Financial Assessment Of Battery Support For Rooftop Solar PV To Address Voltage Rise Issue

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***Abstract* - Distributed energy resources, such as rooftop solar photovoltaic (PV) systems, are becoming more attractive owing to their renewable nature and proximity to the customers' demand. Electricity generation from solar energy is financially profitable in most countries but challenging to connect to the distribution network because of possible voltage violations during peak production. When voltage violations are expected, one possible mitigatory measure is to install a properly sized battery storage system to store the energy over the duration of the violation. This paper presents an analysis of battery capacities required to connect solar PV to the grid during peak generating hours. It then calculates the levelized costs and possible feed-in tariffs required to make such investments viable from an investor's point of view. However, this study does not analyze whether such a feed-in tariff is affordable from the customers' perspective.**

Keywords - Distributed energy resources, Photovoltaic system, Voltage violations, Sri Lanka feed-in tariffs

I. INTRODUCTION

Distributed energy resources are small or medium-sized power sources that are primarily connected to distribution networks and located near end-use consumers. Distributed generation such as rooftop solar PV systems, feeds the grid at low voltage (LV). The global deployment of rooftop solar PV systems has increased dramatically in recent years, largely due to supportive regulations, including net metering and financial incentives, as well as reduced costs.

Overvoltage situations on LV networks during mid-day are becoming increasingly widespread in metropolitan areas in Sri Lanka and elsewhere when a significant number of rooftop solar PV systems are installed in close proximity to each other. To transfer electricity from a solar PV system to the customer, the inverter automatically fixes its voltage to be equal to that of the grid. When generation from a rooftop solar PV system exceeds the customer's consumption, the inverter transfers power to the grid, which causes the network voltage to be raised. The magnitude of such raised voltage depends on the distance from the customer to the distribution transformer and the amount of surplus power to be transferred to the grid. When a large number of solar PV installations are connected to the same LV line, and if each solar PV installation is transferring electricity toward the distribution transformer, it may cause the network voltage to rise over the statutory limit (presently +6% in Sri Lanka). This has the potential to damage or cause malfunctioning of sensitive electrical equipment of customers connected to the network, irrespective of whether they have a rooftop solar PV system or not. Therefore, the number of household solar PV systems that can be absorbed by a LV network is limited. Several researchers have analyzed this problem of voltage rise.

To identify the potential power quality impacts on LV distribution networks with high penetration levels of solar PV systems, a study of a network in Sri Lanka's Kotte area has been reported recently [1]. This LV network hosts solar PV capacity amounting to more than 40% of the capacity of the distribution transformer serving the network. The study modeled and compared the network with 15-minute data recorded using remote metering facilities. The capacity of solar PV that can be accommodated depends on many variables. The authors have simulated the network with different penetration levels and assumed that customer demand is constant at different penetration levels. The study concluded that the solar PV capacity that can be connected to this network was principally limited by voltage increase, which occurs initially at LV feeder ends.

Sri Lanka implemented the net metering scheme in June 2010. It enables the customers to install solar PV or other renewable energy plants with a capacity equal to or less than the customer's contract demand linked to the grid. The customer pays for the net amount of electricity used. There is no payment for surplus energy sent to the grid, but the customer is permitted to carry forward the surplus to the next billing month, and the grid functions as an energy bank. In addition, two new choices, Net Accounting, and Net Plus were launched in September 2016, in which the surplus energy, or the total energy amount, respectively, can be sold to the grid at the end of each billing month. [2].

PV system installations must be on actual functional roofs rather than on the ground or structures created for the purpose of adding greater solar capacity. Ground-mounted solar PV facilities (which are typically connected at medium voltage levels) are structured as projects and procured under competitive bidding (2016-2020) and on feed-in-tariffs (2022 onward).

Starting in 2018, Sri Lanka's "Rooftop Solar PV Power Generation Project" provided electricity consumers with long-term debt financing at concessionary interest rates to install rooftop solar PV power generation systems [3].

