Energy Flow Strategy For A Small Scale Grid-Tied Photovoltaic System Under Net-Metering

Nibaruta Régis, Christopher Maina Muriithi, Livingstone Ngoo

Abstract— Grid connected PV systems continue to attract investors and electricity customers all over the world. Due to interconnection with the utility grid, the system can glean some benefits such as selling PV electricity surplus to the utility grid or purchasing electricity from grid for battery storage charging at off peak hours for either self-consumption or selling back to the grid during peak hours. This paper present an optimal energy flow dispatch for a small-scale grid-tied PV system in order to reduce the owner's system electricity Bills. The simulations take into account the available PV Energy, the battery stored energy and the grid energy. On-peak and Off-peak Electricity charges dictated by the utility grid and a residential load from Market analysis and information System (MAISY) database are taken into account for energy flow scheduling. A case study of a garage with an installed 5kWp system at Strathmore University in Nairobi, Kenya was considered. The results analysis demonstrated that an appropriate battery size determination for a grid-tied PV system is highly governed by electricity tariffs and battery degradation cost.

Index Terms—Grid-tied PV; excess energy; energy flow; Battery Energy Storage; electricity tariffs; net metering; Battery degradation.

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1 Introduction

Prior to emergence and development of renewable energy sources, electricity has been generated from big central station plants in the history of power systems. The main part of this electricity generation have consisted of Fossil-fuel plants [1]. Solar energy is one of the leading renewable energy sources. The whole solar energy amount reaching the Earth is much higher than world's current and anticipated energy requirements. The amount received by the terrestrial surface per minute is much greater than the energy utilization by the entire population in a single year [2]. If appropriately harnessed, this greatly diffused source could potentially satisfy almost all future energy needs. Unfortunately, while solar energy is free in its nature, costs associated to its aggregation, conversion, and storage are still very high and restrict its exploitation in various locations. Fossil energy generation is the most costly form of energy across the globe, yet it is the prime source of energy production in Africa. This is a worrying matter for continent striving to push its overall power capacity from the actual 147GW which is relatively equal to the total capacity installed in Belgium, and what China installs every one to two years as reported by the African Development Bank [3]. Over the past decades, renewable forms of energy have been among the most active area of research in power systems. PV systems as energy source has several advantages compared to fossil-fuel based energy source such as short construction period, low operational complexity, fuel price independency and sustainable rural electrification of remote areas [4]. The grid-connected Residential Photovoltaic systems can produce excess energy, especially during the summer. This extra energy is either stored in ESSs or sold to the grid [5]. The goal of adding a battery energy storage to a PV system is to cover the load when PV generation is not sufficient or not available at all (rainy days or night). In all feasible types of energy storage technologies, battery energy storage system can be considered as widely used and fairly developed [6]. In many developing countries, despite government and private sectors effort, reliable access to electricity is still a big challenge. The ever-increasing power utility bill is a nightmare to deal with, for electricity users whose homes are connected to the monopolistic utility grids. Significant researches have been conducted to improve cost, efficiency, and system reliability of energy storages to reach a certain maturity in relation to their rise in electric grid. Beniwal *et al* in [7] considered a scenario in which a grid-tied solar system with battery storage is operated in fixed power mode. Y. Ru *et al* in [8], introduced an efficient algorithm for evaluating the storage size of a customer's grid connected PV system. Vukovic [9] proposed a grid-tied PV configuration with battery energy storage for own consumption within the building with possible zero export of energy to grid. F. Mavromatakis *et al* in [10], presented an economic analysis of a PV system under net-metering scheme. A. Zahir *et al* in [11] investigated the techno-economic viability of grid-tied PV system which can be massively deployed in the residential areas of a developing country. J. Dulout *et al* in [12] suggest a new methodology to size a lithium BESS integrated in a PV renewable microgrid in order to minimize the cost of stored energy. The main stress factors influencing both battery lifetime and performance were modelled and described. Developing an optimal energy flow schedule within the PV system and BES is crucial for many reasons. Firstly, it maximizes the utilization of PV-generated energy. Secondly, minimum running costs can be achieved. In this paper, an optimized energy dispatch is developed in order to reduce the daily electricity cost of the PV owner. A grid-tied PV system with battery storage is presented with a configuration that allows the PV system owner to either sell the excess PV output to grid or buy the shortage from the later. The paper focuses on sizing the battery energy storage for a typical customer already owning a 5kW PV system in order to reduce the daily electricity bills.

