Conceptual Design and Cost Estimate for A Stand-Alone Residential Photovoltaic System

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***Abstract*- Interest in photovoltaic systems, both large and small scale applications, has been growing since the renewable portfolio standard in the US was enacted as Law. This paper provides state-of-the-art information on photovoltaic energy applications, various types of PV collector systems, and how to size the stand-alone PV system in a hybrid design. In addition, this paper provides the cost comparison of various PV system designs.**

***Index Terms*— Photovoltaic System, PV System, Inverter, Power Systems, Hybrid Design, PV Cost**

I. Introduction

Due to the increasing impact of Renewable Portfolio Standard (RPS) on the electricity market, energy generation using renewable resources such as solar, wind, biomass, and geothermal is becoming more common and has created challenges to solar power delivery systems design, operation and maintenance. In remote areas where there is no access to power grids, residences rely upon expensive diesel generators. The price of electricity generated this way can be very high due to the cost of fuel including transportation costs. This provides an excellent opportunity to apply a stand-alone renewable generation and/or hybrid system which combines two or more sources of generation.

II. Design and Energy Output of PV System

Photovoltaic (PV) systems utilize solar panels to directly convert solar energy into electrical energy. These panels consist of many PV solar cells which are semiconductor devices that convert incident solar energy into dc current. The most attractive features of PV panels are the nonexistence of moving parts for some designs, slow degradation of the sealed solar cells, modular flexibility (from a few W to MW), and the simplicity of use and maintenance. In addition, solar energy is clean and renewable as well as being an inexhaustible source with great reliability [1].

Currently there are a number of technologies available for PV cells with various ranges of efficiency and cost. National Renewable Energy Laboratory, Golden, Colorado (NREL) has published the average commercial module efficiencies. According to this source, commercial silicon efficiencies are between 14-18% as shown in Figure 1 [2]. The key issues that are considered in the design are discussed below:

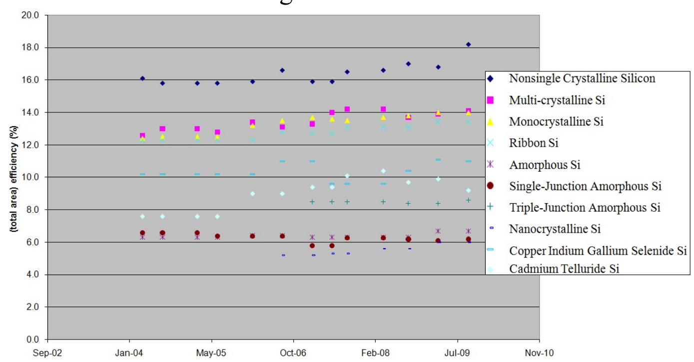

Figure 1. Best Average Commercial Module Efficiency by Technology [2]

A. Solar Energy

The solar power intensity falling on a square meter (m^2) of area is called *"solar insolation"* and is measured in W/m^2. Outside the earth's atmosphere the solar insolation is about $1.37kW/m^2$ and on the surface of the earth the insolation is usually assumed to be around $1.0kW/m^2$ which is the called "*1-sun*" or peak sun hour (PSH). The amount of average insolation at a particular site is also used to determine the panel and battery sizes.

Due to the tilted axis of the earth, the apparent path of the sun through the sky depends on the day of the year, the latitude and longitude of the observer, and the solar declination. In order to produce maximum energy a PV panel should face the sunlight at a 90° angle. To achieve that, a fixed collector should be pointed directly south and tilted at the angle of the local latitude positioning the collector parallel to the earth's axis.

B. Different Collector System

In order to maximize the energy output of a PV system, there are four basic types of collector system design: (i) fixed, (ii) dual-axis tracking, (iii) single-axis tracking: polar mount and (iv) horizontal mount. Each system has its advantages and disadvantages, and different sets of equations are used to calculate the total radiation and panel power output.

<u>*Fixed System*</u>:

Fixed system does not have any control to change the panel angle or direction. In order to maximize the energy on PV panel, the collector is tilted at an angle of the local latitude and pointed directly south.