Following such government initiatives to expand choices on distributed generation, there is a greater demand for increasing solar penetration levels across the network. Net-metered solar PV customers often size their rooftop solar PV capacity so that the PV energy output equals to their monthly electricity use. Customers may over-size their rooftop solar PV capacity significantly, even up to their contract demand, if they have adequate roof area, to sell more energy and earn profits. Alternatively, energy storage business models, if implemented, could enable customers to store power generated by rooftop solar PV and use it later when needed or sell it to the grid. Sri Lanka had 32,411 rooftop solar PV installations with a total capacity of 367 MW by the end of April 2021. Out of the foregoing, 16,472 (121 MW) were net metering installations, 14,392 (113.5 MW) were net accounting installations, and 1,547 (132 MW) were net plus installations. By the end of December 2022, the total such installations increased to a total installed capacity of 662 MW [4].

II. Emerging technical problems of solar PV

Distribution networks have been traditionally designed assuming unidirectional power flow, without considering the possibility of bi-directional power flow resulting from renewable energy-based generation. Power flow in an LV network occurs across a voltage gradient from the transformer secondary to the customer load. With higher levels of solar PV penetration, there is a risk of voltage limit violations, increased harmonic levels, feeder, and transformer overloading, and malfunctioning of protection devices. The maximum level of solar PV that can be integrated without violating the operational performance criteria of the LV network is defined as the hosting capacity [5].

Different strategies can be adopted to avoid such violations and enhance PV penetration. These strategies include the use of active network management technologies such as reactive power compensation using static VAr compensators, distribution bus voltage control using on-load tap changers on distribution transformers, and the inclusion of battery storage. Another strategy is making the installation of batteries mandatory. Battery storage is fast and easy to adapt to manage the voltage rise in distribution lines. By storing all or a portion of the excess energy exported by the customer to the grid, the voltage rise can be controlled, and the stored energy can be sold to the grid when the customer demand is high and the solar PV output is absent, i.e. during the system peak time in the evening.

This study examines the capacity of batteries required, in case future customers are mandated by the distribution utilities in Sri Lanka to install a battery to selectively store the energy output from the solar PV system. The objective would be to prevent the customer's PV system from causing line over-voltages at peak generation time at mid-day. The study estimates the feed-in tariff required to be paid, so that the customer's investment in the PV system and the battery storage will be viable, from the customer's point of view.

III. Feed-in Tariffs for Solar PV and TOU Customer Tariffs in Sri Lanka

Under the net accounting system, if the generation exceeds the customer's own use, the customer gets a reimbursement for the net quantity of energy exported to the grid (total generation - own consumption) at a flat tariff of 37.00 LKR/kWh (for a PV system less than 500 kW ac capacity), throughout the 20-year contract period. For a system of 500 kW ac or more, the corresponding tariff is 34.50 LKR/kWh. Under the net plus program, customers are permitted to build rooftop solar PV systems of capacities up to their contract demand and export the entire generation to the national grid at the same flat tariff given for net accounting, for the entire contract duration of 20 years.

Specific investment for larger solar PV systems is lower owing to economies of scale. Therefore, the tariff for a system larger than 500 kW ac cannot be only 2.50 LKR/kWh (7%) lower than smaller systems. The above prices are very appealing to customers investing in solar PV with more than 500 kW dc.

In contrast, the announced tariff causes negative net cash flow typically for 10 kW and 50 kW systems in the first and second years. Negative cashflows in the first few years is a common feature in any investment, but for renewable energy, there has been an implicit policy that a tiered tariff will be offered to enable positive net cashflows from the first year itself. Systems larger than 50 kW ac capacity will generate windfall profits throughout the 20-year contract. Previously there was a two-tier tariff that benefited both the PV investor and the public, particularly in the latter years. In the two-tier tariff, the investor will receive a profit from year 1 itself due to the higher tariff in the first tier. During the second tier, the system would generate the same profit to the investor while delivering cheaper renewable energy to the public over the long term.

