AIMS Energy

http://www.aimspress.com/journal/energy

AIMS Energy, 5(6): 997-1012.
DOI: 10.3934/energy.2017.6.997
Received: 08 September 2017
Accepted: 03 November 2017
Published: 14 December 2017

Research article

Integration of electric vehicles with optimum sized storage for grid connected photo-voltaic system

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Abstract: The necessity of energy storage by means of battery/EV is exceedingly expected in event of energy blackouts. Different advantages incorporate sparing the cash in purchasing top time power and support the grid when grid power is deficit against the load demand. In this paper, ideal size of energy storage in a grid associated photovoltaic (PV) framework is proposed. The methodology of energy flow choice is produced with the appraisal on accessibility of PV yield control and the load demand. The energy flow decision is changed by peak and off peak hours to shorten the functional cost of the grid associated PV framework with storage. Naturally, the quantities of electric vehicles that can be associated are resolved.

Keywords: distribution grid; energy storage; electric vehicle; photo voltaic system; cost-benefit analysis

Nomenclature

EV	Electric Vehicle
PV	Photo Voltaic
$P_{PV,DC}(d,t)$	Power output from the PV panel (kW)
$P_{PV,AC}(d,t)$	PV power at the AC bus (kW)
η_{inv}PV	inverter efficiency (%)
$P_{DC,bat}$	Charge/Discharge power of the battery (kW)
E_{bat}	Stored energy in the battery (kWh)
P_{AC-bat}	Charge/Discharge rate of the battery on the AC bus (kW)
$P_{DC,bat}$	Charge/Discharge rate of the battery (kW)
η_{bat}	Battery inverter efficiency (%)

C_{bat}	Usable battery capacity (Ah)
$P_{DC,bat}$	Charge/Discharge rate of the battery (kW)
a	Self-discharging factor
$C_{loss,cumi}$	Cumulative battery capacity loss (kWh)
Z	Ageing coefficient
C	Nominal battery capacity (Ah)
C_{bat}	Usable battery capacity (Ah)
$C_{loss,cumi}$	Cumulative battery capacity loss (kWh)
BCL_{cost}	Cost of battery capacity loss ($)
B_{invest_cost}	Investment cost rate of the battery ($/kWh)
$E_{cost,benefit}$	Cost or benefit of Electricity ($)
E_{price}	Electricity tariff ($/kWh)
P_{grid}	Power transfer to and from the grid (kW)
CRF	Capital recovery factor
N	Lifetime (years)
i	The real interest rate
$\sum_{d=1}^{365}\sum_{t=1}^{24} E_{cost,benefit}$	Annual Electricity cost and benefit ($)
$\sum_{d=1}^{365}\sum_{t=1}^{24} BCL_{cost}$	Cost of annual battery capacity loss ($)

1. Introduction

Installation of photovoltaic system in distribution network has been increased by 40% since 2007 [1]. Energy stored in batteries can be used in case of power outages/reduced generation. Additionally, electrical energy can be stored during high availability of PV output or off-peak hours from the utility grid and feedback to the grid at higher price at the time of peak hours.

Several other benefits anticipated with availability of adequate capacity of battery/EVs; the bidirectional charging and discharging power control can be applied for peak load reduction [2,3], valley filling [4], minimizing load variance [5], and alleviation of frequency fluctuation [6].

High penetration of PV in distribution network may lead to voltage rise, which will cause potential issues to the distribution system [7–10]. The viable solution against the voltage violation is to integrate energy storage device into grid connected PV system to attain real power control. It is verified that energy storage devices could support to flexible AC transmission system (FACTS) devices for preventing voltage violation issue in grid connected PV system [11,12]. All these studies are effective to prevent the violation in network constraints, but further analysis with storage characteristics is still needed.

There are many papers, which depict the concerns in site location and size of energy storage capacity in the distribution network [13,14,15]. The over-sized energy storage increases the cost of the system. An optimum size of energy storage may be explicitly computed and therefore the cost-benefit of storage size is significant and beneficial. The study [16] suggests a methodology to shave the peak load demand in a distribution network with PV system. The cost and size of hybrid PV and battery system has been also analyzed for demand side application, considering the electricity price difference for on-peak and off-peak [17].

The work carried out in [16,17,18] could not offer precise cost assessments due to assumption of fixed storage lifetime. The energy storage lifetime varies greatly under different usage, which depends on the PV-bus location, PV penetration level, weather conditions and type of storage system.

