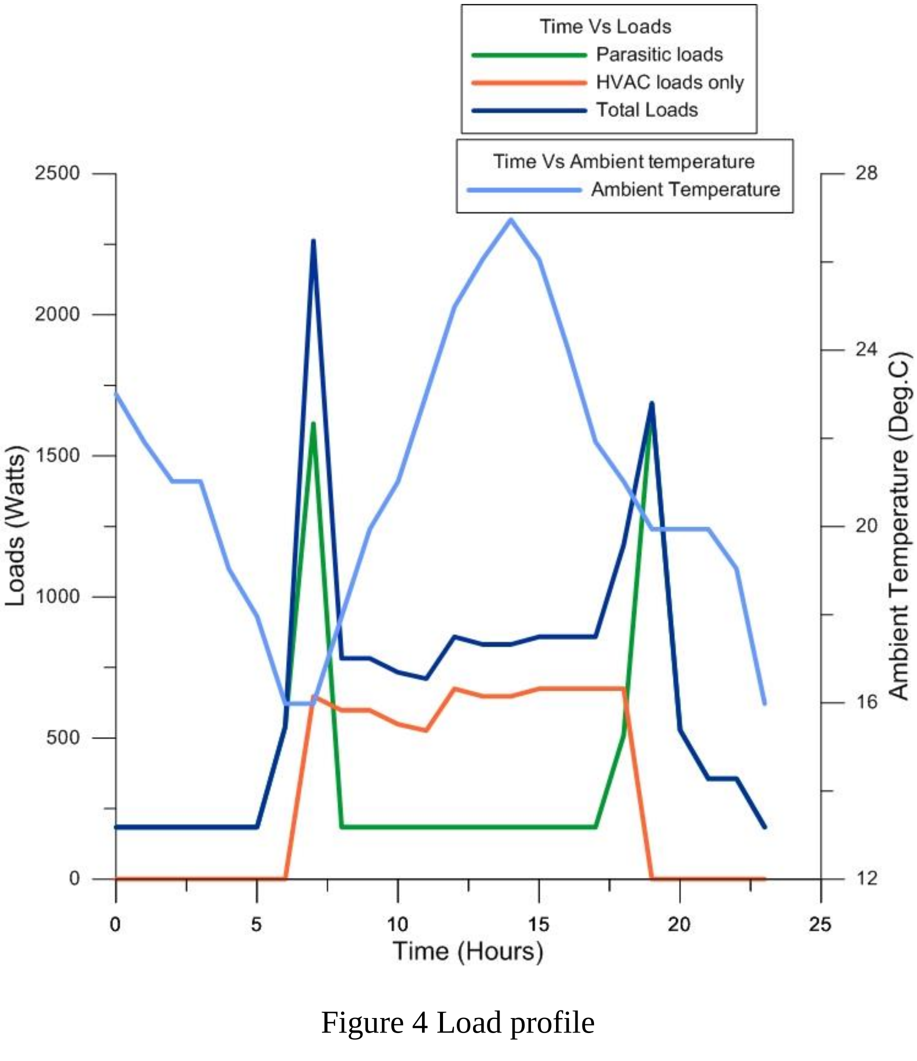

Figure 4 Load profile

An energy load profile was developed by adding the total wattage of each appliances and HVAC loads in hourly basis. Figure 5 shows the energy load profile of household in hourly basis for one day. The load starts to rise at 05:00 and peaks at 07:00. AC Energy would remain almost constant from 09:00 to 17:00, and rises to 3.5kWh at 18:00. The AC Energy starts to drop after 19:00. A worst case will occur in the morning. The AC energy will peaks at 4.5kWh since the usage of water, microwave, coffee machine, vented hood, electric stove, lights, and vented range hood. Therefore, the average AC energy for this scenario (winter, week day) will be 1.4kWh/day.

