Sizing and cost estimation methodology for stand-alone residential PV power system

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Abstract: This paper investigates the sizing and costing methodology for a stand-alone photovoltaic (SAPV) power system based on the number of sunshine hours available in the world. The sizing and costing of the PV system for the electrical load of 3.65 kWh/day was presented in this paper for different continents of the world. The unit cost of electricity generated from the PV system was determined based on their life cycle cost analysis. The capital cost and unit cost of electricity for the SAPV systems were evaluated as \$9,198/kWp and \$0.6/kWh respectively for India. The total CO_2 emission mitigated by the PV power system in its lifespan was estimated at 63 tons which correspond to the carbon credits of \$2,048.

Keywords: photovoltaic; PV; stand-alone photovoltaic; SAPV; LCC; mitigation of CO_2 emissions; carbon credits.

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1 Introduction

Photovoltaic (PV) energy generating systems directly convert solar energy into electricity using PV effect. An off grid or stand-alone PV (or SAPV) system means that the sole source of power is utilised for electric load of home appliances, water pump and street lights, etc. which are located in remote areas. In such areas, the grid extension is either costlier or not feasible due to physical barriers. The SAPV systems often store energy generated during the day in a battery bank for use at night. These systems represent a cost-effective and eco-friendly alternative to conventional high cost diesel-fired generators, particularly in developing countries where most of the population lives in rural and isolated areas. It was reported in the literature that the SAPV systems were designed and implemented at several locations around the world to provide power in remote areas. Vallve and Serrasolsest (1997) reported that in Spain, the local authorities promoted an electrification project of 65 sites with 50 kWP SAPV systems for rural electrification of a remote mountainous site. Bhuiyan and Asgar (2003) had designed an SAPV for a residential area using standard methods for four hours of operation per day for climatic conditions of Dhaka. Similarly, Habali and Taani (2005) reported that in Jordon, a 1 kWP SAPV system was implemented to supply power to rural houses for 24 hours a day. Somchai et al. (2006) had studied the performance of 500 kWp grid connected PV system in Thailand which supplied power in the range of 1,452.3 kWh/day to 2,042.3 kWh/day.

The final cost of any PV system ultimately depends on PV array size, battery bank size and on the other components required for the specific application. Hence, the lack of PV system design results in high design costs for PV power system projects. The State Energy Conservation Office (SECO, 'Estimating PV system size and cost') in Texas has designed a fact sheet to generate an estimate for the PV array size, battery bank size and total cost of an SAPV system. Numerous methodologies were developed by several scientists for optimal sizing of the SAPV systems. These approaches use the analytical solutions and numerical methods. The analytic solutions developed by Gordon (1987) were believed to bring the price of the SAPV systems to economic viability and helps local designers in developing countries to design these systems. The SAPV system performance parameter such as overall efficiency can be increased using maximum power point tracking (MPPT) as compared to conventional system performance as reported by Salas et al. (2005).

Groumpos and Papegeorgiou (1991) addressed the subject of load management for the SAPV systems. This approach involves a general load classification in order to manipulate the controllable loads to reduce the battery size. This leads to the reduction in initial investment for the SAPV system and reduction in cost of electricity generation. In the year 1970, PV electrical energy was very expensive with an estimated cost of US\$30/kWh as mentioned by Lesourd (2001).

Lesourd (2001) reported that for the year 1997, the cost of PV electricity production for grid-connected systems was in the range of US\$0.25/kWh (for Sunbelt areas of Europe and the USA) and US\$0.33/kWh (for less favourable climatic conditions in the USA, Europe and Japan). Nounia et al. (2006) estimated the levelised unit cost of electricity (LUCE) for 18 selected locations situated in different Indian geographical regions. The LUCE reported by Nounia et al. (2006) varies in the range of 28.31 Rs/kWh to 59.16 Rs/kWh (or 0.65 US\$/kWh to 1.35 US\$/kWh) for the PV projects of capacity in the range 1 kWP to 25 kWP. The unit cost of electricity for 2.7 kWP grid connected mono-crystalline PV system in Singapore was estimated about five to seven times costlier than that of oil or gas fired power plant as reported by Kannan et al. (2006).

Rehmana et al. (2007) carried out LCC analysis of 5 MWP grid connected PV system. They had estimated various economical indicators like internal rate of return (IRR), simple payback period and number of years required for positive cash flows from the PV system, net present value, annual life cycle savings, profitability index and unit cost of electricity.

Energy payback time (EPBT) is a commonly used indicator in life cycle assessment of the solar PV systems to justify the primary use of energy for the production of the PV system components. The EPBT is the ratio of total embodied energy incurred in making the PV system components and annual energy produced by the PV system. Slesser and Houman (1976) had first made this analysis for PV module and reported EPBT of 40 years for the PV system. Further, Kato et al. (1998) had reported EPBT of the PV system as 12 years. Battisti and Corrado (2005) had investigated that EPBT of building integrated multi-crystalline PV system was reduced from 3.3 years to 2.8 years when the PV system is retrofitted on a tilted roof of building located in Rome (Italy). Alsema and Nieuwlaar (2000) had attempted to forecast EPBT of 1.5 years to 2 years for mono-crystalline solar cell for the year 2020 by considering the advancement in technology and improvement in efficiency of solar cell. The EPBT value is to be used site specific for major decision-making in power generation planning.