Now day's Electric vehicles are widely used as storage devices [19]. In respect of smart grid paradigm, demand side management can be also applied to EVs, and EVs may be influenced by real-time pricing, charging/discharging location, or their consumption pattern. In this context, an optimal charging/discharging mode of EVs in a distribution network having PV system with intermittent power characteristics will improve the system reliability, addressing the technical challenges such as voltage limits violation or line congestion.

2. Motivation And Problem Formulation

The two important perspectives from which optimal energy storage via controlled EV charging/dischargingcan add significant value includes its ability to be shifted in time according to variation in PV output and avoid peak demand.

Due to varying output of PV system, uncorrelated with power demand, situations can occur showing low energy price at the time of high demand. As a result, a coordinated response to the changes in real-time price of energy, and available PV power will allow achieving optimum number of EVs connection and thus maximizing the benefit to end-consumers and system operators.

In this paper, therefore, the study presents optimum battery capacity, with EV charging/discharging strategy under varying amount of PV output power, electricity price and load connected to the network.

The main objective is to determine the optimum battery capacity that minimizes the annual operation cost with insights of varying PV power into the network and peak load period. In this paper, a novel strategy is presented to address the above issues. The presented work in the paper is organized as follows. Section 2 gives a description of test system, followed by problem formulation in Section 3. The strategy applied for obtaining optimum storage size and thus number of EVs is discussed in Section 4. The simulation results are given in Section 5, and finally, the conclusions on the presented work in Section 6.

3. Test System and Data

The optimum battery capacity with charging formulations and the resulting demand are considered idealized profiles assuming perfect knowledge of prices, driving patterns, and network load. It is assumed optimized battery power and thus the number of EVs does not lead to technical network constraints, such as thermal limits of cables and voltage violations at buses. In the study, the aggregator-based EV charging management is assumed where in the objective is to meet the energy needs of EV users with the minimum charging cost. The hourly PV output data [20] and load data [21] for the period from 1st January to 31st December of 2010 is considered in simulation. During the entire year, summer period lasts from 1st May to 31st October and remaining months are considered as winter period. The peak hours are defined as 7 a.m. to 1 p.m. and 4 p.m. to 10 p.m. while rest of the hours as off-peak hours.

Average daily consumption in summer days is 1321.5 kWh. The yearly average daily energy consumption is 1365.5 kWh. The PV module efficiency is taken as 15% [22]. The annual daily average peak PV output in the summer season is approximately 220.2 kW. The average daily PV energy output is 934.5 kWh. The nominal voltage of the battery in each case is taken as 12 V and the self-discharging factor of the battery is as 2.5% per month. Minimum and maximum state of charge is taken as 30% and 90% respectively. The nominal charging rate is taken as 10 hour rate and round trip efficiency as 81%. Battery charge and discharge efficiencies are taken as 90%. The battery inverter cost rate is considered as $ 606/kW and assumed the battery inverter lifetime as 10 years [23]. The battery investment cost rate of $ 200/kWh [24]. It is desirable to have accurately sized energy storage for a cost effective PV system. The extra cost for storage system can be overcome by scheduling its operation in smarter way.

4. Optimized Energy Flow Schedule

The purpose of the energy flow schedule is to lower the daily operating cost of the client having the PV system. The process requires data of the PV output, electricity price and the consumer load during the entire year. The aggregators will conduct load shifting in order to provide reduced energy cost to consumers against the variation in energy prices. In other words, EVs will be charged when the energy price is low, and sell at peak hours. The cost of the battery capacity loss due to ageing of the battery is also measured when optimizing the energy flow [25].