2 System Configuration

The function of a battery energy storage in a grid-tied PV system varies according to the configuration. Some configurations use direct charging method by charging the battery with DC voltage from PV modules. In such type of configuration an MPPT charge controller is installed between the PV modules and the battery. A different configuration is presented in this paper, figure 1, where the battery is connected to the AC bus bar via an inverter/charger and the PV module output is also injected to the AC bus through a DC/AC converter. Therefore, PV array, the utility grid, the battery and the load appliances are all connected to a common AC bus.

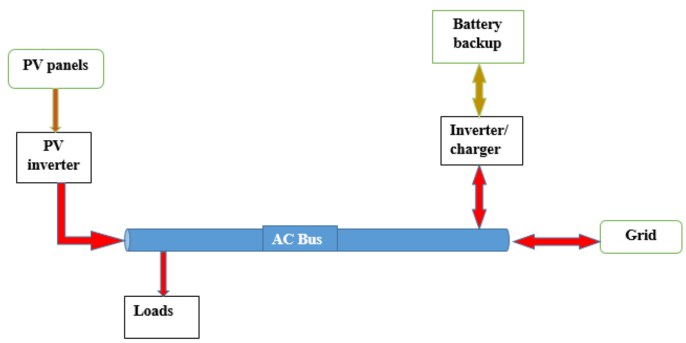

Fig. 1. Basic Topology of the Grid Connected PV System with BESS

2.1 Data acquisition and Battery modeling

2.1.1 Data Acquisition

Data used throughout the simulation are taken on hourly basis in order to minimize the daily electricity bills of a typical PV owner. A 5kWp PV capacity mounted on the roof of the garage at Strathmore university, Nairobi, Kenya is considered.

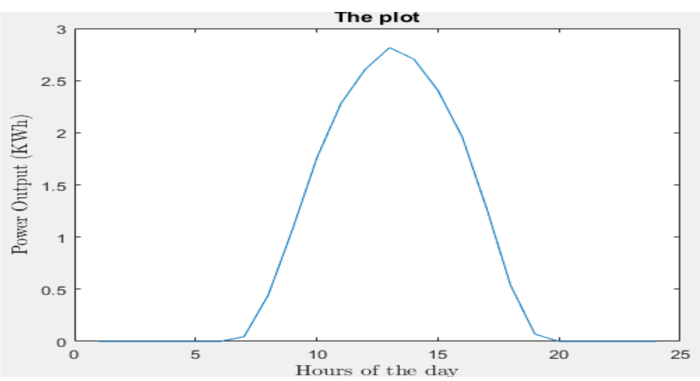

Fig. 2. Average hourly PV output throughout the year 2016

The output of the PV module is to be represented as a linear power source of global horizontal irradiation and expressed in [13], [14].

$$P_{pv}(d,t) = Gi \times A \times \eta_{pv} \quad (1)$$

Where Gi is the solar radiation at time interval i, A is the PV panel area and η_{pv} is the PV efficiency.

A residential load profile have been collected form MAISY database and adapted to the Kenyan context. The average hourly load profile throughout the year has been calculated and plotted in figure 3.

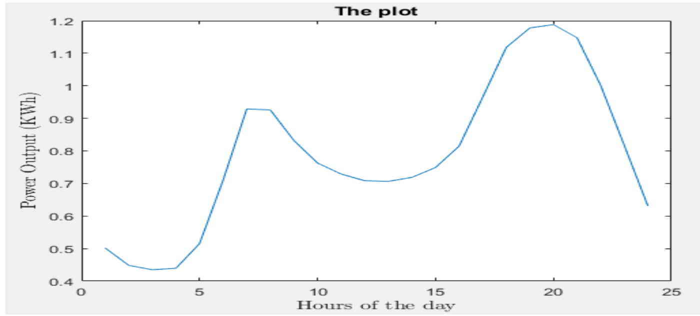

Fig. 3. Average hourly load profile of the household

Predictably, it can be noticed in figure 2 and figure 3 that the PV output is higher during the time periods where there is lower demand as depicted in figure 4. We can also observe that the annual daily average peak PV production is approximately 2.82kW which is much higher than the annual daily peak load demand 1.1881kW.