For agreements signed since November 2022, the flat tariff throughout the 20 years contract period will impose an undue burden on the public in the form of higher electricity sales tariffs. Table 1 shows the estimated investments and calculated equity internal rate of return (IRR) for 10 kW, 50 kW, 500 kW, and 1 MW DC PV systems using the newly announced feed-in tariffs. The common assumptions included a debt-to-equity ratio of 70:30, an interest rate of 18.52%, and a loan repayment period of 7 years.

Table 1:Estimated investments and Equity IRR for the announced feed-in tariffs in 2022

System Capacity (kW)	Estimated Investment (LKR million)	Calculated Equity IRR
10	2.8	18.17%
50	13.2	20.96%
500	109.6	34.30%
1000	207.0	33.29%

IRR is generally used to estimate and compare the profitability of different projects. The project with a higher IRR will generate more profits compared to other projects. Therefore, a PV system rated more than 50 kW DC will produce a substantial profit for the investor, which will eventually become a burden on electricity customers.

Feed-in tariffs presently do not discriminate based on time of production. However, Sri Lanka has an optional time-of-use (TOU) tariff to charge household customers.

In the TOU pricing of electricity sold to customers, the price of energy depends on when the energy is consumed. In Sri

Lanka, the TOU pricing structure consists of three-time intervals: the day interval (05:30 to 18:30), the peak interval (18:30 to 22:30), and the off-peak interval (22:30 to 05:30). Under the optional TOU structure, household customers who have opted in for TOU pricing are charged LKR 70.00 per kWh during the day interval and LKR 90.00 per kWh during the peak interval. Therefore, if a domestic customer opts to take the TOU tariff while storing the excess energy during daytime and using that during the peak interval (rather than using the grid) will save LKR 20.00 per kWh.

IV. Types of Batteries and Battery Capacity

There are four main types of battery technologies in the industry: lead-acid, lithium-ion, nickel-cadmium, and flow batteries [6]. Each technology has its own characteristics. The suitability of a technology depends on the charging rate, discharging rate, cost, reliability, maintenance requirements, expected lifespan, depth of discharge, operating temperature and scale of battery storage. Although lithium-ion batteries are the most expensive, they have a longer lifespan and depth of discharge.

A. Battery capacity required

The representative rooftop solar PV unit considered for this study is rated at 10 kWp. When the grid voltage exceeds the stipulated value, the inverter switches to battery charging mode. The specific moment the grid voltage crosses the threshold and initiates battery charging, as well as the time at which the inverter switches back to normal operation, were not covered in this study. The study aimed to calculate the energy output of the 10 kWp unit which needs to be stored in the battery during the period when the grid voltage exceeds the nominal value.

The representative solar PV output profile used was that of the 740 kW solar PV pilot power plant in Hambantota, Sri Lanka. It was used to calculate the energy output and the required storage battery capacities for a 10 kWp solar PV facility. The average power output of the 10 kWp solar PV over 2-hour, 3 hour, 4 hour, and 6 hour time intervals is shown in Figure 1.