The PV power system is eco-friendly because the amount of carbon dioxide (CO_2) emissions associated with the production of electricity from the PV system is negligible as compared with conventional coal thermal power plant. An average intensity of CO_2 emissions from coal based thermal power plant is 0.98 kg/kWh for generation of one unit of electricity as reported by Watt et al. (1998) and Chel et al. (2008). This average CO_2 emissions intensity factor in India can be considered 1.6 times than that of 0.98 kg/kWh which accounts for 40% transmission and distribution losses and 20% loss due to inefficient equipments in the power plant. Hence, the average intensity of CO_2 emissions from coal thermal power plant in the case of India is 1.568 kg/kWh.

The typical 5 MWP grid connected PV system power plant has the potential to prevent or mitigate greenhouse gas (GHG) emissions on an average of 8,182 tons as reported by Rehmana et al. (2007). Similarly, Kannan et al. (2006) reveal that GHG emission from 2.7 kWP grid connected mono-crystalline PV system in Singapore is one-fourth that from oil fired steam turbine plant and one-half that from gas fired combined cycle plant.

The literatures are available on building integrated PV system with two types of configurations:

a building roof integrated PV (BIPV) system

b SAPV.

Benemann et al. (1999) had reported the first installation of BIPV system in Aachen, Germany. In a BIPV system, the PV arrays are installed over the roof surface of the building facing due south in northern hemisphere at an inclination equal to 0.9 times latitude of the place to intercept maximum solar radiation over the year as reported by Messenger and Ventre (2000). In the case of the SAPV system, PV arrays are mounted on fixed aluminium frames mounted on the steel truss structure on the ground surface. Both the systems require PV arrays, solar charge controller (SCC), battery bank, inverter and connected load, etc. The PV module arrays are connected in such a configuration to supply the desired voltage and current for charging battery bank reported by Benghanem and Maafi (1998). The battery bank is not necessary if there is no electricity use during night time which considerably reduces the cost of electricity.

The BIPV system is more economical than the SAPV system because the PV arrays are mounted on the roof surface or utilised as roof structure material which reduces the cost of roof construction as reported by Benemann et al. (2001). The BIPV system is most suitable for cold climatic regions in India e.g., Srinagar, Leh and Laddakh, etc. because of the application of the PV system for space heating using hybrid PV thermal air duct system and daylighting of rooms through transparent portion of PV modules in the case of glass to glass PV modules. This leads to the reduction in annual heating and electric lighting requirement for the room of building which considerably leads to energy saving. These allied applications of the PV systems help in reducing the cost of electricity generation. Many researchers and scientists are presently working on the hybrid PV thermal applications for different renewable energy technologies e.g., PV thermal air heater for space heating, PV thermal solar water heater, PV trombe wall facade, PV thermal greenhouse dryer, etc. The hybrid PV thermal system used for room air heating has improved the efficiency of solar cells due to heat removal from the back surface of PV module reported by Tripanagnostopoulos et al. (2002) and Joshi and Tiwari (2007). This hybrid PV thermal technology integrated with building has the advantage of space heating, reduction in cost of structure material for roof, provision for electrical energy and daylighting of building using glass to glass PV modules. In the case of the glass to glass PV module, the conventional opaque tedlar material is replaced with transparent glass; hence, sunlight can pass into the interior of the building through the transparent portion (or non-packing area) of PV module and hence provides daylighting which ultimately conserve electricity use for lighting during daytime for The Energy and Research Institute (TERI) retreat building in New Delhi. Similarly, roof integrated PV systems are installed at various places in India e.g., Indian Institute of Science, Banglore, Punjab Energy Development Agency (PEDA) building, etc.

The Ministry of New and Renewable Energy (MNRE) Systems of the government of India (GOI) had reported that about 1 MW aggregate SAPV power capacities were installed in different regions in India, mainly at Sagar Island in West Bengal, Uttar Pradesh, the north-eastern region, Lakshadweep and the Andaman and Nicobar Islands.

The GOI is planning to convert 60 cities (with population range of 5 lakhs to 50 lakhs) into solar townships that run partially on renewable energy sources (11th Five Year Plan, GOI) so that cities shall either cut power consumption by at least 10% or shift as much as possible to renewable energy sources.

There are three basic configurations widely adopted for the SAPV systems:

a The PV array supply power to the electrical load directly. This is the simplest configuration and it is only possible when demand matches availability of solar insolation suitable for water pumping in overhead tank for storage.

b The most common configuration is a PV array that powers the load and charges a storage battery, allowing electricity to be used at night and during periods of low insolation.

c The PV-hybrid system relies on an auxiliary source of power e.g., a fossil fuel generator to complement the power generation from the PV array. This configuration still requires some battery storage to avoid short-term fluctuations. It is particularly suitable for applications that are critical or in regions with large variations in sunlight conditions through the year.