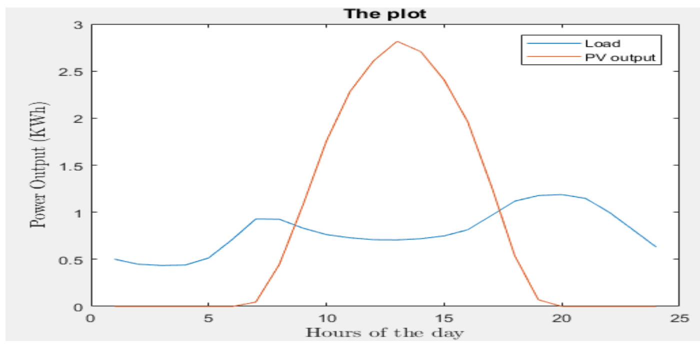

Fig. 4. average hourly load and PV output throughout a year.

There are a lot of different battery types in the market. For a residential PV system, battery should have a low cost, deep discharge using most of its capacity, long life and free from maintenance. VRLA gel type deep cycle lead acid battery is used in this study. The battery investment is taken as 200$/kWh [15] and the battery inverter cost has been estimated at 6006$/kW [16]. The rest of input parameters are given in the table 1.

TABLE 1 BASIC INPUT PARAMETERS

Parameter	Value	Unit
PV capacity	5	kW
PV efficiency η_{PV}	14.91	%
Battery investment cost	200	$/kWh
State of charge ($SOC_{min,max}$)	30 and 90	%
Aging Coefficient (z)	$3 * 10^{-4}$	n/a
Nominal charging rate	10	hrs
Self-discharging factor (a)	0.0000347	n/a
PV inverter efficiency η_{inv}	97	%
Bat. Inverter efficiency η_{bat}	94	%
Sampling time interval (δ_t)	1	hr
Annual Real interest rate (i)	4	%
Bat. Charge/discharge eff. η_{ch}/η_{disch}	90	%
Electricity charges	0.1583 off-peak 0.3560 on-peak	$

It should be noted that periods from 7:00 to 13:00 and from 16:00 to 22:00 are taken as on-peak periods whereas the rest periods of the day are taken as off-peak periods.

2.1.2 Battery Energy Storage Model

The battery has the following dynamic equation in [17]:

$$\frac{dE_B(d,t)}{dt} = P_B(d,t) \qquad (2)$$

Where P_B is the battery energy and $P_B(d,t)$>0 during battery charging state; $P_B(d,t)$<0 during battery discharging state and $P_B(d,t)$=0 during battery inactive state.

In order to take into account the battery aging effect, a battery usable capacity is considered after each sampling time and denoted $C(t)$. Obviously, at initial time t_0 the usable battery capacity is same as the battery nominal Capacity C_n. Then $C(t_0) = C_n$.

The above defined usable battery capacity is updated every sampling interval by subtracting a cumulative battery capacity loss $C_{Bloss}(d,t)$ from the battery nominal capacity as shown in (3):

$$C(d,t) = C_n - C_{Bloss}(d,t)$$
$$C_{Bloss}(t_0) = 0 \qquad (3)$$

Therefore, the battery capacity loss on day d at time t can be expressed as:

$$B_{CL}(d,t) = C_{Bloss}(d,t) - C_{Bloss}(d,t-\delta t) \qquad (4)$$

The model of the battery aging has been formulated in [18] as:

$$\frac{dC_{Bloss}(d,t)}{dt} = \begin{cases} -Z \times P_B(d,t), & if\ P_B(d,t) < 0 \\ 0 & otherwise \end{cases} \qquad (5)$$

Using the conventional efficiency of the battery η_B and the sampling interval δt, the above relation becomes:

$$C_{Bloss}(d,t) = \begin{cases} C_{Bloss}(d,t-\delta t)\dfrac{-Z \times P_B(d,t) \times \delta t}{\eta_B} & if\ P_B < 0 \\ C_{Bloss}(d,t-\delta t) \quad otherwise & \end{cases} \qquad (6)$$

Where Z is the battery aging coefficient.