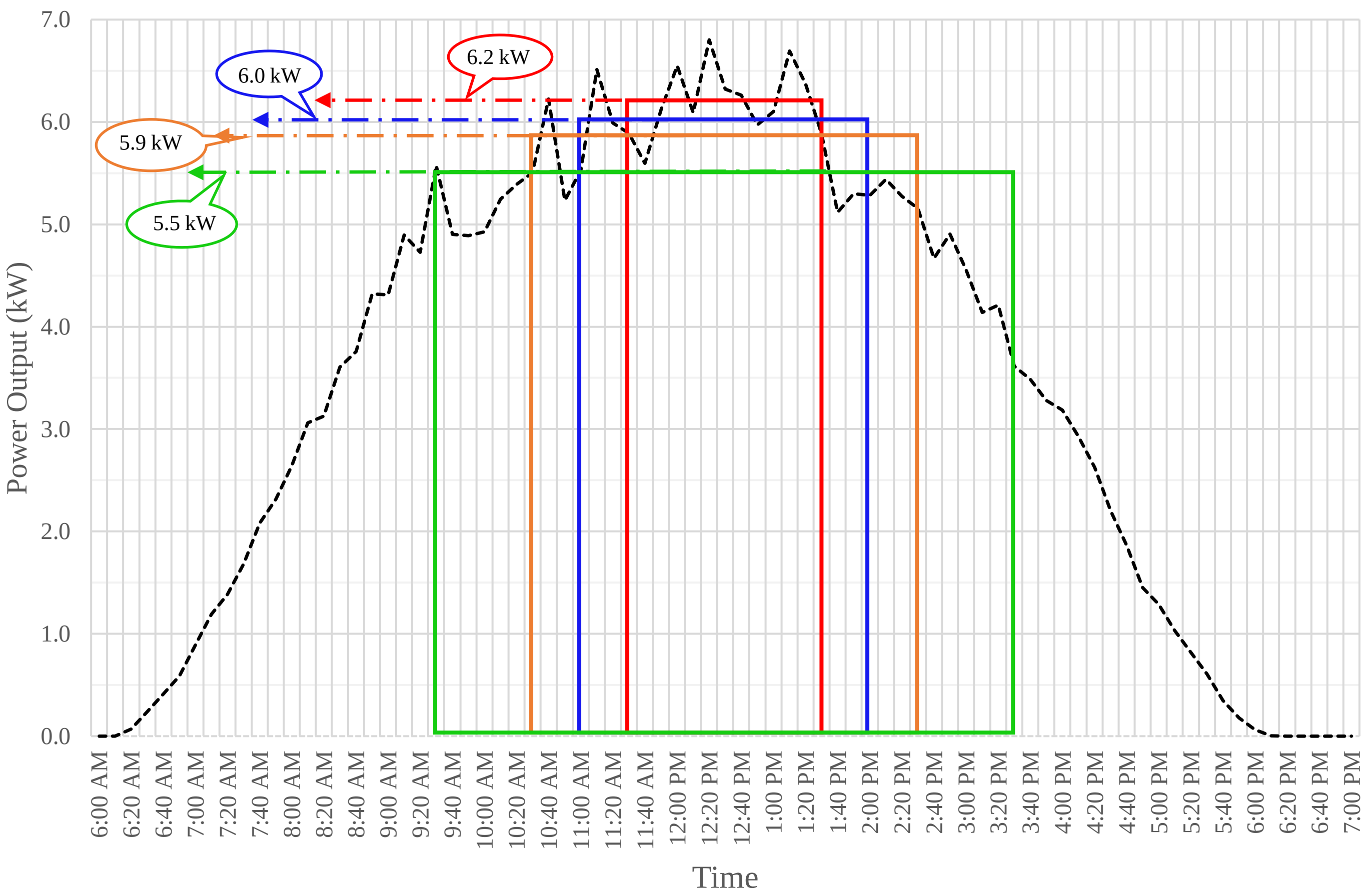

Figure 1: Average power output curve of a 10 kW solar PV over one day

The use of batteries in PV systems is distinct from their use in other applications. The important technological concern for PV systems is that the battery should have a long lifetime under nearly full discharge circumstances [7]. Using the profile shown in Figure 1, the required energy storage capacities for 2 hour, 3 hour, 4 hour, and 6 hour of generation periods were calculated.

Table 2 displays the power output values and energy storage for each storage interval. The required battery capacity was calculated by considering that only 85% of the battery capacity would be discharged, which will helps increase the lifetime of the battery. The power output of a 10 kW rooftop PV system was calculated using Eq. 1.

$$\text{Power output} = \frac{Power\ output\ for\ 740\ kW\ system}{74} \qquad \text{Eq 1}$$

Table 2: Energy storage capacity of the battery for each duration

Installed battery capacity and duration of storage	Battery charging capacity required (kW)	Battery energy storage capacity (kWh)
10 kW (2 h)	4.59 kW	16.80
10 kW (3 h)	4.45 kW	22.43
10 kW (4 h)	4.36 kW	28.87
10 kW (6 h)	4.08 kW	40.05