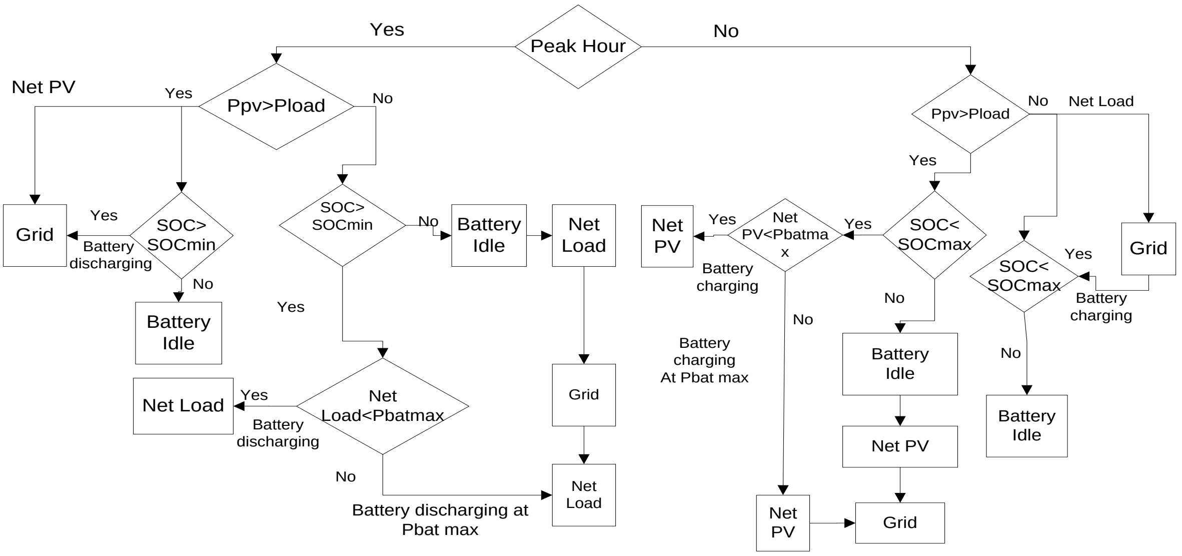

Figure 1. Energy flow schedule.

Figure 1 depicts a flowchart of the Optimized Energy flow schedule for Grid Connected PV System with battery/EV as energy storage. According to the Figure 1, it will be able to manage the charging (G2V) and discharging (V2G) schedule as per the logic at each sampling time ($\Delta t = 1\,Hour$). The sampling time interval in each energy transfer is taken to be one hour during the simulation. Therefore, through each hour t, energy transfer will be equivalent to the power transfer. Due to violation in charging/discharging, this optimized energy flow schedule will automatically achieve battery charge state within selected minimum and maximum limits of SOC_{min} and SOC_{max}, consistently. This energy flow schedule of the storage will also gain profit by selling the stored energy to loads during peak hours, when the price of electricity is high and purchase low-priced electricity from the grid during off peak hours at night to charge the battery for using it during the peak hours of the day.

As depicted in Figure 1, the power flow variation is fragmented into the four straightforward states. These states are proposed to generate the optimized energy flow in proposed grid connected PV system.

Case 1: $(P_{pv} > P_{load})$

During peak hour of the day when delivered PV power is larger than the load demand, the net PV power, consumed in loads will be fed to the utility grid. If battery is charged by more than minimum SOC, the battery will discharged its energy to the utility grid to get benefits as electricity price is higher during peak hours. Else the battery will be left in its idle state.

Case 2: $(P_{pv} < P_{load})$

During peak hour of the day when the delivered PV power is less than the load demand, the discharge energy from the battery get importance, to cut the net load. It monitors that the battery should be charged by more than minimum SOC. Also, if the net load is less than the maximum discharging rate of the battery, the battery will discharge at a rate which equals to net load. If the above circumstances are not appeared, the battery will discharge its energy at maximum discharging rate.

If the battery capacity is not able to feed the net load, then electricity is purchased from the utility grid to feed the net load demand.

Case 3: $(P_{pv} > P_{load})$

During off peak hour when delivered PV power is larger than the load demand, the net PV power after feeding the loads will be used to charge the battery. It includes that the charging state of battery should be less than the maximum SOC. Similar to Case 2, if the net PV is less than the maximum charging rate of the battery, the battery will charge at a rate which equals the net PV. If the above conditions are not satisfied the battery will be charged at maximum charging rate. If the batteries are fully charged, then the excess net PV will be sold to the utility grid.

Case 4: $(\mathrm{P}_{pv} < \mathrm{P}_{load})$

During off peak hour when PV power is not adequate to supply the load demand, the electricity must be purchased from the utility grid. It is commercial to buy electricity from the grid even if the battery is charged enough to deliver the energy for loads. Because battery discharge involves aging capacity loss of the battery, which will be added as degradation cost to the total operating cost.

At the same time, if the battery is not fully charged, then grid electricity will be purchased to charge the batteries. The energy flow schedule, as illustrated in Figure 1, is optimized within the Matlabprogramme and it is simulated throughout all the 8760 hours of the year to update all the variable constraints with (d, t).

Figure 2 depicts flow chart for determination of optimum battery capacity. As depicted in flowchart, the load data, PV data and the electricity price data should be detached conferring to the summer and winter months. Then again, it should be detached according to the peak and off peak hours. After that by selecting a random sized battery, hourly optimized energy flow at the AC Bus of the grid associated PV system has to be calculated. Once optimum battery capacity is calculated, ensuring network constraints limit optimum number of charging EVs can be quantified.