In this paper, the second configuration of the SAPV system as mentioned above was analysed to cater partial electrical load of home system in different parts of the world. This investigation was carried out based on the experiences gained from the experimental case study of an existing 2.32 kWp SAPV power system integrated with solar energy research laboratory in New Delhi (28.58ºN, 77.2ºE, 216m above MSL) in India. The life cycle cost analysis was carried out for the SAPV system to estimate the capital investment for 1 kWp PV power station and cost of one unit of electricity. The mitigation of CO_2 emissions and the carbon credit that can be earned from the PV home system was also determined at the end of this paper.

2 SAPV power system

The SAPV system consists of components e.g.:

a PV modules array

b ground based steel frame structure

c blocking diode

d logic based intelligent solar charge controller (SCC)

e battery bank

f DC/AC grid interactive sine wave inverter

g miniature circuit breaker (MCB)

h electrical loads of the home system as shown in the block diagram of the PV system (Figure 1).

The SAPV power system located at the Solar Energy Park, IIT Delhi is shown in Figure 2.

Figure 1 Block diagram of SAPV power system

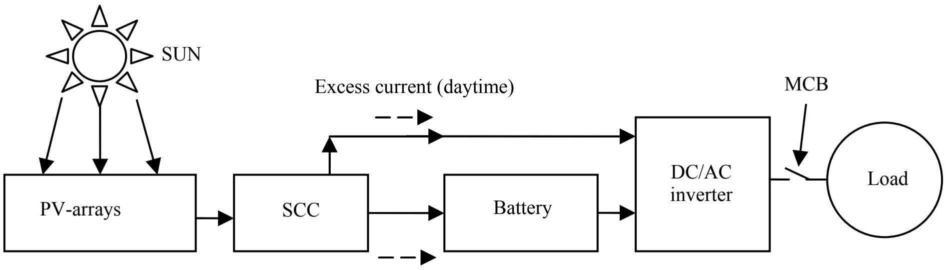
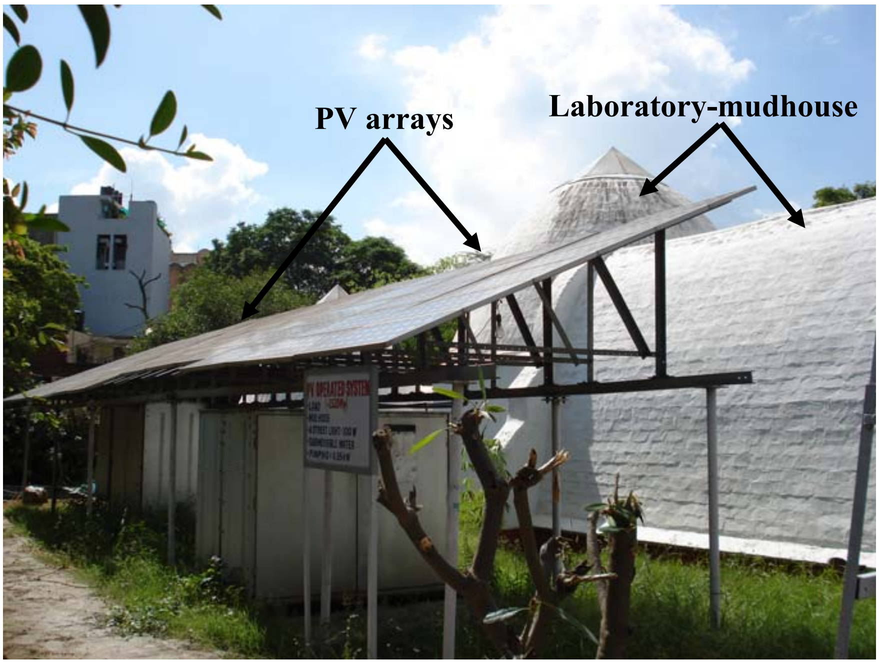


Figure 2 Pictorial view of SAPV power system at Solar Energy Park (New Delhi) (see online version for colours)



The steel structure of the SAPV system consists of antirust coated L-shaped steel angles and round pillars. These materials are assembled using nuts and bolts to form a steel frame structure for supporting PV modules facing due south in the northern hemisphere. The PV modules have fixed position throughout the year in the present SAPV system hence annual average inclination angle for PV arrays is taken as the latitude (ø = 28.58°) of New Delhi as per Messenger and Ventre (2000). If PV array tilt angle adjustment is possible, then the optimum inclination angle values in winter and summer are (ø + 15) and (ø – 15) respectively as reported by Messenger and Ventre (2000). The power generated by the PV system is supplied to the battery bank through SCC. The battery bank is placed inside the mild steel sheet box below the PV array. A sine wave DC to AC converter (or inverter) is mounted inside the box to convert the DC power supplied by battery bank into AC power of 230V and 50 Hz. This power is then fed to the electrical load through the MCB as shown in Figure 1. The MCB is designed for maximum connected load current and if the load current exceeds the designed value, the power flow circuit breaks and hence safeguards from short circuit accidents. There is provision to use grid power for the laboratory in the case of additional heavy loads for short duration.

The functions of important SAPV components are given below for the complete understanding of the typical SAPV power supply system.

2.1 Logical based intelligent solar charge controller

The logic based SCC controls the charging current of the battery to ensure the long life of the battery. This charge controller is important to prevent over charging in the battery bank and also to ensure recharging of the battery when voltage falls below a predefined value.

