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Economic Battery Sizing for Reliable Quantized Solar PV Power Output

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Abstract

Generation of power from Solar PV inherently possesses a set of reliability issues. These issues are magnified with increasing penetration, and mitigation provides increased compatibility, especially for power systems with lower inertia. This paper addresses the intermittency issues. It provides and sustains a more deterministic output obtained by a quantized prediction input utilizing a demand response system. Utilization of the proposed method would allow Solar PV to be considered semi-dispatchable when connected to the grid. It would add virtual inertia, as well as improving the ability to safely operate in stand-alone mode. An algorithm is incorporated as an alert system in a 'worst case scenario' as a safety measure in the rare case of not being able to meet commitment.

The financial impact due to the addition of the device has been evaluated and the levelized cost of generation is shown to be 16.5 LKR/kWh. For rooftop solar, the cost- benefit ratio is shown to be above 1.3 after implementation. A battery sized at 2.7% of rated daily energy (1.5 Ah for a system operating at 450 V) is shown to be sufficient for a PV system generating a daily peak energy of 25 kWh to effectively convert Solar PV into a semi-dispatchable source. This allows special benefits from the utility service provider, which increases the feasibility of the incorporation.

Keywords

Solar PV • Battery storage • Semi-dispatchable • Reliability • Demand management • Economy

Introduction

The incorporation of Solar PV to the power system is of concern due to its intermittent nature, which affects system stability. The system inertia constant; which is the ratio between kinetic energy of rotating masses and the apparent power connected, determines the stability. When PV interconnection is significant, it increases the connected apparent power, without any rotating mass, lowering the inertia of the system, resulting in complications. A typical Utility Service Provider (USP) would expect the incorporation of an energy storage device large enough to maintain a constant output throughout the day, akin to Figure 1, with the hope of mitigating stability concerns. Power is expected to be injected to the power system irrespective of weather conditions; not unlike for a conventional power plant.

The most obvious difficulty with the implementation is the sheer cost of such a device in the context of rooftop solar. The required storage capacity would incur a cost comparable to the PV system itself. The integration of a solution must also be considered for existing PV, keeping economy in mind. Typically, energy storage, such as pumped hydro with concentrated solar, would be used as a more economical solution to mitigate intermittency related to renewable energy penetration [1,2]. A Battery Energy Storage System (BESS) is presented in [3] such that it is optimally sized by choosing an optimal location, considering the solar duck curve phenomenon, but not constrained to rooftop PV.

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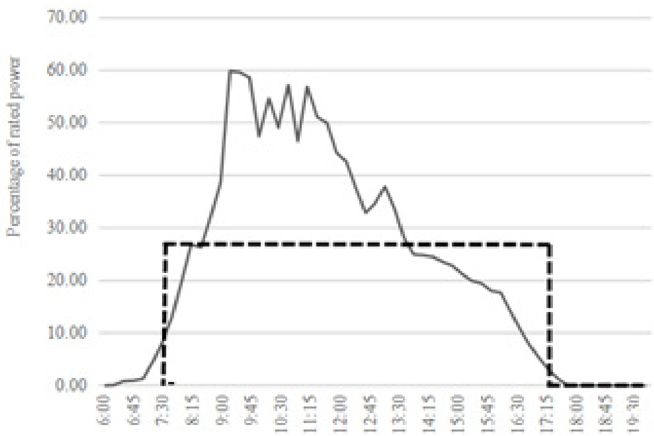

Figure 1. Solar output *vs.* USP expectations.