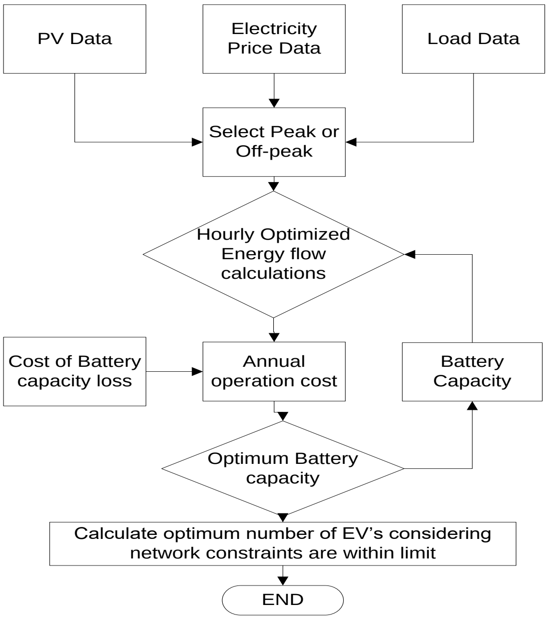

Figure 2. Flow chart for determination of optimum battery capacity.

4.1. Mathematical modeling for battery cost

In this subsection, the objective of achieving reduced battery size with minimum cost is mathematically formulated to construct the charging profile of EVs. In the perspectives of EV charging from the view of distribution grid operator, some form of incentive regulation is assumed to exist in the market.

The DC electricity generated at the PV array is converted through PV inverter in to AC power at the AC bus.

$$P_{PV,AC}(d,t) = \eta_{inv} P_{PV,DC}(d,t) \tag{1}$$

The charge and discharge power transfer to and from the battery in a particular sampling hour can be defined as:

$$P_{DC,bat}(d,t) = \frac{E_{bat}(d,t) - E_{bat}(d,t-\Delta t)}{\Delta t} \tag{2}$$

AC power at the AC bus is converted into DC when it passes through the inverter/charger unit. The conversion efficiency of the inverter η_{bat} is assumed to be constant while charging and discharging the battery.

$$P_{AC-bat}(d,t) = \begin{cases} \eta_{bat} P_{DC,bat}(d,t), P_{DC,bat}(d,t) < 0 \\ \frac{P_{DC,bat}(d,t)}{\eta_{bat}} P_{DC,bat}(d,t) > 0 \end{cases} \tag{3}$$

The charge state of the battery is updated every sampling hour with the charging/discharging of power, to and from the battery. Charging,

$$SOC(d,t) = SOC(d,t-\Delta t) \times (1-a) + \eta_{charge} \frac{P_{DC,bat}(d,t)}{C_{bat}(d,t)V} \Delta t \tag{4}$$

Discharging,

$$SOC(d,t) = SOC(d,t-\Delta t) \times (1-a) + \eta_{discharge} \frac{P_{DC,bat}(d,t)}{C_{bat}(d,t)V} \Delta t \tag{5}$$

The cumulative battery capacity loss during the charging and discharging process of the battery is [16]:

$$\mathrm{C_{loss,cumi}(d,t)} = \begin{cases} \mathrm{C_{loss,cumi}(d,t-\Delta t) - ZP_{DC,bat}\Delta t, P_{DC,bat}(d,t) < 0} \\ \mathrm{C_{loss,cumi}(d,t-\Delta t) P_{DC,bat}(d,t) > 0} \end{cases} \tag{6}$$

Battery capacity loss during any sampling time can be found using Eqn. (7).

$$C_{loss}(d,t) = C_{loss,cumi}(d,t) - C_{loss,cumi}(d,t-1) \tag{7}$$

C_{loss}Battery capacity loss (kWh)

Eqn. (7) updates the cumulative battery capacity loss of each hour and that loss has to be deducted from the nominal battery capacity to get the usable battery capacity for the next hour. In Eqn. (8), cumulative battery capacity loss is converted to Ampere hour (Ah).

$$C_{bat}(d,t) = C - \frac{C_{loss,cumi}(d,t) \times (10^{-3})}{V} \tag{8}$$

The cost of the battery capacity loss during any particular hour of the system operation [16] is given as:

$$BCL_{cost}(d,t) = \frac{C_{loss}(d,t) \times B_{invest\_cost}}{1 - SOH_{min}} \tag{9}$$

Minimum state of health of the battery ($SOHmin$) is taken as Zero. Electricity cost due to purchasing from the grid and benefit due to selling to the grid, can be calculated by using the equation stated below. Sampling time (Δt) is equal to 1 hour as stated earlier in the paper. Therefore the power transfer is equal to energy transfer.

$$E_{cost,benefit} = E_{price}(d,t) \times P_{grid}(d,t) \times \Delta t \tag{10}$$