2.2 Battery bank

The battery bank is a principal energy storage device to ensure continuous supply even when the solar array is unable to produce any power. The battery bank for the system shown in Figure 2 consists of 16 rechargeable batteries each having a capacity of 6V/180 Ah (ampere hour). Out of the 16 batteries, eight batteries are connected in series to each other in parallel with the other eight series connected batteries to ensure required levels of voltage (48V) and current (360 Ah).

2.3 Blocking diode

In addition to solar array and battery bank, a blocking diode is required to prevent battery current to drain through the solar cells at night.

2.4 DC/AC grid interactive sine wave inverter

The battery bank provides DC power that can be directly used for DC loads, but to drive the AC loads, a DC/AC converter rated at 3 kVA is used to provide 230V/50 Hz AC power for the system shown in Figure 2.

2.5 Miniature circuit breaker

If the electrical load exceeds beyond certain limit, the SAPV power distribution system is provided with MCB system which gets trip off the power supply and avoids accidents due to any short circuit.

2.6 Electrical load on SAPV system

Table 1 Typical household electrical appliances and their run times

Appliance	*W*	*Hours used per day*	*Wh/day*
Ceiling fan	100	8	800
Coffee maker	600	0.3	180
Cloth dryer	4,856	0.8	3,885
Computer	150	2	300
Dishwasher	1,200	0.5	600
Four CFL lamps (each 15W)	60	5	300
Microwave oven	1,300	0.5	650
Radio	80	4	320
Refrigerator	600	9	5,400
Television	300	8	2,400
Vacuum cleaner	600	0.2	120
VCR	25	8	200
Washing machine	375	0.5	188
Total			*15,335*

The energy consumption by typical home is estimated about 16 kWh/day as given in Table 1 excluding thermal comfort devices such as air heater/air cooler. The number of hours of operation and power rating of typical home appliances are given in Table 1. The total connected electrical load for the SAPV system is given in Table 2. The remaining load is to be met by using grid power connection. The PV system is designed to operate at minimum daily electrical load of 3.65 kWh/day. The electrical load comprises of different appliances as mentioned in Table 2.

Table 2 Electrical loads on the SAPV power system

Appliance	*W*	*Hours used per day*	*Wh/day*
Ceiling fan	100	8	800
Coffee maker	600	0.3	180
Computer	150	2	300
Dishwasher	1,200	0.5	600
Four CFL (each of 15W)	60	5	300
Microwave oven	1,300	0.5	650
Radio	80	4	320
Vacuum cleaner	600	0.2	120
VCR	25	8	200
Washing machine	375	0.5	188
Total			*3,650*

2.7 PV power distribution to loads

The block diagram of the SAPV power system is shown in Figure 1. The electrical energy is generated by PV array during day time at threshold solar intensity (about 200 W/m^2). During daytime operation, the electrical energy generated and fed into the battery bank through SCC and the excess energy is directly supplied to the inverter to supply AC power to the electrical load through MCB. While during night time or low sunshine periods, electrical load is driven solely by battery bank power supply. The blocking diode is used to prevent current drain from battery bank to the PV array system during night time.

3 SAPV system maintenance

The following are the standard maintenance schedules usually followed for the SAPV system mentioned by the *Solar PV Training Programme Field Technician Manual* prepared by the Central Electronics Centre, IIT Madras in association with SIEMENS in the year 2001 (SIEMENS and Central Electronics Centre IIT Madras, 2001).

3.1 Weekly maintenance

It includes checking of the state of charge of the battery using standard procedure given in the training manual. Dusting of the PV array surfaces on every weekend is recommended for city climatic conditions.

3.2 Monthly maintenance

It includes the battery maintenance which is regularly carried out at the end of each month e.g., cleaning the battery connections, applying periodically a corrosion inhibitor such as petroleum jelly (anti-oxidants grease) available from any auto parts store and adding distilled water in each battery to recommended level. It also includes inspecting break down of an array.

3.3 Annual maintenance

The annual maintenance of the SAPV system includes all the major checks for physical damage and replacement of inefficient system components such as inverter/battery. The check for physical damage to the system should also be carried out to ensure system performance. Battery terminals are applied with anti-oxidant grease to avoid rusting. It is necessary to inspect the SCC for battery charging using standard manual test specified by the service provider such as SIEMENS.

4 Estimating PV system size and cost

The methodology presented here will help to estimate the size and cost of a PV system in any part of the world. The methodology was adapted from a method developed by Sandia

National Laboratories (http://www.sandia.gov/pv or http://www.InifinitePower.org). The PV system size and cost analysis was conducted in two steps. In the first step, the size of the PV array and battery bank size required were determined based on the electrical load and available sunshine hours specific to the location. In the second step, the system specifications are converted into the cost for the PV system.