Prediction can be used to convert the stochastic behavior of renewable generation into a deterministic model. Unfortunately, due to the inability to accurately predict the behavior, an energy storage device would need to be used to manage the mismatch between the actual and prediction [4]. Provided that the time intervals of the prediction are sufficiently spaced, the use of prediction can be beneficial in minimizing the required capacity whilst preventing curtailment. Minimizing the battery capacity however results in a trade-off with surplus energy. This may be minimized by the usage of short-term prediction, given that the error is usually within a tolerable margin. Constant power control during intermittencies is proposed in [5] using a power controller. This also runs into the concern of storage capacity since the research speaks of a battery bank charging and discharging as necessary. The choice of the energy storage device would undoubtably be lithium ion battery energy storage due to its superior controllability, faster charge rates, high energy densities, extended cycle life and low maintenance even though lead acid seems more economically feasible [6] at first glance. The economics of choosing the battery are directly tied to the levelized cost of generation after any proposed system is added. A method to calculate the levelized cost for a particular plant [7] can be modified easily to obtain the levelized cost of a system with implementation of battery storage. Using this model, it is possible to either obtain the minimum cost for energy to be sold or the maximum cost of the implemented system for breakeven.

Weather based predictions have been proposed [8] which show that taking local weather can give sufficiently accurate predictions. A method of using local weather data for a weather based prediction [9] uses data from a free online source 'Accuweather.com'. The output prediction gives 15 minute resolution prediction of the actual data, 30 minutes in advance, within an accuracy of 88% expecting the remainder to be taken up by energy storage device. A minor concern would be the utilization of rooftop solar in the event of load shedding, be it for maintenance or the power system moving to a state of emergency. Typically, due to the stochastic nature of PV generation, it is not recommended to directly connect the PV system to user loads. In this paper, the mitigation of the intermittencies is done by initially converting Solar PV to a semi-dispatchable source of distributed generation by proposing a Quantized Power Injection (QPI) scheme for Solar PV based on a prediction. A control algorithm is designed to limit the power output to the predetermined value by charging and discharging a Battery Energy Storage System (BESS). To overcome intermittency, a USP alert algorithm is set in place to function in an extreme circumstance. The results show an evaluation of the financial impact of adding the control system to a Solar PV system, and the levelized cost of generation after the implementation of the proposed system. Determination of the rooftop solar maximum capacity, considering breakeven and the minimum payment maintain a reasonable Cost Benefit Ratio (CBR), is also shown.

Materials and Methods

Data of the roof-top PV site

Location: Mount Lavinia, Sri Lanka

Rated peak power: 4.16 kW

Rated terminal DC voltage: 450 V

Estimated maximum daily energy: 25 kWh

Estimated annual energy production: 6500 kWh

Cost of PV System: LKR 695,000

Quantized power curve

A model to predict a quantized output for solar PV [9] is considered as an input to the system (Figure 2). The resulting stepped output Pp suggests that a load PL can be connected to the PV system within the guaranteed duration. The incorporation of a Battery Control System allows the discrepancy between actual supply and predicted supply to be minimized.

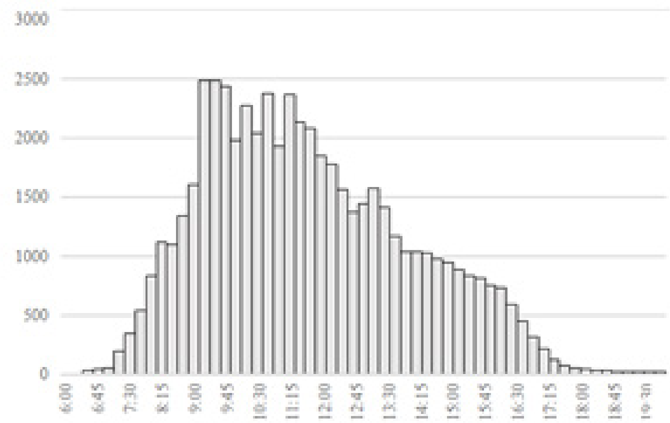

Figure 2. Quantization of a typical solar curve.

Battery state of charge control

Due to the extreme uncertainty of Solar irradiation, the availability of solar can deviate massively from the expected trend as shown in Figure 3. It is possible that even a prediction algorithm used provides erroneous values on such days. A contingency must be used to minimize the damage caused to the system by the error. This is addressed by the USP alert algorithm incorporated. As the occurrence of such drastic deviations is low, a penalty method may be adopted in such a rarity.