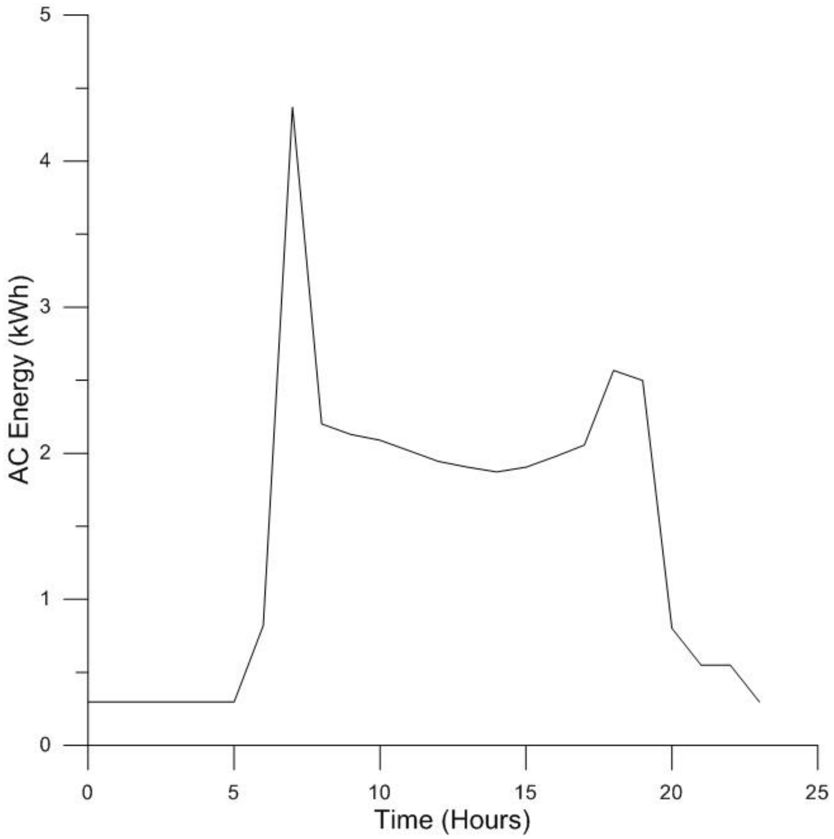

Figure 5 Energy load profile

Inputs for a model. In order to effectively model the performance of the PV/UCAP hybrid system to meet the required load profile, it was important to effectively size the system. For getting solar Insolation and Ambient Temperature from a different location, System Advisor Model (SAM) is used as developed by the US Department of Energy and National Renewable Energy Laboratory (NREL). For grid-connected power projects based on installation and operating costs, SAM makes performance predictions and cost of energy estimates and system design parameters that you specify as inputs to the model. To get solar insolation and ambient temperature, select PV model with residential. Then, select the desired location. In the system design, tilt should be equal to latitude. On stimulating, there will be a list of the data. In these calculations, ambient temperature from the weather station file and POA total radiations (nominal) are selected. So, Finally, Solar insolation and ambient temperature for the desired location are obtained.

Sizing of the system. The system must be effectively sized to optimally meet the required loads at various locations throughout the United States. In order to determine effective performance of this system to meet required loads during emergency power conditions. Calculations were performed to determine the time it takes to charge and discharge an UCAP, a number of batteries can be determined. Charging time (T_C) (TDK-Lambda, 2009) and discharging time (T_d) (Elna, 2011) can be calculated by using (13),

$$T_C = \frac{0.5 \times C \times V_{charge} \times V_{rated}}{P_{peak}} \tag{13}$$

where T_C has units of seconds, V_{charge} is charge voltage, V_{rated} is the rated system voltage, P_{peak} is the peak AC load power in watts and C is capacitance in farads.

UCAP discharge time (T_d) (Elna, 2011) can be calculated by using (14),

$$T_d = \frac{0.5 \times C \times (V_{charge}^2 - V_{rated}^2)}{P_{ac}} \tag{14}$$

where T_d has the units in seconds.

If discharge time is increased, the capacitance should increase and thereby the number of UCAPs will increase. In the same way, if charging time is to be decreased, then the numbers of panels are increased. Based on the charging and discharging time required for the system, the number of panels and batteries are obtained. In this current analysis, the location of St Louis, Missouri area is considered. System design calculations were based on requiring UCAPs to provide emergency power during discharge for a minimum of five minutes, and the system must have charge time of minimum. The system required six UCAPs and 60 panels to meet the required load, discharge time and charge time requirements. Based on the number of panels, batteries and loads the system can be designed with cost analysis as Table 4.

Table 4 System design and cost analysis of the PV/UCAP hybrid System

System Components	**Name of the Component**	**Number of components**	**Cost of each component ($)**	**Total cost ($)**
PV panel	Canadian Solar 255 Watt Smart Module with Solar Edge Optimizer	60	240	14,400
Batteries	Maxwell Technologies BMOD0165P04801	6	1352	8,112

Table 4 System design and cost analysis of the PV/UCAP hybrid System (cont.)