V. CALCULATION OF FEED-IN TARIFFS

To assess the rooftop solar PV with an energy storage system, equity internal rate of return (IRR) and levelized cost were calculated. Feed-in tariffs payable were calculated to ensure that the simple payback period would be less than 7 years and the internal rate of return to be 4% higher than the lending rate. Average Weighted Deposit Rate (AWDR) and the Average Weighted Fixed Deposit Rate (AWFDR) are published in the Central Bank of Sri Lanka's momentary policy document for the month of September 2022 [8]. [8]. The lending rate was calculated as the sum of the margin for commercial banks and the average of AWDR and AWFDR. The lending rate so calculated was assumed to gradually decline to reach 10% by the 7th year, which was the average value before the economic crisis. Furthermore, the return on equity was calculated by adding 5% to the lending rate. The local inflation rate at the time of the study (April 2022) was 33.8% [9], and it was assumed to reach 25% in the year 2023 and a 5% reduction was assumed every year from the year 2023 until it reaches 5% in the year 2027.

$$Lending\ rate = \frac{AWDR + AWFDR}{2} + Margin\ for\ commercial\ banks$$

$$Return\ on\ Equity = Lending\ rate + 5\%$$

Table 3: Input parameters to the financial model

AWDR	11.63%
AWFDR	15.41%
Margin for Commercial Banks	5.00%
Calculated Lending Rate	18.52%
Assumed Annual Return on Equity Required (1st year)	23.52%
Loan Tenure (Years)	7
Average Plant Factor (dc)	19%
Annual Degradation	0.50%
Grid availability	99%
Peak time price (% of daytime price)	130%

The total investment for the system is the sum of the cost of the solar PVs, inverter, and battery. The investment for solar PV and standard inverter costs was the same in all cases, but there will be an additional cost due to the hybrid inverter in all the cases where the battery was included. Furthermore, the volume-weighted average battery market price for 2021 was 132 USD/kWh according to BloombergNEF's annual battery price survey, and the cost for the battery was calculated accordingly without adding customs duty or any taxes [10]. Even though solar panels could perform well for 20 years with an annual degradation of 0.5%, the inverters and Lithium-ion batteries may not last for 20 years. Battery capacity was assumed to decline by 5% each year relative to the previous year's capacity, and it was assumed that both the inverter and battery would be replaced after 10 years of operation.

Table 4: Comparison of total system cost with different battery capacities

	Battery Capacity				
	Without battery	2 hours	3 hours	4 hours	6 hours
Average charging power to battery (kW)	-	6.20	6.02	5.89	5.52
Required Energy to be Stored (kWh)	-	13.44	19.06	24.54	34.04
Required battery capacity to limit discharge to 85% (kWh)	-	16.08	22.43	28.87	34.04
Standard inverter (LKR million)	2.75	2.75	2.75	2.75	2.75
Additional investment in the hybrid inverter (LKR million)	-	0.25	0.25	0.25	0.25
Investment in battery storage (LKR million)	-	0.80	1.07	1.37	1.90
Total investment (LKR million)	**2.75**	**3.80**	**4.10**	**4.37**	**4.90**

Table 5 shows the calculated feed-in tariff for a 10 kW capacity without a battery over a 20 year period. The annual revenue requirement was calculated by combining operation and maintenance costs, inverter replacement, loan settlement, and return on equity. The tariff for each tier was calculated as the Net Present Value (NPV) of the revenue requirement divided by the NPV of electricity generation for that tier. The feed-in tariff for the first seven years was calculated to be 42.5 LKR/kWh, and from the eighth year to the twentieth year, it was calculated to be 23.0 LKR/kWh.

Table 5: Calculated feed-in tariff (PV Without Battery)

Installed Capacity	Levelized tariff (LKR /kWh)	Feed feed-in tariff (LKR/kWh)		Equity IRR	Simple payback period (years)
		Up to 7th Year	8th to 20th Year		
10 kW dc	37.50	42.50	23.00	18.57%	3.9

Table 6 shows the feed-in tariff for a 10 kW dc solar PV system with different battery capacities. The tariffs need to be paid for each battery capacity were calculated separately.