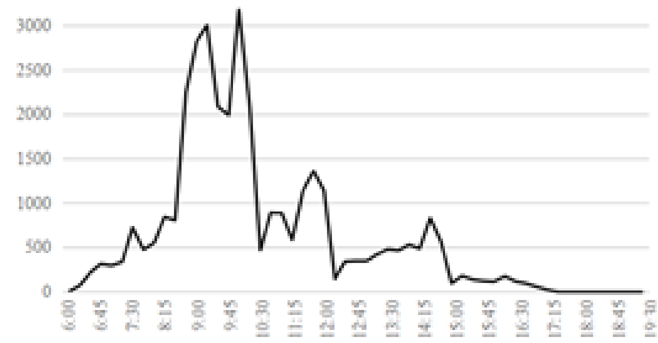

Figure 3. A cloudy day (9th October 2020).

For a majority of the time the battery control system follows a simple algorithm designed to limit the power output of the system to the predetermined value [10,11]. The algorithm tracks the instantaneous production, compares it with the prediction algorithm implemented and ensures that the predicted injection is maintained within the respective time interval. Figure 4 illustrates the flow chart for the logic used in the battery control system.

A traditional rooftop PV system would consist of the PV panel, followed by a Buck-Boost MPPT connected to the inverter terminals. The proposed system considers a module connected in cascade to the existing setup which would house the mechanism. A battery storage module would be connected to it to be charged and discharged regularly to maintain the level of power available.

In an event, such as the 9th of October shown in Figure 4, the USP may expect a higher supply, which the State of Charge (SoC) is unable to handle. In such an instance, an alert algorithm, as portrayed in Figure 5, must be utilized. The algorithm will run at the beginning of each quantization interval and validate the state of charge and report to the control center if there is likely to be a mismatch between the available and required energy. This algorithm would ensure that even in the worst case scenario, the uncertainty of power supply is minimized, to improve the reliability of adding Solar PV, considering the intermittent and chaotic nature of solar irradiance.

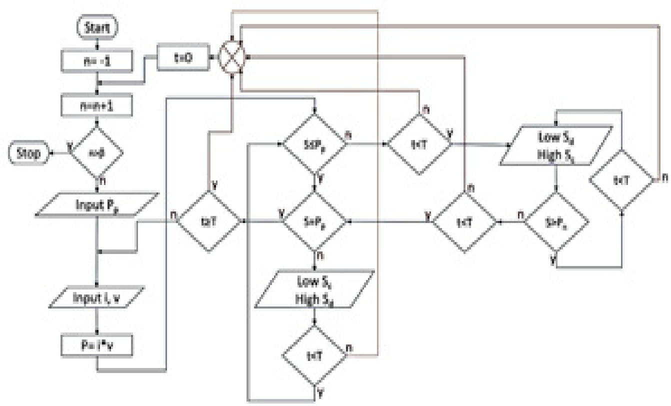

Figure 4. Battery control algorithm.

The minimum time to alert can be considered as 15 minutes in advance based on starting times of peaking plants. The energy production of an operational plant in the pool may also be increased if sufficient reserve exists, or a new peak generator would need to be added to the generator pool. In such a situation, the PV system may be expected to pay a "cost of unserved energy" charge to the USP as compensation for lack of reliability.