If the lifetime of a system is N years and the annual real interest rate is i, the annualized cost is calculated as [22]:

$$\text{Annual inverter cost} = \text{Inverter capital cost} \times CRF \tag{11}$$

CRF can be found by using the Equation 12

$$CRF(i,N)=\frac{i(1+i)^N}{(1+i)^N-1} \tag{12}$$

The annual operating cost of the system is:

$$\text{Annual operating cost} = \sum_{d=1}^{365}\sum_{t=1}^{24} \mathrm{E}_{\text{cost,benefit}}(\mathrm{d},\mathrm{t}) + \sum_{d=1}^{365}\sum_{t=1}^{24} \mathrm{BCL}_{\text{cost}}(\mathrm{d},\mathrm{t}) + \text{Annualised inverter cost} \tag{13}$$

5. Results and Discussion

To determine the optimized storage capacity of EV, an analysis of the distributed network with base load, PV output is performed. A 24-hour load demand profile is used as input data in the optimisation problem. The main consideration is given to reduce the energy purchase from the utility grid during peak time. The priority is given to discharge the battery energy during peak hour to meet the demand when PV power is not sufficient or not available.

Thus, during the day time, battery is required to release its energy to the utility grid only up to a predefined value of the state of charge (SOC > 70%). This value is selected so that the total annualized operating cost remains minimum. The remaining capacity is reserved to compensate the peak load demand during night hours. Figure 3 shows the power flow profiles for the grid connected PV system, including battery storage on a typical day. E-pv, E-load, E-grid and E-battery are represented the power transfer to and from each of the constituents in the precise hour. As observed in Figure 3, during off peak hours until 7 a.m., the load demand is met from grid supply and also the excess available power charges the battery. Subsequently, as load increases up to 10 a.m., batterydischarges power to the grid till minimum SOC is attained.

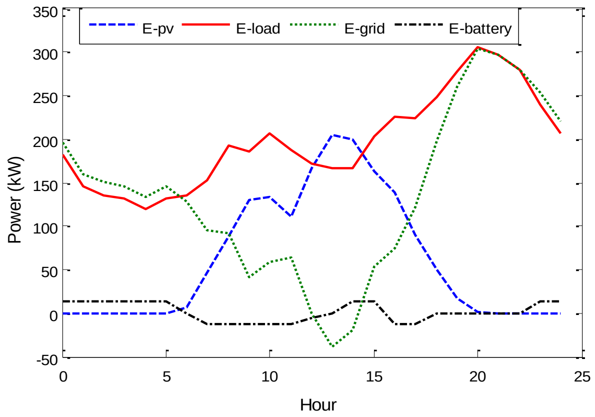

Figure 3. Power transfer sequence of the grid connected PV system.

Subsequently, the battery remains idle until 1 p.m. and keeps its power to support grid for night peak hours. Besides, the PV power supports to the grid to compensate the load. On the availability of high PV power (off-peak hour), the battery is charged until 4 p.m.. From 4 p.m. to 5 p.m., the battery discharges power to the grid, until the SOC reaches 70% of its capacity. The battery supports to the grid in reducing the peak load demand from 6 p.m. to 10 p.m.. Then again after 10 p.m. battery is charged from grid supply.

According to the Figure 3, the maximum PV power of 220.55 kW is received at 1 p.m.. During the same time battery is kept at its idle position and load consumes 155.10 kW out of 220.55 kW of PV power. The excess PV production of 65.45 kW is sold to the grid. Figure 5 shows the variation of annual operating cost with different battery capacities. For different battery capacity sizes starting with 10,000 Ah to 13,000 Ah is entered in the Matlab programme and annual operating cost for each of the battery size is obtained. The critical size of the battery, which gave the minimum annual operating cost of the system, is selected as 12,625 Ah. Figure 6 depict the storage capacity loss profile in a typical summer day. The annual operating cost of the network having 12,625 Ah battery is $ 2841.74. The calculation of annual battery capacity loss and annualised inverter cost is $ 3457.45. The annual electricity retailing amount by the PV system has noted a higher value than the electricity buyingquantity from the grid. Hence, the totalprofit for the consumer is $ 615.71.

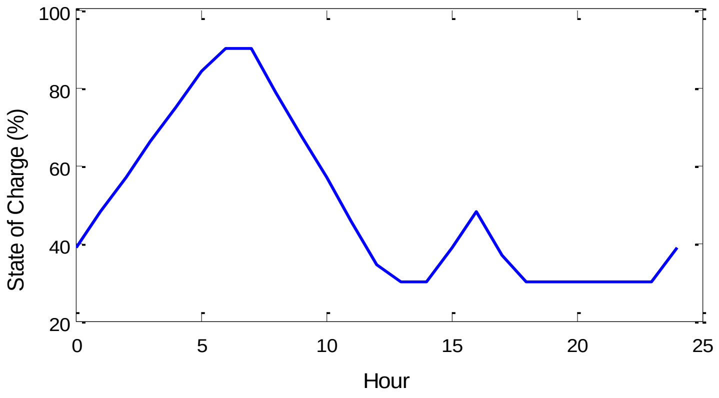

Figure 4. Battery SOC variations.