Table 6: Calculated feed-in tariffs (PV with Battery)

Installed Capacity (Battery capacity)	Levelized tariff (LKR /kWh)	Feed feed-in tariff required (LKR/kWh)		Equity IRR	Simple payback period (years)
		Up to 7th Year	8th to 20th Year		
10 kW dc (2h)	53.00	57.50	35.50	18.6%	3.9
		74.50	**46.50**		
10 kW dc (3h)	57.00	61.00	39.50	18.6%	3.9
		79.50	**51.50**		
10 kW dc (4h)	61.50	65.00	44.00	18.6%	3.9
		84.50	**57.50**		
10 kW dc (6h)	69.50	71.50	51.50	18.6%	3.8
		93.50	**67.00**		

Note: Tariffs shown in **bold** lettering are the tariffs required to be paid during peak time (6.30 pm-10.30 pm), while others are the tariffs to be paid during daytime, for the investments in battery storage to be viable. Figure 2 shows the required feed-in tariffs for a 10kW DC PV system with a 2-hour battery over a 20 year period.

It was assumed that the investor's equity would account for 30% of the total investment, with the remaining amount financed by a commercial bank at a calculated lending rate. Table 7 shows the cash flow to equity throughout the operation of a 10 kW PV system with a 2-hour battery, based on the assumptions provided in Table 3. The revenue from electricity sales was calculated by multiplying the expected energy output of a 10 kW PV system by the corresponding tariff in Table 6. The net cash flow was calculated by subtracting the equity, O&M cost, battery and inverter replacement costs (10^{th} year replacement), and loan settlement from the revenue earned from electricity sales.

Table 7: Cash flow (10 kW PV system with a 2 hour battery)

Year	Equity	O&M Cost	Loan Settlement	Electricity Sales Revenue	Net Cash flow
0	1.14	-	-	-	(1.14)
1	-	0.06	0.84	0.97	0.08
2	-	0.07	0.76	0.97	0.14
3	-	0.08	0.66	0.96	0.22
4	-	0.09	0.57	0.96	0.30
5	-	0.09	0.50	0.95	0.37
6	-	0.10	0.44	0.94	0.41
7	-	0.10	0.40	0.92	0.42
8	-	0.11	-	0.56	0.45
9	-	0.11	-	0.55	0.44
10	-	0.12	-	0.54	(1.60)
11	-	0.12	-	0.58	0.45
12	-	0.13	-	0.57	0.45
13	-	0.13	-	0.57	0.44
14	-	0.14	-	0.57	0.43
15	-	0.15	-	0.56	0.42
16	-	0.16	-	0.56	0.40
17	-	0.16	-	0.54	0.38
18	-	0.17	-	0.53	0.36
19	-	0.18	-	0.52	0.34
20	-	0.19	-	0.51	0.32

Note: Cashflow is in LKR million

Sri Lanka's average bulk supply energy cost (the price at the transmission/distribution boundary) for January-June 2023 has been submitted by Ceylon Electricity Board (CEB) to the Public Utilities Commission of Sri Lanka (PUCSL) as follows: 39.63 LKR/kWh (day), 52.07 LKR/kWh (peak) and 23.51 LKR/kWh (off-peak).

Therefore, it can be concluded that: (a) offering 37.00 LKR/kWh during the day-time is economical for the buyer (CEB) and thereby beneficial for the electricity customer, while also being profitable for the investor (subject to resolving the issue of negative cash flow in the early years through a tiered tariff), (b) compelling customers to install battery storage to address the voltage rise issue at the LV would be financially wasteful, as all the levelized costs calculated to make battery storage viable, are significantly higher than the costs and prices on the grid.