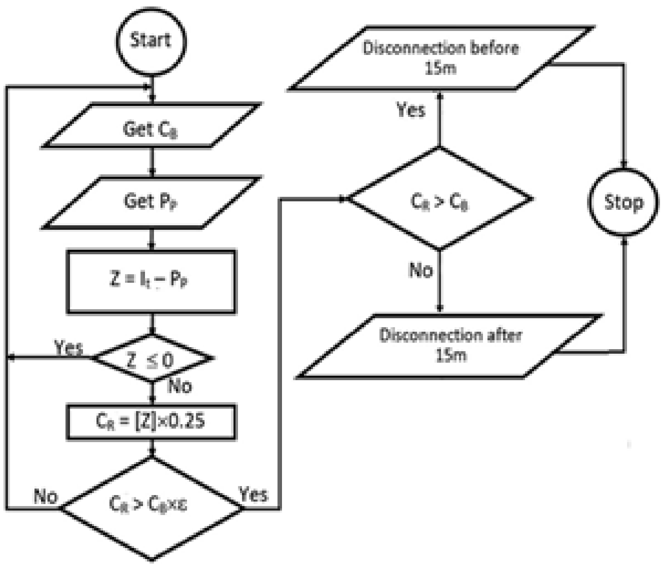

Figure 5. USP alert algorithm.

Value added capacity charge

The inclusion of extra components in the proposed method would incur additional costs. A method proposed by Bano and Rao [7] can be used to achieve a breakeven point for the proposed system. A few modifications have been included to incorporate the cost of the proposed system. Since it improves the dispatchability of the PV System, a value added cost is expected to be paid by the USP. A new total capacity charge can be derived such that the proposed meets breakeven.

The proposed method considers the Minimum Guaranteed Energy per Annum (MGEA), the Performance Ratio (PR) and the Net Present Value (NPV) to calculate the maximum cost of the system which can be implemented. PR, also known as a quality factor for solar, is denoted by equation 1.

$$PR = \frac{E_{avg}}{Irr_{panel \times A \times \eta}} \times 100\%$$

The minimum guaranteed energy value can be calculated using equation 2.

$$MGEA = PR \times P_{rated} \times 8760$$

Equation 3 is used to calculate the present equivalent cost of operation and maintenance.

$$C_{pe} = \left(\frac{C_{om}}{f-i}\right)\left[\frac{1+f}{1+i}\right]N - \eta$$

The equivalent annual cost over the lifetime is calculated based on the costs of the PV system, proposed modification and the net present value of the PV system O and M as in equation 4.

$$C_a = \left(C_{PV} + C_{sys} + C_{pe}\right)\left[\frac{i(1+i)^N}{(1+i)^{N-1}}\right]$$

Hence the levelized cost of generation can be obtained using equation 5 to compare with the energy charge that exists to verify if an increment is necessary.

$$Levelized\ \cos t = \left[\frac{C_a}{MGEA}\right]$$

Results and Discussion

The data used is mainly derived from a rooftop solar PV system located in Mount Lavinia, Sri Lanka with a peak power output for the site on a cloudless day rarely exceeding 3.3 kW. The actual power output curve on 29th May 2019 is as shown in Figure 6. This curve follows the 'typical' curve but has deviations from it, which happens commonly.

Quantized output

The first step in the proposed method would be the construction of the quantized output curve using the prediction method [12]. Figure 6 illustrates the quantized output from the production and compares it to the actual power output. Since the power output early morning and late evening are too low to inject a significant power to the system, the quantization starts at the 07.30 hrs and usually ends at 16.30 hrs.

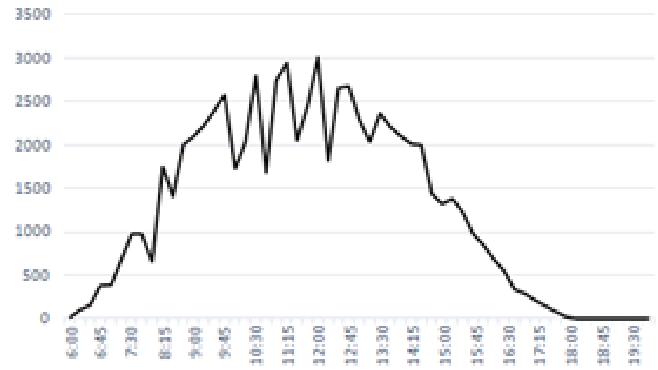

Figure 6. Power output on May 29th 2019.