This expression simply indicates that for the battery-aging model, capacity loss is encountered only in discharge process. Thus, we can see that in (4), $B_{CL}(d,t)$ equal to zero when battery is charging. The battery state of charge is updated after each sampling period as:

$$SOC(d,t) = SOC(d,t-\delta t)(1-a) + \eta_{ch} \times excess\ power\ ; \quad \text{for Charging}$$

$$SOC(d,t) = SOC(d,t-\delta t)(1-a) + \eta_{disch} \times deficit\ power; \quad \text{for Discharging} \qquad (7)$$

Where $C(d,t)$is the usable battery capacity.

3 Energy Flow Strategy and Cost Calculation

3.1 Energy Flow Strategy

As depicted in the complete Simulink model of our system, three different sources of energy are at residential load disposal. These are PV energy, Battery energy, and utility grid energy. However, these sources have to be optimally scheduled with the ultimate goal of lowering the daily operating cost. An energy flow scheme is therefore developed and the approach considers some important input data such as, Electricity Price, data of the PV output, and the residential load profile throughout the whole year.

The energy flow strategy is divided into four basic cases intended to create an optimized energy flow within our grid-tied PV system as in figure 5. These scenarios are intended to automatically manage/control the charging or discharging process of the battery with respect to the logic of each sampling interval (δt).

Case1: ($P_{pv} > P_{load}$) during On-peak period

When the PV production exceeds the load consumption under On-peak periods, the surplus power that is not taken by the load will directly be exported to the grid for sell. Given that it is under peak period and the energy price is high, if the state of charge of the battery is higher than its predefined minimum ($SOC > SOC_{min}$), the battery discharges its power to grid to generate profit. Otherwise, the battery is kept inactive.

Case2: ($P_{pv} < P_{load}$) during On-peak period

In the case PV generation is not sufficient to cover the load under On-peak period, the first option in this set up is discharging the battery to cover the load. Accordingly, the state of charge of the battery has to be higher than the minimum ($SOC > SOC_{min}$). If the energy from the battery is not sufficient to cover the load, the shortage power must be bought from the utility grid. Otherwise, the battery remains inactive and waits for Off-peak period to charge. The grid covers the full load.