<u>*Dual-Axis Tracking System*</u>:

In a day, the sun moves from the east to the west, and the altitude of the sun above the horizon changes. This system

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has a control mechanism which tracks the sun with dual axis and faces it to maximize the insolation from the sun.

Single-Axis: Polar or Horizontal Mount System:

Single-axis mount systems have a similar control system as the 2-axis tracking system, but the array pivots around only one axis. Therefore, the amount of energy collected by a single-axis collector is less than that collected by a 2-axis tracking system.

C. Current-Voltage (IV) Curve and Maximum Power Point Tracking (MPPT)

The electrical characteristic of a PV cell is given by the *"IV Curve"*. When the cell is exposed to the sun it produces current and a voltage which varies depending on insolation and the nature of the load on the cell. By proper control the power output of the cell can be maximized using a *"maximum power point tracking"* (MPPT) system. The MPPT system keeps the apparent load resistance on the panels at the point where the panels can deliver their maximum power. MPPT systems can also be built into inverters or battery chargers. Figure 2 shows the typical IV Curve and the corresponding MPPT point.

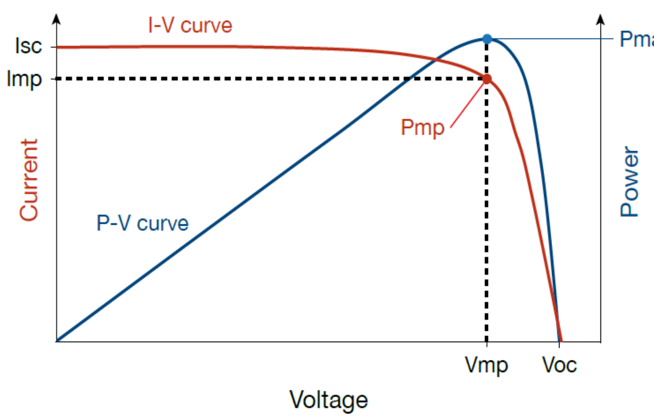

Figure 2. Normal IV curve and PV Curve from a Single Cell [10]

D. Temperature Effects

Voltage and the power output of a panel vary with ambient temperature. Temperature effects can be described using two conditions; one is the *"standard test conditions"* (or STC) which is 1-sun, 25ºC cell temperature, and air mass ratio of 1.5. The second method is the *"pacific test conditions"* (or PTC) which is 1-sun, and 20ºC ambient temperature.

III. Design of a Stand Alone PV System

Stand-alone systems, a very common application, are usually applied remote from the grid and use batteries for a short-term storage and diesel generators for a backup (long-term) system (called *"Hybrid Design"*). To design a stand-alone PV hybrid system, four important characteristics have to be addressed. A diagram of a simplified stand-alone system is shown in Figure 3.

A. Loads

In order to design a stand-alone system it is necessary that load requirements (W) and the number of hours each load must operate (or energy usage) must be determined (Load Cycle). For each load the starting or surge value, peak continuous load, and average load per day must be determined.

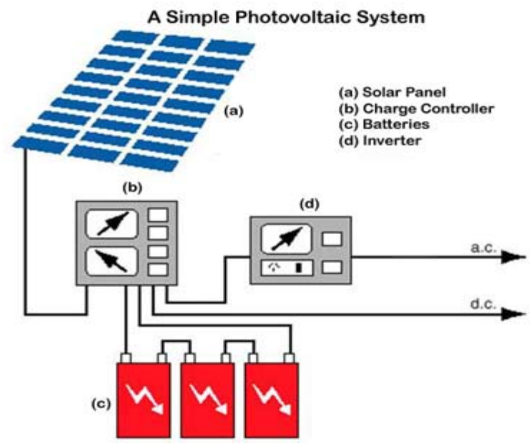

Figure 3. Schematic of a Stand-Alone PV System [11]

B. System Voltage and the Inverter Characteristics

The system voltage and output voltage of a PV array or a battery bank must be chosen. This is commonly 12V, 24V, 48V or higher depending on the system size. One common practice used to choose the system voltage is to pick a voltage so that the maximum steady-state current from the battery system is less than 100A if possible. This limit is chosen based on the easy availability of electrical hardware, wire size, and electrical safety [3].