Energy storage

The output power would follow the quantized curve given in Figure 7, restricting the power output to whatever value defined by the prediction. This process uses a Battery Energy Storage System (BESS) where the deficit energy is extracted from the battery and the surplus is stored in the battery. Figure 8 illustrates the deviation of the quantized power output from the actual power output. Where the difference is positive, the battery would charge, and it would discharge when it is negative. The Accumulated State of Charge (SOC) for the 29th of May is shown. The peak energy output per day, estimated to be 25 kWh by the operator, corresponds to 56 Ah at 450 V DC.

Considering the USP requirement of injecting a constant power over a period (Figure 7), the data shows the availability of 15 kWh for 90% of the time. Any remaining energy therefore would be stored in the energy storage device and be injected as the production drops. Accordingly, this method requires a reserve of 10 kWh (22 Ah). The proposed method allows for a maximum of 675 Wh (1.2 Ah), which is a significant reduction in reserve capacity.

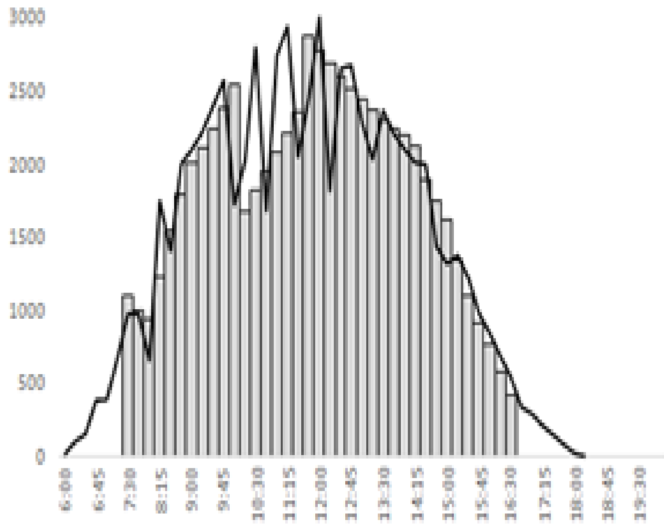

Figure 7. Quantized power output on May 29th.

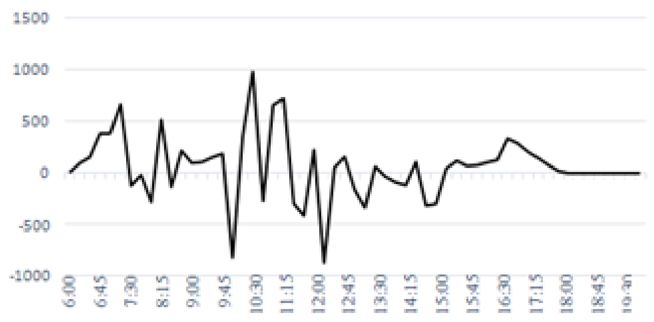

Figure 8. Charge and discharge instances on May 29th.

It is observable that throughout the day, charge is being accumulated with a rise till 07.30 h as all of the power would be fed into the BESS. At 16.30 hrs, the rise is visible again and the battery bank continues to collect the remaining charge. This stored charge can be injected to the power system as required by the USP. Thus, the upper limit of 16.30 hrs can be exceeded to give out constant output on a good sunny day.

The curve for the 29th of May shows a curve closer to an ideal curve, but as mentioned, the possibility of unforeseen fluctuations of solar irradiation may exist which would be felt by the prediction algorithm. Fig.10 illustrates such a curve on the 13th of May 2019. It is clear that the fluctuations of the power curve cause a slight complication in the predicted power output [13,14]. Figure 8 illustrates the differences between the actual and predicted power throughout the day. The discrepancy between the actual and predicted would have to be managed by the BESS and Figure 9 illustrates the Battery SOC for this particular day. The BESS stores power from 0600 h to 0730. On this day, the error in prediction causes the injection to be larger than the actual production, which quickly depletes the reserve. Such an event calls for a USP alert algorithm which will track the SOC and alert the USP. Such that necessary action may be taken, the time delay has been set to 15 minutes since in a worst case scenario, an emergency unit can be powered up within that duration. However, after 0930 hrs, the system operates as intended. The need for the USP algorithm is extremely evident on cloudy days such as 9th of October shown in Figure 3. It is clear that the fluctuations of the power curve cause a slight complication in the predicted power output. Figure 10 illustrates the differences between the actual and predicted power throughout the day. The reliability of the system can be further improved by ensuring the initial SOC of the BESS (at the beginning of the day) being set to 10% of the total capacity. Figure 11 shows how the