4.1 Determine load, available sunlight, PV array size and battery bank size (Step 1)

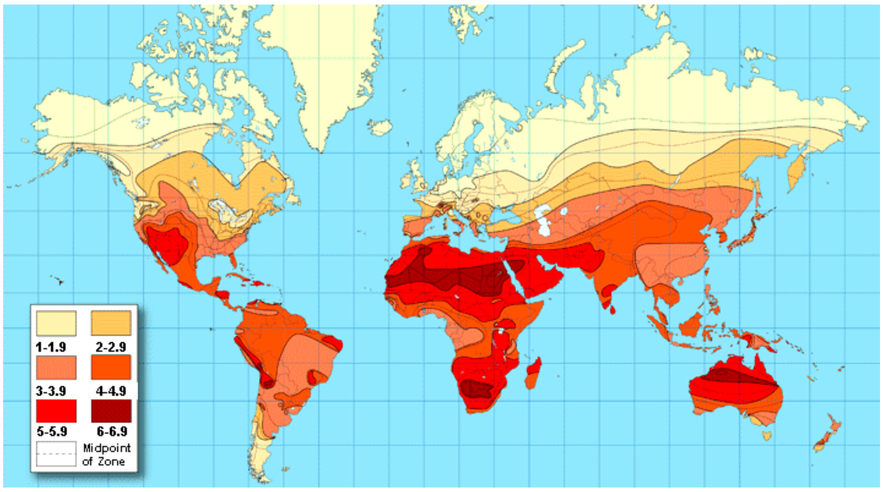
4.1.1 Determine electric load

The preferred method for determining the PV system loads is explained in Table 1. Table 1 provides an example calculation for a household to determine daily electrical load in Wh/day. For complex loads like households, it is sometimes difficult to anticipate every electric load. Electric clocks, TV, stereos and other appliances sometimes draw small amounts of power even when they were turned off. For this reason, it is recommended to multiply daily estimated load by a 'fudge factor' of 1.5. This accounts the system efficiencies, including wiring and interconnection losses, as well as the efficiency of the battery charging and discharging cycles.

4.1.2 Determine available sunlight

The amount of useful sunshine available for the solar arrays on an average day during the worst month of the year is called the 'insolation value'. It is desirable to use the worst month for analysis to ensure the PV system to operate year-round. The insolation values or number of sunshine hours per day on optimum tilted PV array surface in different parts/continents of the world are given in Figure 3. The insolation value can also be interpreted as kWh/m^2 per day of sunlight energy that fall on each square meter of solar panels at latitude tilt given in Figure 3. The insolation value was explained by Bhattacharya (1998) as equivalent hours of full sunlight (EHFS) for horizontal surface. The EHFS is a simple and convenient way to express the incident solar radiation on a horizontal unit surface area as explained by Bhattacharya (1998). It is to be noted that two widely separated places with the same latitude, but with different longitudes, can have the same value of daylight hours, with entirely different EHFS values. Hence, the EHFS should not be confused with the number of daylight hours for any site which are generally given in meteorological handbooks explained by Bhattacharya (1998).

Figure 3 Solar insolation values for the world (see online version for colours)



Notes: This map shows the amount of solar energy in hours, received each day on an optimally tilted surface during the worst month of the year. (Based on accumulated worldwide solar insolation data).

Source: http://howto.altenergystore.com/Reference-Materials/Solar-Insolation-Map-World/a43/

4.1.3 Determine PV array size

The PV system supply power to the load which will be used everyday, the size of the PV array is determined by the daily energy requirement divided by the sun-hours per day.

4.1.4 Determine battery bank size

Most batteries will last longer if they are shallow cycled – discharged only by about 20% of their capacity – rather than being deep-cycled daily. A conservative design will save the deep cycling for occasional duty and the daily discharge should be about 20% of capacity. This implies that the capacity of the battery bank should be about five times the daily load. It also suggests that the PV system will be able to provide power continuously for five days without recharging (such as during cloudy days). Hence, multiply the daily load by five and then divide the result by the voltage of the battery bank (typically 12 volts). The result is the recommended Ah rating of the battery bank. If system to be more secure and design for more days of cloudy weather, multiply by a number greater than five. However, it is generally not recommended to design for more than 12 days of cloudy weather unless it is a highly critical load.

4.2 Calculate PV system cost components (Step 2)

4.2.1 Estimate PV array cost

Many PV modules can be purchased at retail for about $5 per watt for most small systems in the 150W to 8,000W range. There are opportunities to purchase modules for a lower price, especially when the PV system is larger than the specified range. Some PV module manufacturers offer modules with 10–20 year warranties.

4.2.2 *Estimate battery bank cost (if needed for night time load)*

Many flooded lead acid batteries designed for use with the PV systems can be purchased at retail for under $1 per amp-hour.

4.2.3 *Estimate inverter cost*

An inverter is needed for operating AC load in home system. For stand-alone systems, the inverter should be sized to provide 125% of the maximum connected loads to run PV power system simultaneously at any one moment. For example, if the total load is 1,600W, choose an inverter with a rated continuous power output of 2,000W. The input rating of the inverter should never be lower than the PV array rating. Inverters are designed for residences and other small systems which are purchased at retail shop for about $1 per rated W.

4.2.4 *Estimate balance of system cost*

Besides PV modules and batteries, complete PV system requires mounting structure for PV modules, electrical wire, switches, fuses, connectors and other miscellaneous parts. It is recommended to use a factor of 20% to cover balance of system costs.