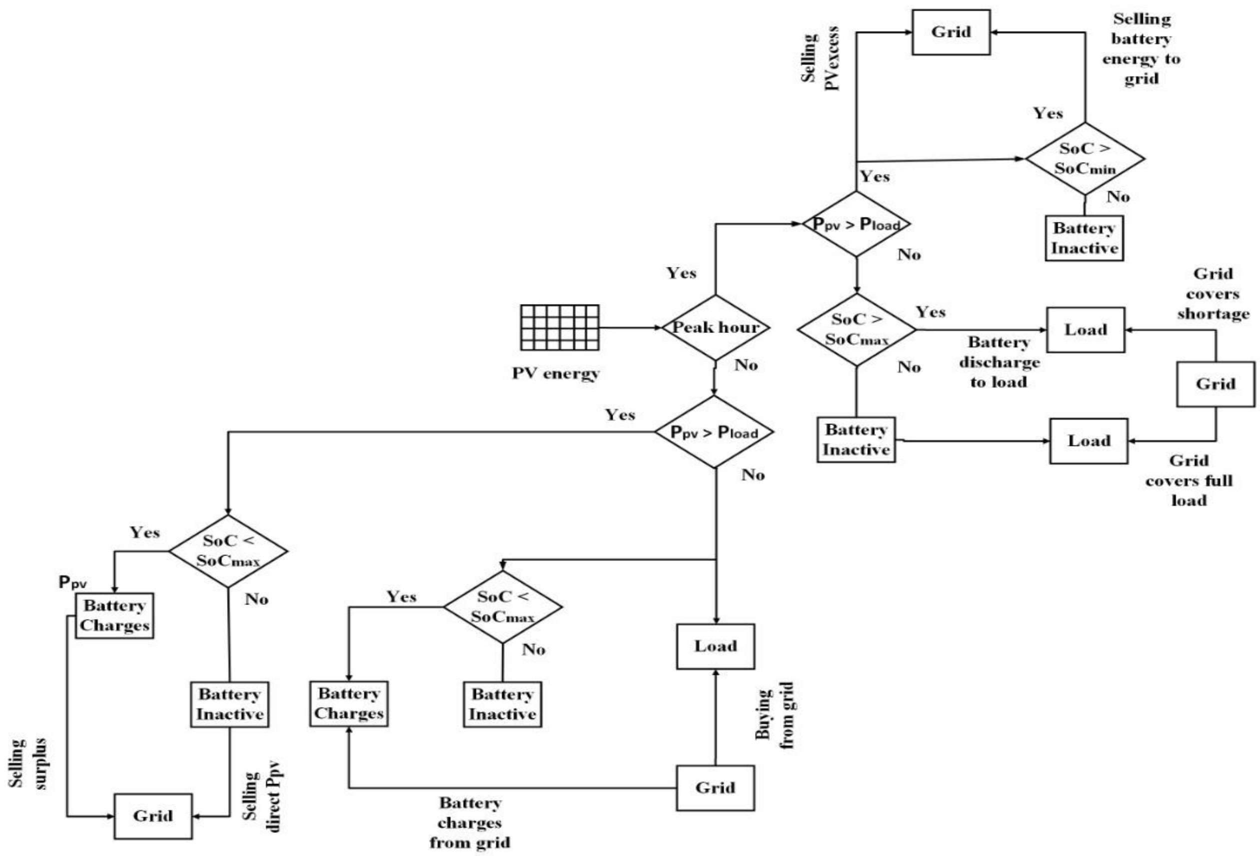

Fig. 5. Optimized Energy flow schedule

Case3: ($P_{pv} > P_{load}$) during Off-peak period

When PV energy exceeds the load consumption under Off-peak period, it is not beneficial to sell to the grid because the prices are low. The surplus energy after covering the load shall be utilized to charge the battery while satisfying its charging rate and then feed the excess to grid. This entails that the state of charge of battery should be below its predefined maximum state of charge ($SOC < SOC_{max}$), otherwise the battery remains inactive and the excess will be exported to the grid.

Case4: ($P_{pv} < P_{load}$) during Off-peak period

Under Off-peak periods, when output from PV is not enough to cater for the load demand, the only beneficial option is to buy the completely necessary energy from the grid. Even when the battery is fully charged, it is still cost-effective to use the cheap grid power for our load since discharging our battery comes at the expense of battery aging which add a degradation cost to the total running cost that need to be minimized. Similarly, if the battery is not fully charged, grid power is bought to charge the battery.
The energy flow strategy of figure 5 is optimized through the proposed algorithm and it is evaluated across all the 8760 hours of the sample year to update all variable parameters with (d, t). Grid connected PV systems with an energy storage provide operational costs and some benefits to the system owner.

3.2.Cost calculation

The total annual operation cost is therefore calculated as:

$$Annual\ op.cost = \left(\sum_{d=1}^{365}\sum_{t=1}^{24} C_{BCL}(d,t) + E_{CB}(d,t)\right) + AC_{inv} \quad (8)$$

Where $C_{BCL}$is the cost of battery capacity loss; E_{CB} is the energy cost and benefit; AC_{inv} is the annualized battery inverter cost and d, t are day and time respectively.
The cost of the battery capacity fade for a given hour of the system operation is expressed [19] as:

$$C_{BCL}(d,t) = \frac{B_{CL}(d,t) \times B_{invest-cost}}{1 - SOH_{min}} \quad (9)$$