Charge controller	Outback Power Systems FLEX max 80 MPPT Charge Controller	4	554.51	2,218
Inverter	SMA Sunny Boy 9000TL-US-12	2	3094	6,188
Racking	Iron ridge xr-1000 rail, 11foot section, mill, (11 x 2) series x 5parallel (4 Packs) (11 x 2 x 5)	(11 x 2) series x 5parallel (4 Packs) (11 x 2 x 5)	Iron ridge $53 L-Foot kit $14	56
Combiner boxes	MIDNITE SOLAR MNPV3 COMBINER BOX	2	75	150
Wiring	100’ SMK connector cable #10AWG	5	76	380
Total system cost ($)				**38525**

The model was then analyzed for five different locations in US. These locations are Los Angeles CA, Lubbock TX, Miami FL, New York NY, and Seattle WA with latitudes and longitudes as shown in Table 5. These locations were selected in order to obtain the wide range of solar insolation data and to see how the model functions under various inputs for solar insolation, latitude and ambient temperature. These places are selected to get the wide range of insolation data and can see how the model functions for different solar insolation, latitude, and ambient temperature.

Table 5 Latitudes and longitudes of five different locations (NREL 2016)

Locations	**Latitude**	**Longitude**
Los Angeles, CA	34.1° N	118.2° W
Lubbock, TX	33.6° N	101.9° W
Miami, FL	25.8° N	80.2° W
New York, NY	40.7° N	74.0° W
Seattle, WA	47.6° N	122.3° W

RESULTS AND DISCUSSIONS

The model was analyzed for five locations described in Section F. The system was analyzed as an emergency power system. Figure 6 shows the average time it would take to completely charge the UCAP at each location as a function of solar time. The average charging time in hourly readings shows, Seattle has highest charging time followed by New York, St. Louis, Los Angeles, Miami, and Lubbock. This means solar insolation and the ambient temperature is low in Seattle and high in Lubbock. So, if this model is installed in all these locations, model in Lubbock charger faster compared to all other locations. Figure 7 shows the average time the system can power the required loads at each location as a function of solar time. The average discharging time in hourly readings shows, Lubbock has highest discharging time followed with Los Angeles, St. Louis, New York, Miami, and Seattle. Figure 8 shows the average energy the system could provide as an emergency power system during a typical meteorological day. The average AC Energies in hourly readings shows, New York has highest charging time followed with, St. Louis, Seattle, Lubbock, Los Angeles, and Miami. AC Energy is varying based on the temperatures. HVAC loads are calculated with the function of ambient temperature. Loads are almost lined up together. But, since there is variation in temperatures for different locations loads are also varies. The model is initially generated for St. Louis, MO. The same model is applied to different locations to see how the model functions with the change in solar insolation, ambient temperature, and latitude. The charging time, discharging time and loads for different locations are calculated and are shown in Figures 6, 7 and 8 respectively.