4.3 *Worksheet for sizing and estimating the cost of SAPV power systems*

Step 1 Determine the electrical load, available sunlight, array size, battery bank size:

- Determine total electrical power requirement (Wh/day) (Table 2).

  $$\text{Total power requirement } (\text{T.P.}) = 1.5 \times \text{Electrical load Wh/day.} \tag{1}$$

  For uncertainty to anticipate daily electrical load of appliances, it is recommended to multiply daily estimated load by a 'fudge factor' of 1.5. This factor accounts all the system efficiencies, including wiring and interconnection losses, as well as the efficiency of the battery charging and discharging cycles.

- Determine minimum number of sunshine hours per day for the country (Figure 3).

  $$\text{Total number of sunshine hours } (\text{S.H.}) = \underline{\hspace{2cm}} \text{ h/day.} \tag{2}$$

- Determine the PV array size needed. It is calculated by dividing T.P. with the total available sunlight at that site.

  $$\text{Total array size required} = \text{T.P.}/\text{S.H.} = \underline{\hspace{2cm}} \text{ W.} \tag{3}$$

- Determine the size of the battery bank for night load applications. It is determined by multiplying the T.P. with five which results in Wh and this value is divided by battery voltage (e.g., 12V) to get the value in Ah.

  $$\text{Total battery bank required} = (5 \times \text{T.P.})/12 \text{ Ah.} \tag{4}$$

Step 2 Calculate the cost of the PV system needed for the above application.

- Multiply the size of array by \$5 per W to estimate the cost of array.

  Cost estimate for PV array = \$ __________

- If battery bank is used, multiply the size of the battery bank by \$1 per Ah.

  Cost estimate for battery bank = \$ __________

- If inverter is used, multiply the size of array by \$1 per rated W.

  Cost estimate for inverter = \$ _____________

  Subtotal = \$ _____________

- Multiply the subtotal by 0.2 (20%) to account for the balance of system costs (mounting structure, wire, fuses, switches, etc.).

  Cost estimate for balance of system = \$ _____________

  Total estimated PV system cost = \$ _____________

5 Life cycle cost analysis of PV system

The life cycle cost analysis was carried out for the SAPV power system assuming useful life of 30 years for PV array system and ten years life for battery bank because only 20% is discharge/day which improves life of battery. The capital cost break up of the PV system is given in Table 3 (\$1 = Rs. 40). The line diagram of life cycle cost and various cash flows at different intervals of time is shown in Figure 4.

Each battery is replaced after ten years with new battery. This is also considered in following life cycle cost analysis.

C_B = Battery cost = \$2,281.3 (Table 3)

C_M = Annual maintenance cost (1% of capital cost) = \$106.2/year

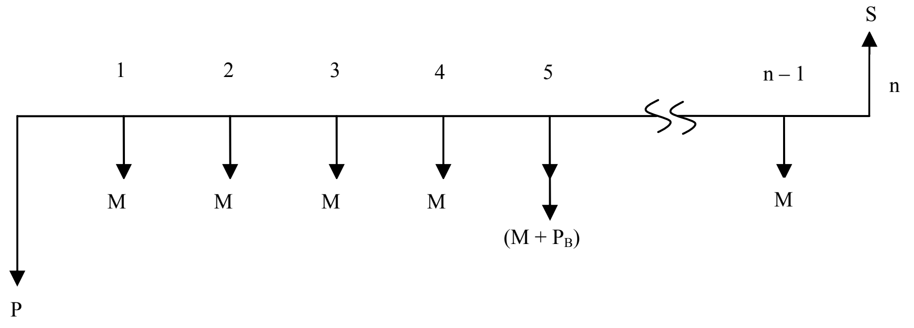
Pi = Capital cost = \$ 10,621.5 (Table 3, N=5)

$$P_M = \text{Present maintenance cost} = C_M \times \left[\frac{\left((1+i)^{30} - 1\right)}{\left(i \times (1+i)^{30}\right)} \right] = \$1{,}837. \tag{5}$$

Table 3 Sizing and costing of SAPV system for home load of 3,650 Wh/day

	Number of sunshine hours (N) distributed in the world					
Load = 3,650 Wh/day	*N = 1*	*N = 2*	*N = 3*	*N = 4*	*N = 5*	*N = 6*
Array size (W)	5,475	2,738	1,825	1,369	1,095	913
Battery bank size (Ah)	2,281	2,281	2,281	2,281	2,281	2,281
Cost of array ($)	27,375.0	13,687.5	9,125.0	6,843.8	5,475.0	4,562.5
Cost of battery bank ($)	2,281.3	2,281.3	2,281.3	2,281.3	2,281.3	2,281.3
Cost of inverter ($)	5,475.0	2,737.5	1,825.0	1,368.8	1,095.0	912.5
Subtotal ($)	35,131.3	18,706.3	13,231.3	10,493.8	8,851.3	7,756.3
Cost of B.O.S. ($)	7,026.3	3,741.3	2,646.3	2,098.8	1,770.3	1,551.3
Total PV system cost ($)	42,157.5	22,447.5	15,877.5	12,592.5	10,621.5	9,307.5
ALCC-1 ($/year) (i = 4%)	2,067.1	1,220.2	937.9	796.7	712.0	655.5
ALCC-2 ($/year) (i = 8%)	3,735.1	2,129.3	1,594.1	1,326.4	1,165.9	1,058.8
ALCC-3 ($/year) (i = 12%)	5,436.6	3,057.8	2,264.9	1,868.4	1,630.5	1,471.9
C-1 ($/kWh) (for i = 4%)	1.6	0.9	0.7	0.6	0.5	0.5
C-2 ($/kWh) (for i = 8%)	2.8	1.6	1.2	1.0	0.9	0.8
C-3 ($/kWh) (for i = 12%)	4.1	2.3	1.7	1.4	1.2	1.1

Figure 4 Line diagram of life cycle cost of PV power system



Notes: i = interest rate (in % for renewable energy systems in India) = 4%.
Let N = solar insolation on tilted surface = 5 hours/day,
Present capital investment (Pi) = $10,621.5 (from Table 3 for N = 5) and
S = salvage value of PV system at the end of 30 years = $1,770.3.