Inverters are electrical devices that convert DC power to AC power. Usually inverters are specified by DC input and AC output voltages, maximum (peak) and continuous power output, the maximum DC input current. The inverter's DC input voltage is the same as the system voltage or voltage of the battery bank and the PV array.

To size inverters for the system both the peak load and the maximum surge current have to be considered. The inverters must be able to supply sufficient power during surge conditions such as motor starting as well as being capable of supplying the maximum system steady state power.

C. Sizing the Battery

Battery characteristics and requirements for stand-alone PV systems are very important. The battery characteristics include the voltage (V), the charge capacity (Ah), the discharge rate, the cycle capability, the ambient temperature, and the efficiency. The stored energy can be calculated by multiplying the voltage by charge capacity (Vah or Wh).

Battery Capacity:

Battery capacity is the amount of energy stored in a battery. The units used are amp-hours (Ah), watt-hours (Wh) or kilo-Watt-hours (kWh). This capacity represents the maximum energy that can be stored and extracted under given operating conditions, such as temperature, and at a particular discharge rate.

Discharge Rate:

The depth of discharge (DOD) of a battery determines the fraction of energy which can be extracted without damaging it. *C-Rating* of a battery is the discharge rate at which the Ah rating given.. For example, if a battery is given a certain Ah rating with a C-20 discharge rate it means the battery bank will have this Ah rating if discharged over a period of 20 hours. At higher discharge rates the Ah rating of the battery will be reduced from the rated value.

Cycle Capability:

Cycle capability is defined by the number of charge and discharge cycles a battery can successfully endure. The rated number of charge-discharge cycles is usually given by manufacturer and depends on the DOD. The shallower DOD, the more cycles a batteries will have. Because the cycles are usually measured under optimum conditions, it is important to consider where batteries are installed. Also, batteries for PV systems require both high DOD and cyclic capabilities.. Figure 4 shows the impact of DOD on the number of cycles for a typical deep-cycle lead acid battery.

Temperature:

Temperature of a battery significantly affects its capacity. Most lead-acid batteries are rated at 25°C. The capacity can be more at higher temperature than at lower temperature. Figure 5 shows the battery capacity in percentage under varying temperature for a typical lead-acid battery which is used for a real PV application. Even though battery capacity may increase at higher temperature it is also true that at higher temperature the battery life decreases by 50% for every 10°C above the optimum temperature.

Battery Efficiency:

The energy efficiency of battery is defined by Equation (1).

$$\text{Energy Efficiency}\,(\eta) = \frac{E_{OUT}}{E_{IN}} = \frac{V_D I_D \Delta t_D}{V_C I_C \Delta t_C} \qquad (1)$$

where,
V_C = charged voltage
V_D = discharged voltage
I_C = charging current
I_D = discharging current
Δt_C= charging time
Δt_D= discharging time

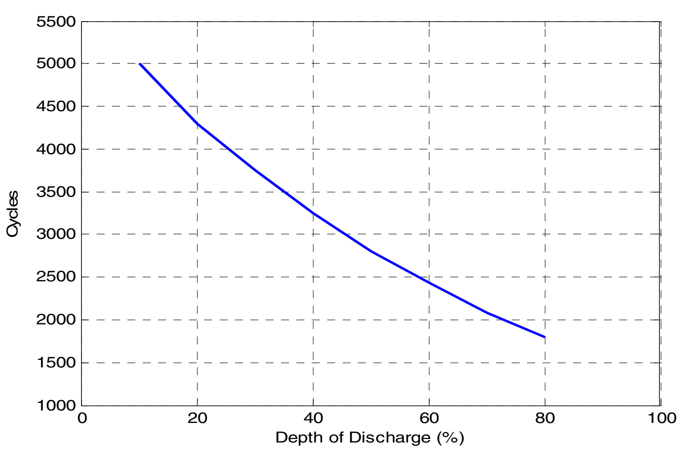

Figure 4. Depth of Discharge (%) vs. Number of Cycles for Typical Deep-Cycle Lead-Acid Battery [3]