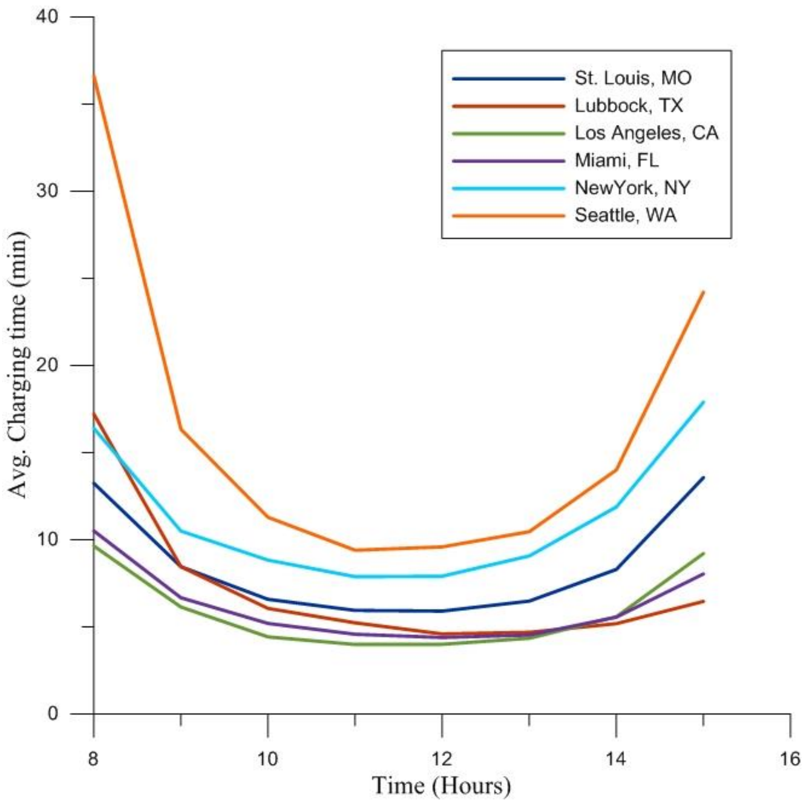

Figure 6 Average charging time for daytime hours

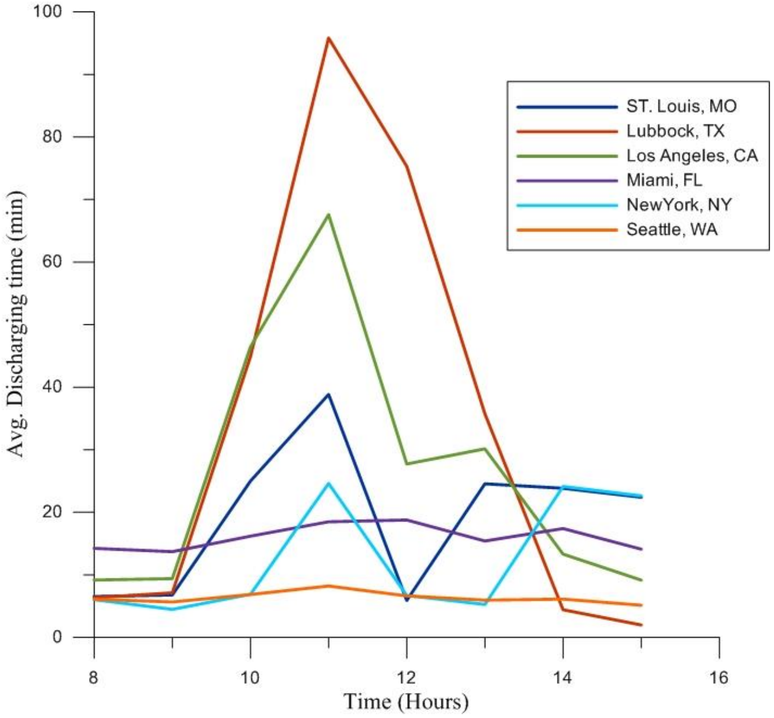

Figure 7 Average discharging time for daytime hours

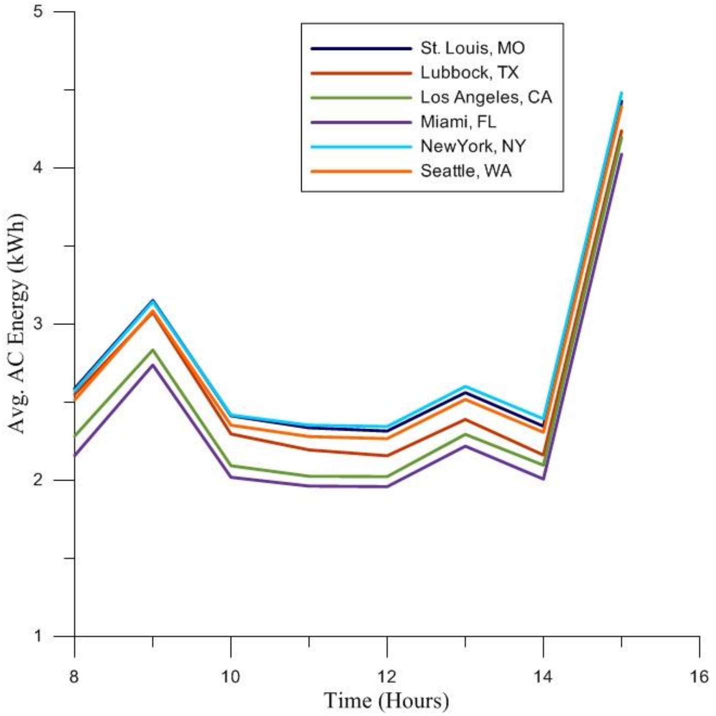

Figure 8 Average AC energies for daytime hours

CONCLUSIONS

The PV/UCAP hybrid system has proven to be a successful alternative for emergency power to traditional systems. As UCAPs has a high power density storage, wide range of voltage, and also it takes less time to charge. The designed system can meet loads at a target location for 5 minutes during a typical meteorological day at various locations, and has proven to be cost effective alternative as long as the system is offline a minimum of 22 minutes each day. The performance of a PV/UCAP hybrid storage system to meet the loads at various locations in the US as a backup energy source is estimated. The estimated load for the system is 15.5kWh/day. System sizing is designed based on the estimated load, charging and discharging time. The results show that a 15.5kW PV array capacity of 60 modules, 6 UCAP 165F/48V batteries, 4 (80Amps) charge controller, 2 (240VAC) are needed to supply the load for the house for short periods of time.

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SECTION

4. RECOMMENDATIONS FOR FUTURE WORK

The following concepts and areas are recommended to continue this research and to address assumptions made in this paper:

- Experiments using several different types of batteries like lithium ion, lead acid battery to characterize the performance of hybrid system and determine the charging and discharging time for different locations.
- Experiments with different batteries and comparing payback period.
- Experiments with various types of renewable energy to charge UCAP. For example wind energy, geothermal heat or tidal waves (coastal area) can be used so that it can used during night times also.

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