Where $B_{CL}(d,t)$ is the battery capacity loss on day d at time t, $B_{invest-cost}$ is the battery investment cost and SOH_{min} is the battery minimum state of health.
The equation (10) describes the mathematical expression of the cost of the energy exchanged:

$$E_{CB}(d,t) = \{[E_{Price}(d,t) \times P_{Net}(d,t)] + [E_{Price}(d,t) \times P_{Net}(d,t)]\}\delta t \quad (10)$$

Where $P_{Net}(d,t) > 0$ Corresponds to cost of buying power from the grid and $P_{Net}(d,t) < 0$ Corresponds to expected benefits for selling excess power to the grid.

$$C = \left(\sum_{d=1}^{365} \sum_{t=1}^{24} E_{price}(d,t) \times P_{grid}^{import}(d,t) \right) \quad (11)$$

$$B = \left(\sum_{d=1}^{365} \sum_{t=1}^{24} E_{price}(d,t) \times P_{grid}^{export}(d,t) \right) \quad (12)$$

Where P_{grid}^{import} is the power imported from grid and P_{grid}^{export} is the power exported to grid.

The capital recovery factor and the annualized battery cost can be calculated as (13) and (14) respectively:

$$Battery\ \ Capital\ Recovery\ Factor\ (CRF) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (13)$$

Where i is the annual interest rate and N is the battery lifetime

$$annualized\ battery\ cost = B_{invest-cost} \times CRF \quad (14)$$

The lifetime of battery is calculated in (15)

$$\text{Battery lifespan } (N) = \frac{C_n \times V}{C_{Bloss-year}} \quad (15)$$

Where $C_{Bloss-year}$ is the annual additive battery capacity loss.

For ease of calculation, we have assumed that prices for sales and purchases are identical. The system is subjected to a number of operational constraints:

$$\begin{gathered} E_{Bmin} \leq E_B(d,t) \\ 0 \leq E_B(d,t) \leq C(d,t) \\ SOC_{min} \leq SOC(t) \leq SOC_{max} \\ SOH(t) \geq SOH_{min} \end{gathered} \quad (16)$$

3.3 Battery Capacity Determination

The battery capacity determination follows the flowchart in figure 6. Input data are handled differently depending on whether it is peak or off-peak hours. A random capacity of the battery is used to calculate the optimal energy flow every sampling interval.

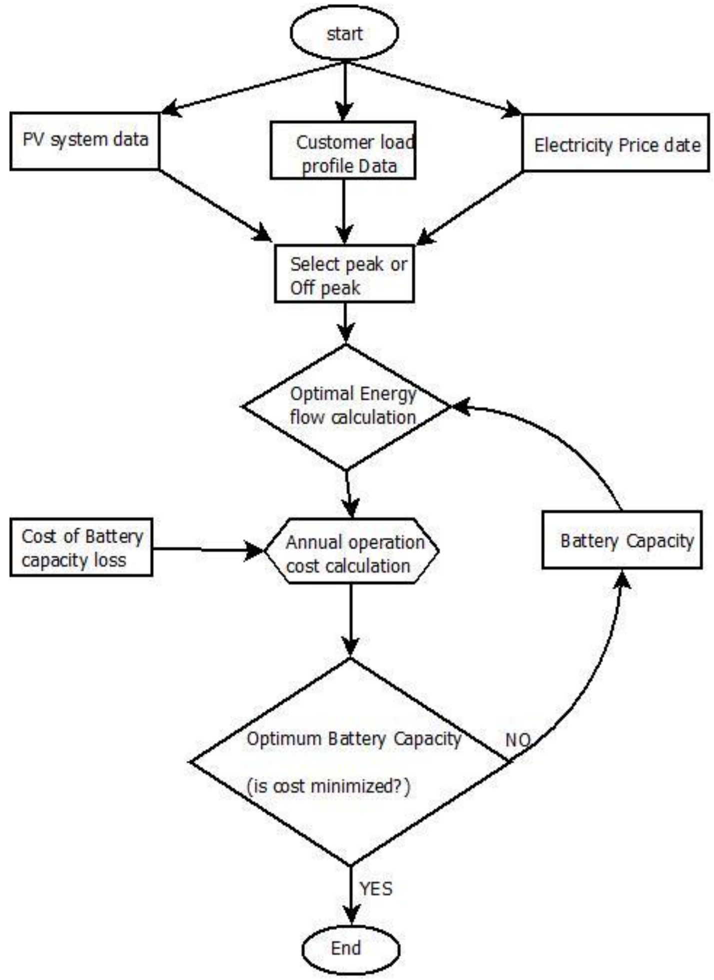

Fig. 6. Flow chart for determination optimum battery capacity for the grid connected PV