Equation (1) can be split into two parts: the voltage ratio and the charge ratio:

$$\frac{V_D I_D \Delta t_D}{V_C I_C \Delta t_C} = \frac{V_D}{V_C} \times \frac{I_D \Delta t_D}{I_C \Delta t_C} \qquad (2)$$

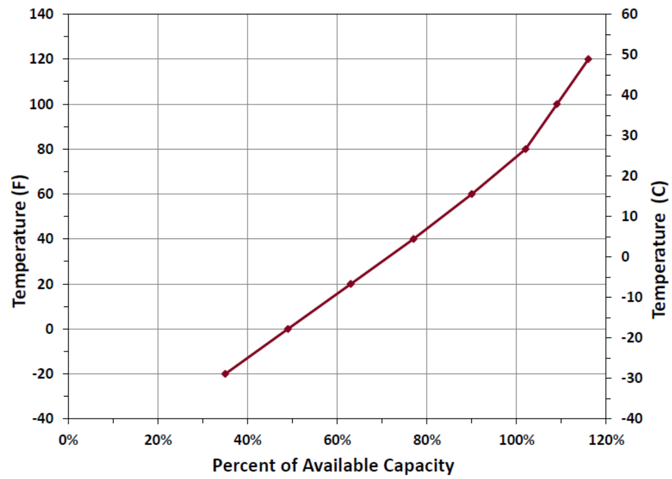

Figure 5. % of Battery Capacity vs. Ambient Temperature [12]

A typical 12V lead-acid battery is charged to a voltage of 14V. The Coulomb (or charge) efficiency is the ratio of the charge out to the charge in, and typically it 90-95% [3]. Therefore, when 90% of Coulomb efficiency is used, the overall energy efficiency of a lead-acid battery is about (12/14)(0.9) = 77.14%.

Battery System Size-Storage Days:

For a stand-alone PV system, it is very important to properly size a battery system. It is often desirable to size the battery system as large as possible to have it available for a larger percentage of the time. However, battery costs can exceed the cost of the array limiting the economic attractiveness of a large battery system. The size of the battery system needed is a function of the number of peak sun hours available at a site during the times of the year when maximum battery usage will occur. A typical relationship between peak sun hours and battery storage days needed is shown in Figure 6 [3]. The term, *"Storage Days"*, means number of days of battery storage that will likely be needed to supply loads when solar energy is not available due to bad weather. By multiplying storage days needed by daily energy of the loads being supplied the needed battery capacity can be determined. For example, if five storage days of the battery power is needed and a site uses 100Ah/day, the battery system must be sized for 500Ah. Figure 6 shows two curves; 99% and 95% system availability. If a battery system is sized using the 99% availability curve, it can be expected that the battery system will be discharged and unavailable about 1% of the year. The other 99% of the year the system will be capable of supplying power to the loads.

The following two equations (3) can be used to calculate the storage days needed.

For 99% availability:

$$\text{Storage days} = 24 - (4.73)(PSH) + (0.3)\cdot(PSH)^2$$

For 95% availability:

$$\text{Storage days} = 9.43 - (1.9)(PSH) + (0.11)\cdot(PSH)^2 \qquad (3)$$

Where, PSH is the lowest monthly average peak sun-hours

Once the battery capacity is known under the optimum condition, the actual battery size can be determined after accounting for discharge rate associated with temperature (Figure 5). Equation (4) shows battery size as a function of battery capacity, DOD, and percent of battery capacity.

$$\text{Battery Size} = \frac{\text{Needed Battery Capacity}}{(\text{DOD})(\text{Perc ent of Battery Capaciy of Temp.})} \quad (4)$$