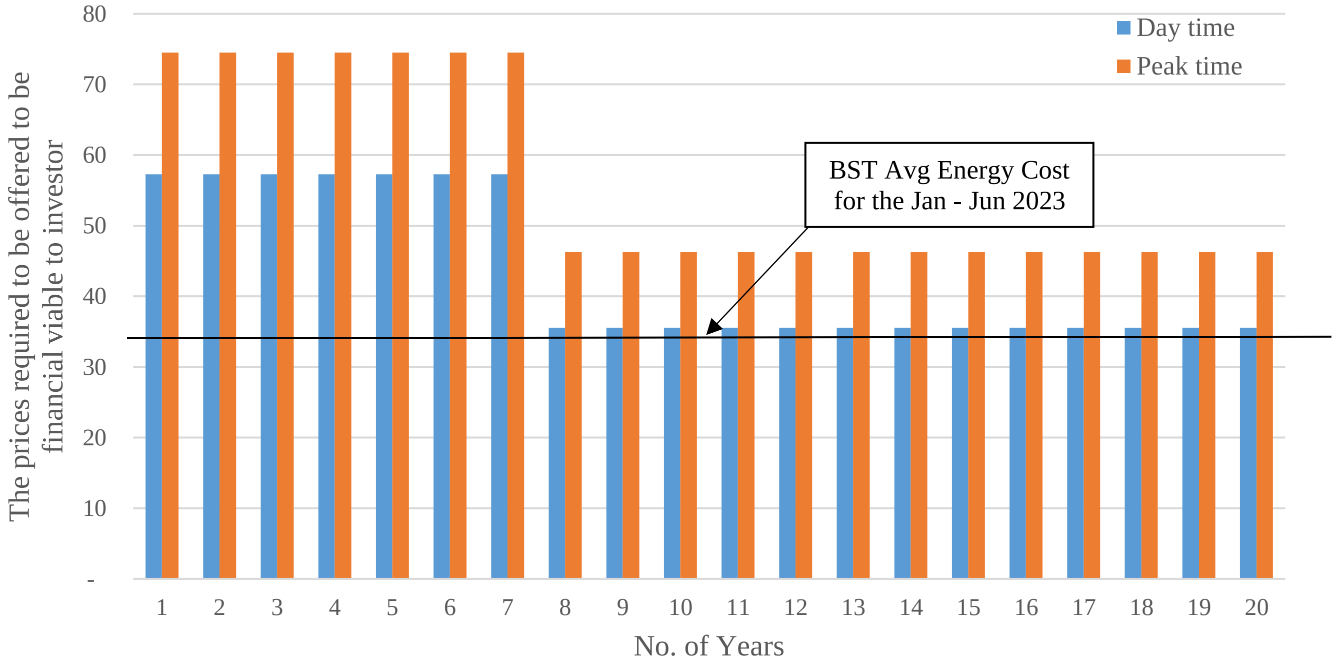

Figure 2: Feed-in tariffs for a Rooftop PV system with a 2h battery

VI. Conclusion

This paper discusses the financial costs and benefits of using battery energy storage as a companion for connecting rooftop solar photovoltaic systems to the grid. Its purpose is to mitigate daytime over-voltages on LV lines. The analysis was carried out for different battery capacities, which would store all the generation of the solar PV system over 2 hour, 3 hour, 4 hour, and 6 hour. The analysis found that when the battery capacity increases, the levelized cost increases rapidly due to the additional investment in batteries and the loss of energy in charging/discharging. Accurate forecasting of solar power generation and daytime line voltages are needed to select the appropriate battery size for a solar PV system to be connected to an LV network.

The feed-in tariffs required to make the investments in solar PV and battery storage financially viable were calculated. This study did not deeply analyze whether these feed-in tariffs are affordable or fair from the customers' point of view. However, all the calculated levelized costs, inclusive of battery storage under different capacities, are higher than the present grid price. This indicates that a policy of compelling customers to install batteries to mitigate daytime LV overvoltage problem (or any other storage-related objective) would be financially wasteful. It is observed that calculated prices to make battery storage viable are all higher than the bulk supply tariffs of 2023. That means customers will have to pay more than they would if solar PV investors are allowed feed-in tariffs to make investments in battery storage viable.

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