P_{Net} = Net present cost for SAPV system ($)

$$P_{Net} = P_i + P_M + \left[\frac{C_B}{(1+i)^{10}}\right] + \left[\frac{C_B}{(1+i)^{20}}\right] - \left[\frac{S}{(1+i)^{30}}\right]. \tag{6}$$

P_{Net} = $12,312

A_A = Annualised cost of SAPV power system ($)

$$A_A = P_{Net} \times \left[\frac{\left(i \times (1+i)^{30}\right)}{\left((1+i)^{30} - 1\right)} \right]. \tag{7}$$

A_A = $712/year (Table 3, N=5)

U = Total annual electrical energy used from SAPV system

$$U = 3.65 \text{ kWh/day} * 365 \text{ days/year} = 1{,}332.25 \text{ kWh/year}. \tag{8}$$

C = Cost per unit of electricity generated by SAPV system ($/kWh)

$$C = \left[\frac{A_A}{U} \right]. \tag{9}$$

C = $0.534/kWh or (Rs. 21.37/kWh)

The LCC analysis was carried out for different interest rates (4%, 8% and 12%) and different values of N (1 to 6) to estimate the cost of electricity produced by the SAPV system. The values of N range from 1–6.9 all over the world which is shown in Figure 3.

6 SAPV system and sustainable environment

At the global level, generation of electrical energy is mostly dependent on fossil fuels. Fossil fuels are however diminishing due to the extensive and continuous use prompted by increasing population and rising level of development. Moreover, burning of fossil fuels is the principal cause of CO_2 emissions leading to air pollution and environmental degradation. Hence, there is a need to conserve fossil fuels and to explore possible alternatives for electricity generation. In this perspective, awareness about the utilisation of renewable energy sources (such as solar energy) has gained acceptance globally. Most of the Indian territory has high potential of solar radiation, which is most suitable for the development of the solar PV system for power generation in India. The PV power system is environment friendly in comparison to other source of energy used for power generation. The average CO_2 intensity of emission for electricity generation from coal based thermal power plant is 0.98 kg of CO_2/kWh given by Watt et al. (1998) and reported by Chel et al. (2008). This intensity factor is modified for Indian conditions by multiplying with factor 1.6 which accounts for 40% loss of energy in transmission and distribution and 20% loss due to the use of inefficient electric equipments at power plants in India reported by Chel and Tiwari (2009). Hence, the revised intensity factor for CO_2 emissions in India is 1.568 kg of CO_2/kWh of electrical energy generation from coal thermal power plant.

Energy conversion through the PV system is one of the most important, more reliable and environmental friendly renewable energy technology which has the potential to contribute significantly to the development of sustainable energy systems for power generation. It also plays an important role to mitigate CO_2 emissions. The numerical computation was carried out to estimate the amount of CO_2 emissions mitigated due to the SAPV power supply system.

An average CO_2 emission intensity for electricity generation from coal based thermal power plant is approximately 0.98 kg of CO_2/kWh as given by Watt et al. (1998) and reported by Chel et al. (2008). This intensity factor is modified to 1.568 kg of CO_2/kWh for Indian conditions as mentioned earlier. If the PV system has a lifetime of 30 years, the CO_2 emissions mitigated can be estimated as follows:

$$\begin{aligned}
&\text{Total } CO_2 \text{ mitigated in lifespan of SAPV due to the power generation}\\
&= 1.568\left(\text{kg/kWh}\right)\times \text{Energy generated}\left(\text{kWh/year}\right)\\
&\times \text{Life of PV system}\left(\text{years}\right)\\
&= 1.568 \text{ kg/kWh}\times 3.65 \text{ kWh/day}\\
&\times 365 \text{ days/year}\times 30\text{years} = 62{,}669.04 \text{ kg}\left(\text{or } 63 \text{ tons}\right).
\end{aligned} \tag{10}$$

In the total life span of 30 years of the SAPV power supply system, the total amount of saving of CO_2 emissions into the atmosphere is estimated to be 63 tons. In this way, if many such SAPV systems with capacity of 1 kW to 25 kW are installed for each house holds or remote villages where grid electricity cannot be reached, then huge amount of environmental pollution can be avoided. The SAPV system is ideally suited for any locations of India especially in the remote villages where there is difficulty of extending transmission lines adding to extra cost of transmission lines and energy losses due to long distance power transmission.