D. Sizing PV Array

The PV array is sized based on amp-hours (Ah) from the panels to the batteries and from the batteries to the load. When daily average load demand, the system voltages, and inverter efficiency are known, inverter DC input needed from the battery system in Ah/day is given by,

$$\text{Inverter DC Input} = \frac{\text{Energy per day in Wh/day}}{(\text{Inverter Efficiency})(\text{System Voltage})} \quad (5)$$

Once the inverter DC input energy is determined, temperature effect and the Coulomb efficiency for the battery system has to be taken into account. The size of the PV array is then determined by,

$$\text{Size of PV Array} = \frac{(\text{Inverter DC input})(\text{System Voltage})}{(\text{PSH})(\text{Temp. Effect})(\text{Coulomb Efficiency})} \quad (6)$$

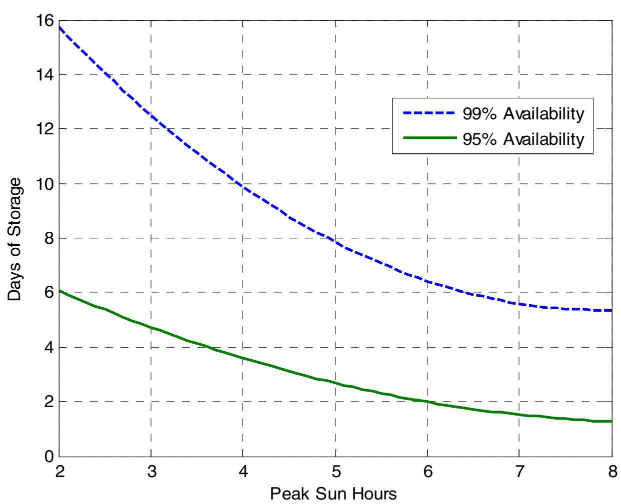

Figure 6. Days of Storage vs. Peak Sun Hours [3]

IV. COSTS ESTIMATE AND PRICING

The total costs of the entire system include the PV panels, inverters, charge controllers, batteries, O&M costs, installation system cost (including labor). Extensive research was done using the cost data available from websites. After studying the price variance between sources, for simplification the average cost given for some components was used in the final estimate.

A. PV Module Prices [7][13]

Module Size	Module Price
Greater than 75W (annual purchases less than 25 MW) [7]	2.36 ($2010/$W_P$)
Greater than 125W [13]	2.42 ($2012/$W_P$)

B. PV Inverter Prices [8][13]

Installation Year	Inverter Price ($2010/W) [8]	Installation Year	Inverter Price ($2012/W) [13]
2007	$0.7	2011 (Jan.)	$0.715
2008	$0.7	2012 (Jan.)	$0.712
2009	$0.8		

C. Batteries (Deep Cycle Design) [4][13]

Battery Specification	Price ($2012)	
Concorde: 12V, 104Ah	$275	$2.64/Ah
Concorde: 12V, 212Ah	$540	$2.54/Ah
Concorde: 12V, 69Ah	$212	$3.07/Ah
Surrette:12V, 342Ah	$1063	$3.11/Ah
Surrette: 12V, 400Ah	$747	$1.87/Ah
Surrette: 12V, 800Ah	$1512	$1.89/Ah
Trojan: 12V, 305Ah	$378	$1.24/Ah
Trojan: 12V, 104Ah	$275	$2.64/Ah
Universal Power Group: 12V, 100Ah	$187	$1.87/Ah
Universal Power Group.:. 12V, 200Ah	$412	$2.06/Ah
Average [4]	$2.29/Ah at 12V (or $0.19/Wh)	
Battery Price (as of Jan. 2012) [13]	$ 2.56/Ah at 12V (or 0.213/Wh)	

D. Charge Controller [4]

Model	Current Limit	Price ($)	
Midnite Solar Classic MPPT 200V	64A	$668	$10.4/A
OutbacFLEXmax 80	80A	$584	$7.30/A
Xantrex XW SCC	60A	$480	$8.0 /A
Morningstar ProStar PS-30M	30A	$174	$5.8 /A
Blue Sky 50L	50A	$448	$8.96/A
Apollo T80	80A	$754	$9.43/A
Average		$8.32 / A	