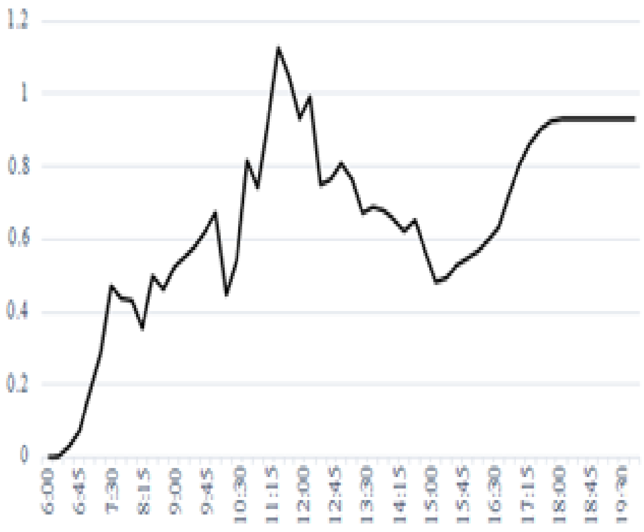

Figure 9. BESS charge accumulation.

alert is avoided on the 13th of May. The additional charge is utilized where the prediction demands more power than produced within the day. The initial 10% can be maintained by limiting the discharge of the final stored charge at 18.45 h.

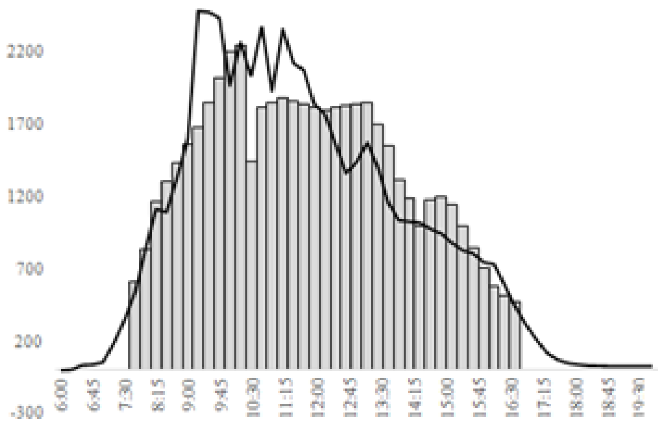

Figure 10. Curve for May 13th 2019.29th.

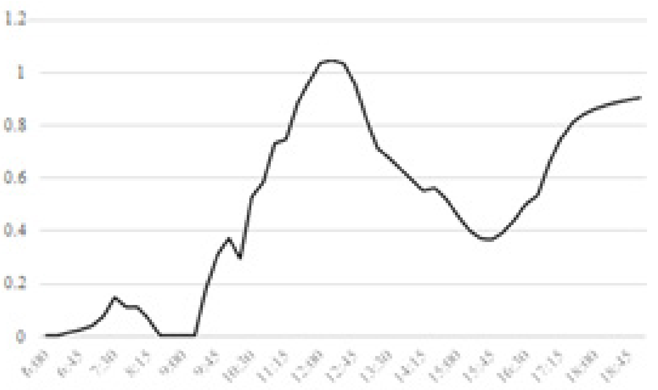

Figure 11. BESS SOC for May 13th.

Cost calculation

The cost of the battery accounts for the majority of the cost of the new system to be implemented due to the simplicity of control. To estimate the cost of the battery, the lithium-ion cells rated at 3.6 V and 1200 mAh is considered. The proposed system requires a total 125 cells costing LKR 31,250.