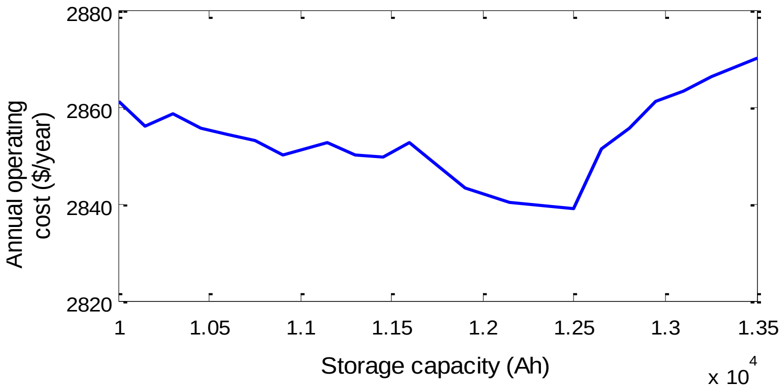

Figure 5. Variation of annual operating cost with different battery capacities.

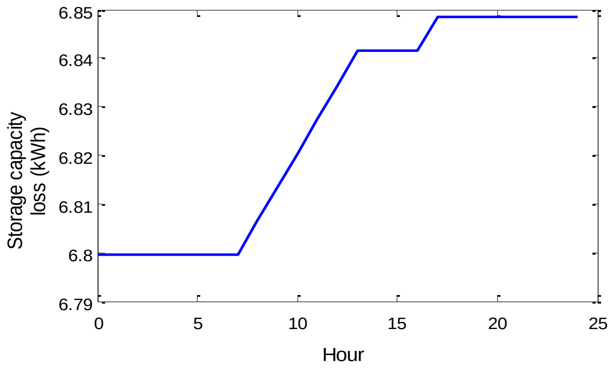

Figure 6. Storage capacity loss profile during a summer day.

At starting of the day the storage capacity loss is 6.7995 kWh. This value remains same until the discharging of storage (V2G) is started at 7 a.m.. The storage capacity reduced due to ageing effect during discharging. There is no storage capacity loss between 12 p.m. to 4 p.m. during this period storage is in its idle condition and the battery is charged from 2 p.m. to 4 p.m.. The loss of storage capacity, due to the discharging of the battery from 4 p.m. to 6 p.m., is added to the storage capacity loss. The battery is kept idle from 6 p.m. to 12 a.m.. At the end of the day, storage capacity loss is shown as 6.8479 kWh.

Figure 7 depicts the power transfer sequence of the grid connected PV system for summer month. It is clearly depicted in Figure 7 that for summer months PV output power increases along with demand thus critical size of storage on behalf of minimum annual operating cost of the system is selected as 12,625 Ah.

Similar study has been performed for winter months, and it is found that the required size of storage is 12,450 Ah. In winter month’s output PV power is less than that of summer months. The annual operating cost of the network having 12,450 Ah battery is $ 2792.35. The calculation of annual battery capacity loss and annualised inverter cost is $ 3209.52. The annual electricity retailing amount by the PV system has noted a higher value than the electricity buying quantity from the grid. Hence, the total profit for the consumer is $ 417.17.

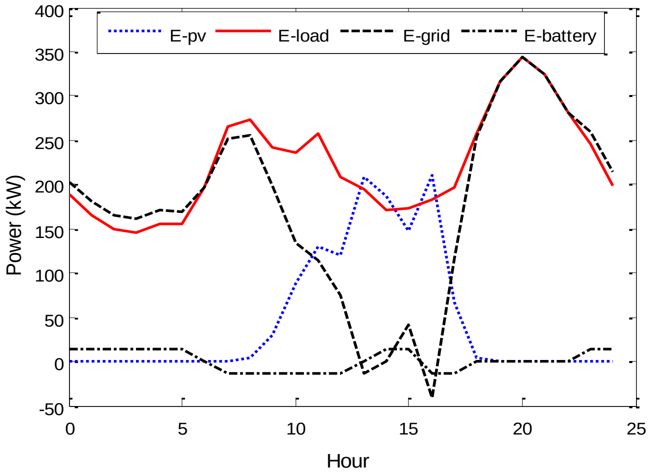

Figure 7. Power transfer sequence of the grid connected PV system in summer month.