E. Installation Cost - Balance-of-System (BOS), and Tracking System Costs

Installation costs vary dependent on the location, operating conditions, and system size. However, one source [3] states that installation and balance of system (BOS) component costs combined would be around 20% of the sum of PV panels, batteries, and inverters, and the other source [5] states that installation and BOS costs are $3/W. According to Reference [3], 1- axis tracking system costs is given by the following equation,

$$\text{Tracking System Costs} = \$400 + (\$100)(\text{Panel Area/m}^2) \quad (7)$$

By using this information, the approximate installation, BOS components, and tracking system costs are calculated.

V. A CASE STUDY

According to the Energy Information Agency (EIA) report of 2009, the U.S. total energy sold to residential customers was 1,364 TWh and total number of residential customers (metering point) was 125.1 million [6]. Therefore, average annual residential energy consumed per meter was 10,900kWh/yr or 29.86kWh/day (≈ 30kWh/day). This was used as the base line for the calculation below. It is also assumed that the location of this project is at Boulder, Colorado.

A. Load Information

Figure 7 shows a typical example of the residential load demand curve indicating about a 3.5kW peak and 30kWh/day of electrical energy demand. Using this information, the inverter size should be greater than 3.5kW and its surge capability should be around 7kW because some components, such as a refrigerator, require higher starting currents. For PV applications, inverters usually have a continuous output that is twice this size [4].

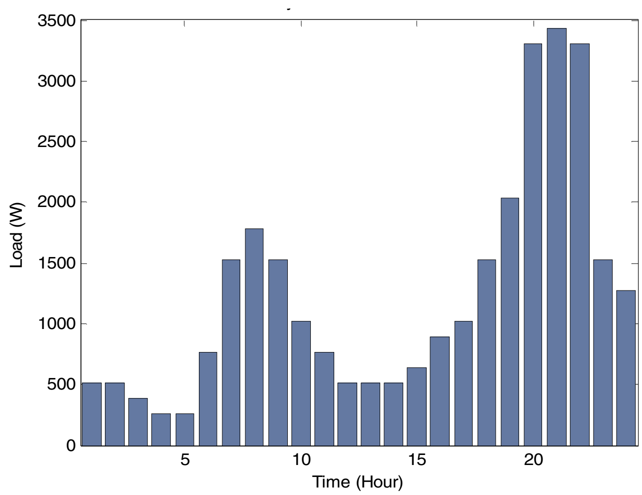

Figure 7. (Typical) Daily Load Curve

Figure 8 shows the annual solar insolation in Boulder, Colorado, US for 1-axis tracking and fixed systems tilted at various angles. The PV system with a 1-axis tracking seems to receive more solar insolation than other systems shown. Since the unit of 1-sun of insolation is defined as 1kW/m^2, the average monthly solar insolation should be identical to the peak sun hours per day and is used to determine the battery size and panel size.

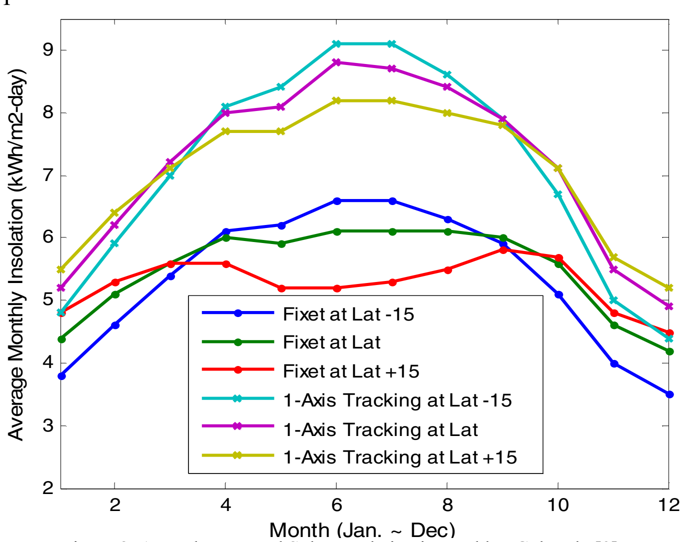

Figure 8. Annual Measured Solar Insolation in Boulder, Colorado [9]