In the case of thermal power plants, out of the total amount of thermal input, 30% to 40% output is in the form of electricity generated and the rest about 60% to 70% part of the total input energy is dissipated into the environment in the form of heat energy which also accounts for global climate change. In addition to this large amount of heat dissipation, a substantial amount of CO_2 along with particulate matter is released into the environment every year. In contrast, a PV power system does not dissipate such enormous amount of heat energy into the surrounding environment and saves huge amount of CO_2 emissions. Hence, the PV system is an environment friendly option for power generation and should be preferred where there is no electricity or extension of grid power is a costlier option.

7 Results and discussions

The keys results for the PV power system are as follow:

1. For the given energy consumption of 3.65 kWh/day in Table 2, the capital cost required for the PV system for different N values is shown in Table 3. The capital cost required for the given load varies in the range of \$9,307 to \$42,158 for different continents in the world. The capital cost (\$/kWp) and cost of electricity (\$/kWh) for India can be obtained from Table 3 corresponding to N = 4 as shown in Figure 3.
2. The total annual energy consumed by home appliances is 1,332.25 kWh/year. This energy consumption from the PV system contributes to the mitigation of CO_2 emissions about 2.1 tons/year. In the total life time of 30 years, the SAPV systems can mitigate nearly 63 tons. The carbon credit is priced at different rates in the range of €15/ton CO_2 to €30/ton CO_2 mitigation. Assuming rate of carbon credit as €20/ton

($32.5/ton) CO_2 mitigation, then the total carbon credits that can be earned by the SAPV system is $2,048.

3 The autonomy day for battery bank was kept as five days for operating electrical load during cloudy days.

4 The LCC analysis of the SAPV power system shows that the capital cost for India is $12,592.5 (Table 3, N=4) for 1,369 Wp PV array system to meet the load of 3.65 kWh/day. Hence, the capital cost required for 1 kWp PV power system in India is approximately $9,198/kWp. The unit cost of electricity in India from the PV system for 4% annual interest rate is $0.6/kWh. This unit cost of electricity for PV in India ranges from $0.6/kWh to $1.4/kWh for the interest rate in the range of 4% to 12%.

It is quite evident that the SAPV system is an environment friendly and reliable option for the generation of electricity to comfortably meet the power requirements of home appliances. This power system is more reliable since it has five days of autonomy for battery bank to operate load during cloudy days without shut down. Also, the system can operate continuously without any break down throughout the life of system if it is properly maintained as per the maintenance schedule discussed in the paper. Further, the PV system does not create any noise during its operation as compared to the conventional diesel generator and is therefore most suitable for remote village locations where there are frequent power cuts or grid extension is a costlier option. Another advantage associated with an SAPV system is the low operation and maintenance cost of the system.

8 Conclusions

The unit cost of electricity is estimated as $0.5/kWh which is comparable to $0.44/kWh as reported by Gronbeck (1994). The capital cost for 1 kWp PV power system is estimated as $9,307/kWp which is lower as compared to $10,563/kWp mentioned by Anon (2003). The total amount of CO_2 emissions mitigated due to the existing SAPV power supply in its life span is estimated as 63 tons. This results in potential of the PV system to earn the carbon credit for 30 years as $2,048.

Over the past decade, there is an increase in the interest on renewable energy for the built environment; the focus is mainly on utilising solar energy with promising developments in the integration of PV technology in buildings. BIPV systems combine functions like natural lighting through transparent portion of glass to glass PV module, thermal energy from back surface of PV module for room air heating and electricity generation as reported by Joshi and Tiwari (2007) and Bloem (2008). The PV system is an efficient source of power and its system cost goes down with improvement in material research and PV module efficiency through research and development of the PV system design. Presently, the hybrid PV thermal technology has proven that the PV system does not only produce electricity, but also can supply thermal energy for room air heating application in cold countries and can provide daylighting if opaque tedlar material is replaced by glass to glass PV module as reported by Joshi and Tiwari (2007) and Bloem (2008).

As the cost of PV module ($/W) decreases, the total PV system cost decreases with appropriate change in cost factor (i.e., $5/W) presented in this paper. This methodology is widely accepted for sizing and costing the PV system for the given electrical load of the house and specific to the location defined in Figure 3 as per SECO, Texas (SECO, 'Estimating PV system size and cost').

In summary, the PV power systems can play a major role which has a potential to convert sunlight energy directly to electrical energy at low operating and maintenance costs and without noise and environment pollution. Hence, this power system is eco-friendly, reliable and a sustainable solution for the near future of the world.

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Nomenclature

A_A	Annualised cost of SAPV power system ($/year)
C	Cost per unit of electricity generated by PV system ($/kWh)
I	Interest rate (fraction)
M	Operation and maintenance cost every year ($/year)
N	Number of sunshine hours on optimum tilt surface of PV array (hours/day)
N	Life of the system (year)
P_i	Capital investment ($)
P_B	Present battery cost ($)
P_{Net}	Net present cost ($)
Rs.	Indian rupee currency ($1 = Rs. 40)
S	Salvage value of PV system ($)
U	Annual electrical energy available from PV system (kWh/year)
Greek symbols	
$	US dollar ($1 = Rs. 40)
Abbreviations	
ALCC	Annualised life cycle cost ($/year)
SAPV	Stand-alone photovoltaic
SCC	Solar charge controller
S.H.	Total number of sunshine hours (h/day)
T.P.	Total power requirement (Wh/day)