In this paper storage capacity is measured in Ampere hour (Ah). It can be converted to kWh as depicted in Eqn. (14).

$$Storagecapacity(kW) = \frac{Storagecapacity(Ah) \times Nominalvoltageofbattery}{1000} \tag{14}$$

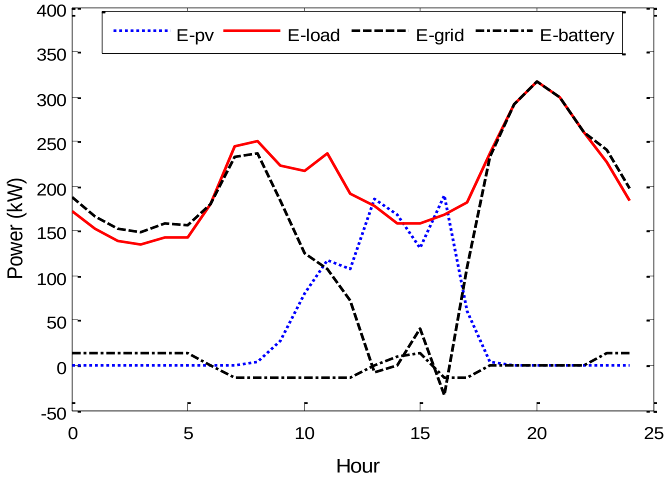

Figure 8. Power transfer sequence of the grid connected PV system in winter month.

5.1. Integration of optimal number of EVs

On the basis of optimal size of storage, optimal number of EV that can be integrated to the distribution network is determined. In this paper battery size for EV is considered as 100 Ah [26]. The maximum number of EVs that could be charged and discharged over a year within the network limits is expressed in Eqn. (15) and depicted in Figure 9.

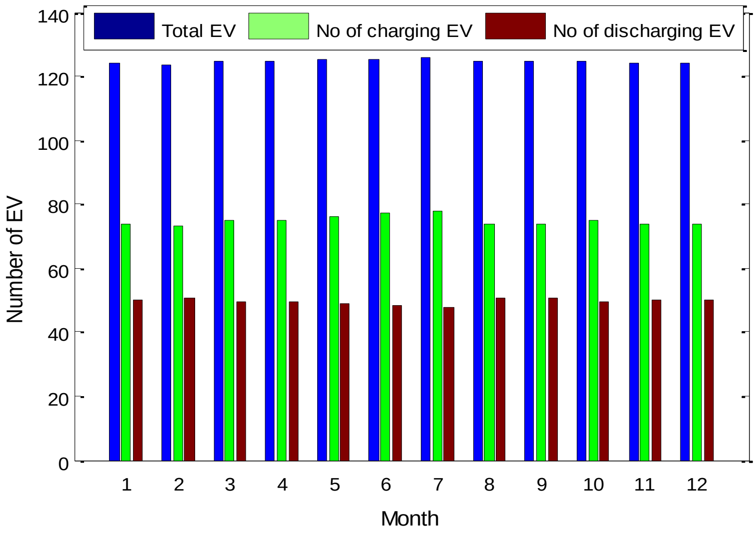

Figure 9. Optimal number of EV.

$$N_{EV} = \frac{Optimalsizeofstorage_{at\,\min\,operatingcost}}{EVsbatterysize} \tag{15}$$

$$V_i^{min} \le V_i^t \le V_i^{max} \tag{16}$$

$$S_i^t \le S_i^{max} \tag{17}$$

Constraint (16) depicts bus voltage to find the network limits, while Eqn. (17) presents total power flow limits.

Further optimum storage capacity of each month is calculated on behalf of monthly operating cost. The optimum storage capacity of each month is depicted in Figure 10. To find optimum storage capacity of each month similar study has been performed as above for annual data. In Figure 11 month wise storage utilization is depicted. Storage utilization means, number of hours storage is used (V2G) in a particular month.

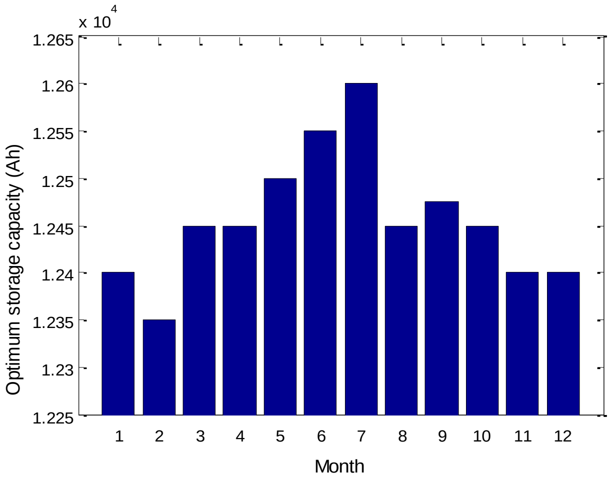

Figure 10. Optimum storage capacity.