B. Sizing Battery

Since the selected inverter size is 3.5kW and less current is recommended to make the system loss lower, 48V is used for this system voltage. DC current is determined by Equation (5),

$$\text{DC Input} = \frac{30{,}000\text{Wh}}{(0.9)(48\text{V})} = 691\,\text{Ah/day}$$

From Figure 8, peak sun hour is about 4.5 hours at the tilted angle, and for 99% system availability, the storage days is determined from Equation (3),

$$\text{Storage Day} = 24 - (4.73)\,(4.5) + (0.3)\,(4.5)^2 = 8.79 \text{ days}$$

When the DOD and discharge rate for the given temperature is assumed to be 0.4, battery size is determined by Equation (4),

$$\text{Battery size}= \frac{(691)(8.79\,days)}{(0.4)} = 15{,}184\,Ah\,,$$

A 12V, 800Ah battery is chosen. Each string of batteries should have a minimum of (15,184Ah/800Ah=) 18.98 batteries. Therefore, 19 strings of 4 batteries (4 x 12 = 48V) are required for this system.

C. Sizing PV Array

Since the system requires 691Ah/day, at peak sun 691/4.5 hour=153.6 A is required. When Coulomb efficiency of 90% and 90% temperature effect are assumed, the total array size would be determined by Equation (6),

$$\text{Array Size} = \frac{(691\text{Ah/day})(48\text{V})}{(4.5)(0.9)(0.9)} = 9.1\text{kW}$$

According to the annual report of thin film project by the National Renewable Energy Laboratory (NREL), the average commercial PV efficiency of the highest four modules (18.2, 14.1, 14, and 13.4 [2]) is 14.92%. Therefore, total area of PV panels would be,

$$\text{Area} = \frac{\text{Array Size}}{\text{Efficiency}} = \frac{9{,}100\text{W}}{(1\text{kWh/m}^2)(0.1492)} = 61\text{m}^2$$

Since the battery capacity, PV panel size, and area increase when storage days are higher, few more cases for lower storage days and lower system availability are analyzed through the same steps as the example. In Figure 8 the system with a 1-axis tracking has a higher monthly average insolation during the winter. Table 1 shows comparison of peak sun hours, storage days, battery size, and PV panel size for the systems with a fixed angle and a 1-axis tracking system for two different system availabilities.

D. The Backup Generator System

According to Table 1, the system with lower availability would have a smaller sized battery, and at higher storage days the size of battery and panel would also be smaller. However, a tracking system requires more capital, and the lower system availability necessitates backup generators such as diesel or gasoline.

The backup generators should supply power during the time when there is no PV power. For 99% PV system, 1% of power should be produced by backup generators, and similarly for the 95% PV system, 5% of power should be provided by backup generators.

TABLE 1.SYSTEM COMPARISON

	Fixed Angle		**1 – Axis Tracking**	
PSH	4.5		5.3	
System Availability	99 %	95 %	99 %	95 %
Storage Days	8.79	3.11	7.36	2.45
Battery Size	15,184 Ah	5,368 Ah	12710 Ah	4,232 Ah
Number of String (800Ah)	19 × 4	7 × 4	16 × 4	6 × 4
Panel Size	9.1 kWp	9.1 kWp	7.7 kWp	7.7 kWp
Area	61 m^2	61 m^2	51.8 m^2	51.8 m^2

E. Cost Comparison

Based on the data and analysis given above, alternative costs for various designs are calculated. The composite results are shown in Table 2. The first column is for the stand-alone PV system with 99% availability. The second column is for 95% system availability, and the third column is for 95% availability with a 1-axis tracking system. For the calculations of PV modules, inverters, batteries, and charging controllers, prices of \$2.42/W_P, \$0.712/W, \$2.423/Ah (at 12V), and \$8.32/W are selected. Calculation for the installation cost is estimated at 20% of the sum of PV panels, batteries, and inverters.