Among all the battery capacities, one critical value that gives the minimum annual running cost of the system is decided. This battery capacity should such that any value higher or lower than the critical value will increase the cost.

4 Results and Discussion

The algorithm calculate the optimal capacity of the battery and its running cost, the additive capacity loss of the battery and its lifetime. This information comes in handy in the optimization of the energy flow in figure 5. Energy purchased and energy sold are separated as $P_{grid} > 0$ and $P_{grid} < 0$ respectively. Similarly, the battery charged and discharged energies are separated as $P_B dc > 0$ and $P_B dc < 0$ respectively. With an ultimate goal of reducing the power imported from the grid at peak periods, the preference is given to discharge the battery under peak hours to supply the load when PV energy is not enough or completely unavailable (cloudy or rainy hours). Therefore, according to the optimized energy flow of figure 5, the battery unleashes its energy to the utility grid up to its minimum state of charge SOC_{min} during peak hours.

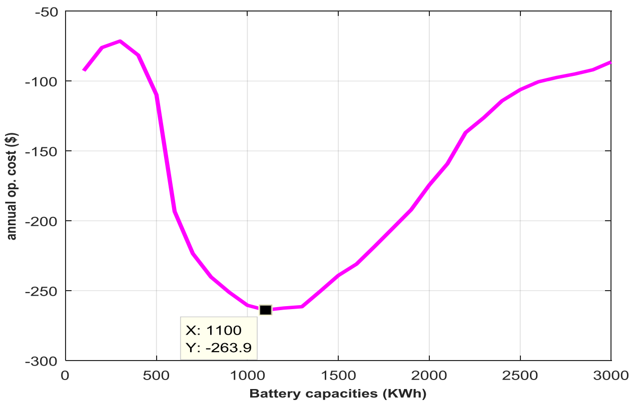

Fig. 7. Optimal battery capacity with respect to cost

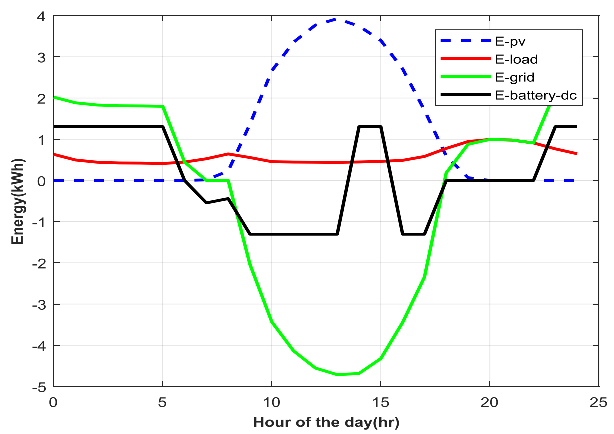

Fig. 8. Optimal energy flow schedule for a typical day of the year

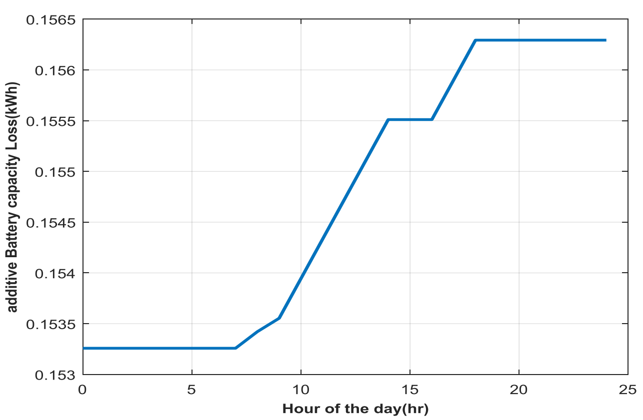

Fig. 9. Additive battery capacity loss during a sample day of the year

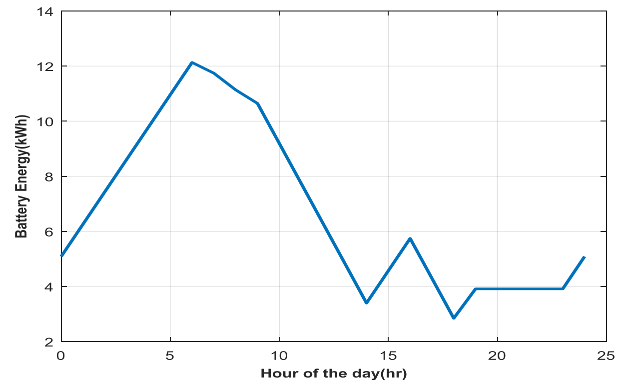

Fig.10. Energy variation in the battery for a sample day

The resulting optimal battery capacity of 1100Ah gives a corresponding annual running cost of 262.4578$ as depicted in figure 7. The negative cost simply means that the net metering has recorded higher electricity export to the grid than imported. The optimum size was determined by investigating a range of battery capacities from 100Ah to 3000Ah where the total running cost for each is computed and compared with others. The optimum size of the battery can be written as 13.2kWh and the battery capital cost is calculated at a rate of 200$/kWh as 2640$. According to the same figure, looking at the rate of change in the costs vs Battery capacities graph, we realize that the optimization algorithm decreases the total running cost as the battery capacities increases until the capacity reaches an optimum value. Subsequently, as the battery capacity keeps on increasing, the total cost starts to increase as well. Figure 8 illustrates the optimal energy flow during a particular day of the year (53rd). It can be seen that during off-peak