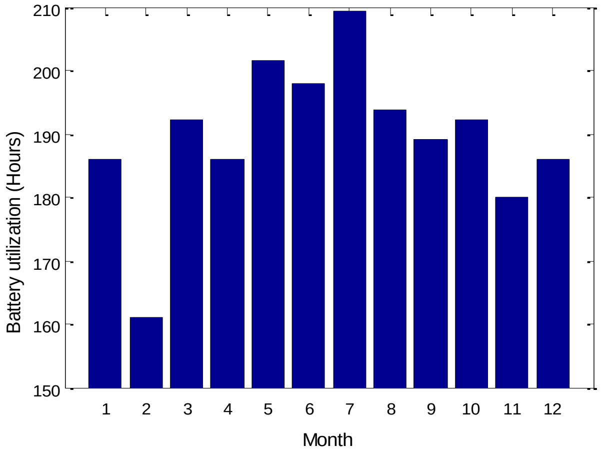

Figure 11. Storage utilization.

5.2. Grid connected PV system with storage: under incentives

The subsequent two distinctive schemes are modeled in evaluating the proposed grid connected PV system with battery storage.

5.3. Feed in tariff (FIT)

As an incentive, it is anticipated that the government pays higher price [27] to the consumer for the self-generated electricity, which supplies to the grid than to the price what consumes from the grid. Here, it is anticipated that the export tariffs in peak hours of both summer and winter are 10% higher than the import tariffs [28]. During off-peak hours, both tariffs will remain at the same price. Tariffs for import and export of energy are depicted in Table 1 and in Table 2. Daily electricity charge over the year: $ 0.14784/day. The above said FITs are used in case study which is discussed under section 5.

Table 1. Import tariff from grid [27].

	Summer		Winter	
Electricity Price ($/kWh)	On peak	Off peak	On peak	Off peak
	0.35146	0.10330	0.13695	0.10691

Table 2. Export tariff for grid [27].

	Summer		Winter	
Electricity Price ($/kWh)	On peak	Off peak	On peak	Off peak
	0.3866	0.10330	0.1506	0.10691

When the tariffs used in section 5 with an optimum storage size of 12,625 Ah for summer months, the annual electricity benefit is improved from $ 615.71 to $ 895.03. Then the total annualized operating cost of the PV system is reduced from $ 3457.45 to $ 3178.13.

When the above tariffs are used for winter months where optimum battery size is 12,450 Ah, the annual electricity benefit is improved from $ 417.17 to $ 596.49. Then the total annualized operating cost of the PV system is reduced from $ 3209.52 to $ 3030.2.

5.4. Battery investment cost

These kinds of platforms are already provided by many countries [29] for promising the consumers to install their own PV arrangements to feed their load demands. In this paper, it is anticipated that the government gives 30% subsidy on storage investment cost as an incentive for consumers who purchase storage for grid connected PV systems.

When we used the above discount for the battery of 12,625 Ah, which depicted in section 5 the new investment cost of the battery is decreased from $ 2841.74 to $ 2668.09. That gives an annualized battery cost of $ 279.32 with the CRF value of 0.1001. Then the total annualized operating cost of the PV system is decreased from $ 3457.45 to $ 3178.13.

When we used the above discount for the battery of 12,450 Ah, which quantified in section 5, the new investment cost of the battery is decreased from \$ 2792.35 to \$ 2613.03. That gives an annualized battery cost of \$ 179.29 with the CRF value of 0.0975. Then the total annualized operating cost of the PV system is decreased from \$ 3209.52 to \$ 3030.2.

6. Conclusion

The aim of the paper was to investigate an ideal size for the energy storage in a grid associated PV network. In the network, the ideal number of EV that can be incorporated to the distribution network, without influencing network limits is resolved. This was accomplished by optimizing the energy flow plan for the system and working expense of the grid associated PV system. Further, the energy flow optimization is performed considering time of use tariff rate and time of use with peak demand charge tariff system. When the above tariffs are used for winter and summer months according to their optimum battery size, the annual electricity benefit is improved. Also, the total annualized operating cost of the PV system is decreased by adding subsidy on storage investment cost.

Conflict of Interest

Theauthor declares no conflicts of interest in this paper.

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