TABLE 2. CAPITAL COST COMPARISON

Availability & Design Components	**99% Tilted**	**95% Tilted**	**99% 1-Axis**	**95% 1-Axis**
Panel	9.1kWp / \$22,022	9.1kWp / \$22,022	7.7kWp/ \$ 18,634	7.7kWp/ \$ 18,634
Inverter	3.5kW / \$2,492	\$2,492	\$2,492	\$2,492
Battery	\$147,318	\$54,275	\$124,058	\$46,521
Charging Controller	153.6A/day \$1,316	\$1,316	130.3A/day \$1,117	\$1,117
Tracker	-	-	\$5,580	\$5,580
Installation Labor	\$34,629	\$16,021	\$29,260	\$13,753
Backup Generator (\$0.50/W)	3.5kW \$1500	\$1500	\$1500	\$1500
Total	**\$209,278**	**\$97,626**	**\$182,641**	**\$89,597**
	\$23.0/Wp	\$10.73/Wp	\$23.72/Wp	\$11.64/Wp

VI. Conclusion

In this paper, the application of the PV solar energy system is discussed, and the procedures for sizing each component of the PV system are outlined. The costs of PV panels, inverters, batteries, charge controllers, and other costs are discussed and used to estimate the costs for a typical stand-alone PV system. For the case study, a typical residence was selected, and the electrical energy usage is assumed to be the average of residential customers in the U.S in 2009. For the cost, comparison four different systems are selected: PV systems at a fixed angle and a 1-axis tracking and systems with batteries sized for 99% and 95% system availabilities. The system with 1-axis tracking would be more economical than the others studied (estimated cost of \$89,600), and this is about 43.8% of the system at fixed angle with 99% system availability.

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VIII. BIOGRAPHIES

Keun Hyuk Lee (Student Member, IEEE**)** was born in Seoul, South Korea. He graduated at the Colorado School of Mines, Golden, Colorado with a BS in Engineering (Electrical Specialty) and MS in Engineering (Electrical / Energy and Power Systems focus) in 2008, and 2011 respectively. He is currently a pursuing his PhD in Engineering Systems (Electrical Specialty) at Colorado School of Mines (CSM), Golden Colorado with the emphasis in Electric Power, Machines and Renewable Energy.

Keith Malmedal (Member, IEEE) received his MSEE degree (Power), a MSCE degree (Structures) from the University of Colorado at Denver in 1998 and 2002, respectively. In 2008 he received his PhD at Colorado School of Mines, Golden, CO in Engineering Systems (Electrical Specialty) focusing on Electric Power/Renewable Energy Applications. He has over 20yrsof combined experience in electrical power system design and system study, teaching, and research, and is presently the President of NEI Electric Power Engineering, Arvada, Colorado, a consulting firm specializing in all aspects of power system engineering and design. He has published over a twenty "peer reviewed" technical papers in archival journal and taught university courses (both undergraduate and graduate level) and short courses related to power systems, machines, protection, renewable energy, and energy policy issues. Dr. Malmedal is also a member of the American Society of Civil Engineers (ASCE) and a registered professional engineer in 17 states and Alberta, Canada.

Pankaj K. (PK) Sen (Fellow, IEEE) received his BSEE degree (with honors) from Jadavpur University, Calcutta, India, and the M.Eng. and Ph.D. degrees in electrical engineering from the Technical University of Nova Scotia (now Dalhousie University), Halifax, NS, Canada. He is a Professor of Electrical Engineering and Site Director of the Power Systems Engineering Research Center (PSerc.org) at Colorado School of Mines in Golden, Colorado. His research interests include application problems in electric machines, power systems, renewable energy, safety and power engineering education. Dr. Sen is a Registered Professional Engineer in the State of Colorado, USA.