The Cost of the PV system is LKR 695,000 and the O and M costs can be considered to be 1% of the initial cost per year. Records of the last 3 years from the existing panels show that the MGEA can be taken as 6500 kWh. The equalized annual O and M cost over a lifetime of 20 years, based on an inflation of 6% and an interest rate of 12% has been calculated to be LKR 19,256. The annual cost of the PV system is hence LKR 108,174. Hence the Levelized cost of generation increases from 14.6 LKR/kWh to 15.3 LKR/kWh.

At present, the USP pays 22 LKR/kWh of energy exported, which is more than the levelized cost of generation resulting in a CBR of 1.44 after implementation. Therefore, it is possible to calculate the maximum cost that may be allocated for the proposed system at LKR 360,000. The 22 Ah system required to satisfy the USP requirements would require a total of LKR 572,000, clearly resulting in the costs outweighing the benefits (Figure 12).

It is highly likely that the USP may reduce the payment from 22 LKR/kWh to a lower value in the future due to the ever decreasing cost of solar generation. To maintain an industry desired CBR of at least 1.2, the price may be allowed to drop to 18.3 LKR/kWh, keeping in mind, that an increased payment may be still expected due to the value addition due to semi-dispatchability of the proposed system.

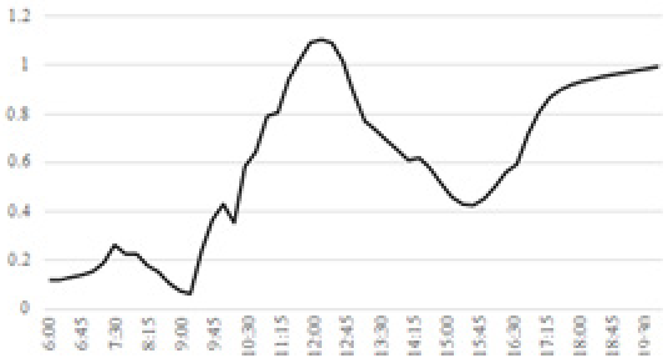

Figure 12. BESS SOC with 10% intial SOC for May 13th.

Conclusion

Solar PV has inherent intermittency, which is detrimental to small power systems. This results in the USP's reluctance to tolerate high levels of PV penetration to the grid unless a certain dispatch profile is met. This paper achieves a semi- dispatchable setup with quantized power output in 15 minute intervals derived from a prediction algorithm. For a 4.16 kW peak panel operating at 450 V, generating 25 kWh on a clear day, the minimum battery capacity is shown to be 1.2 Ah (675 Wh) instead of the 22 Ah (10 kWh) requirement from the USP.

In a worst case scenario, where the SOC of the battery is insufficient to maintain the power output at the prescribed level, a USP alert algorithm is proposed to further improve the reliability of PV.

The levelized cost of generation for the test PV system is shown to increase 14.6 LKR/kWh to 15.3 LKR/kWh and the CBR to 1.3 after the implementation of the proposed system. The system is attractive to IPPs on competitive bidding as they can opt for increased prices considering the cost of reliability due to semi-dispatchability. Rooftop PV on the other hand will receive a fixed remuneration of 22 LKR/kWh and a cost up to LKR 360,000 can be spent to enhance the proposed system. With LKR 360,000 enough capacity would be available to store around 38 days' worth of energy if desired. In the event that the USP decides to reduce the payment, an attractive CBR of 1.2 can still be obtained at even 18.3 LKR/kWh, but an increased pay can be expected considering the cost of adding value through the proposed system

Considering the goals of the long term generation expansion plan, coupled with the green initiatives associated with the promotion of renewables for generation of power, the proposed system becomes very attractive. Solar projects are naturally liable for subsidies since they are expected to be more eco-friendly and the proposed system makes it more attractive to investors. The improvement in reliability to the power system whilst providing a cost effective option to an investor would further promote the implementation.

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