hours (00:00 to 7:00), the load is entirely fed from grid and battery charges from grid as well. PV power is available between 7:00 to 19:00 with a peak production at 13:00. Figure 9 demonstrate the battery behavior with respect to degradation during a typical day of the year. From 00:00 to 8:00 the capacity loss is kept constant as the battery is in charging state. Subsequently, capacity loss starts increasing when the battery starts discharging its energy till 13:00 due to aging effect. Then the battery is kept inactive from 13:00 to 14:00 and starts discharging again. According to Figure 9, the additive battery capacity loss is 0.15345 when the 53rd day kick starts and increased to 0.15623 at the end of the day totaling a daily capacity loss of 0.00278kWh or 2.78Wh. From the daily battery capacity loss, we can trivially calculate the annual battery capacity loss as 1.0147kWh and we can evaluate the battery lifespan as 13 years using equation (15). With the annual interest rate taken as 4%, the capital recovery factor of the battery is computed as 0.1001437 using equation (13). This value helps us to estimate the annualized battery capacity loss cost by equation (14) as 264.37$. Figure 10 shows the battery energy fluctuation during a sample day of the year. According to this figure, energy varies in the battery with respect to the energy flow explained earlier in figure 3.5. As the battery charges, the energy increases until its maximum capacity of 13.2kWh. The discharging process follows the behavior of the electricity prices and does not discharge below the predefined depth of discharge of battery safety.

5 Conclusion

The paper presented an optimal energy flow dispatch with a grid-tied PV system. The aim of the study was to lower both the amount of electricity purchased from the grid and the cost of battery degradation loss due to aging effect. The goals were achieved through optimally scheduling the battery operation with respect to electricity price change on the utility grid. Results of the simulation showed that the battery behavior in terms of degradation rate and utility electricity tariffs highly impact the sizing of battery and the overall operating cost of a grid-tied PV system. Therefore, we have realized that electricity bills of a customer owning a grid-tied PV system with battery can be significantly minimized by optimally sizing and scheduling the battery operation.

Data availability

The raw data used to get the results in this paper can be provided upon request.

Acknowledgment

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