TECHNO ECONOMICAL ANALYSIS ON INTEGRATION OF SOLAR PV WITH BATTERY ENERGY STORAGE SYSTEMS FOR DOMESTIC CONSUMERS

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ABSTRACT

As emphasis on renewable energy increases harnessing the maximum solar energy potential has become imperative. However the effective use of its potential is restricted by certain factors. The inherent feature of intermittency causes variations in power and voltage while the dependency on time of generation during day time limits its actual requirement. A night time peak as in Sri Lanka demands a cost effective renewable solution. Battery Energy Storage systems provide an integral solution for both these limitations. A case is studied on implementing a PV combined Battery Energy storage system on domestic consumers with two investment scenarios. The Levelized Cost of Energy (LCOE) of Photovoltaic and Battery Energy Storage System (PVBESS) reduces with increasing system capacity and a 5kW domestic PVBESS configuration shall have a LCOE of Rs.42.14 on a combined consumer utility investment plan. It is presented that under a peak energy system based on gas turbines could be replaced by a combined investment of consumer and utility on battery energy storage with both parties gaining equal benefit.

However the implementation of such scheme is heavily dependent on the Peak power energy mix. . Hence extensive commitment on implementing a PVBESS solution could lead to a loss to the utility, if the share of Gas turbines energy during the peak hours is less than 80%.

Keywords: Battery Energy Storage, PV systems, Peak Power

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LIST OF ABBREVIATIONS

Abbreviation	Description
BESS	Battery Energy Storage System
CEB	Ceylon Electricity Board
CI	Consumer Only Investment
CNPV	Cumulative Net Present Value
CUI	Consumer and Utility investment
DOD	Depth of Discharge
GT	Gas Turbine
IRR	Internal Rate of Return
LCOE	Levelized Cost of Energy
LTGEP	Long Term Generation Expansion Plan
MOPRE	Ministry of Power and Renewable Energy
NPV	Net Present Value
PV	Photovoltaic
PVBESS	Photovoltaic and Battery Energy Storage System
SOC	State of Charge
VRLA	Valve Regulated Lead Acid

Problem Statement

The Solar Energy being a source of renewable energy only produces energy during daytime. However a country like Sri Lanka has the highest demand occurs during the night hours mainly due to the lighting load. Since solar energy produced by domestic consumers is excess additional energy for the national gird, its ideal utilization should be to cater the excess demand during the peak hours.

Objective

The Objective of the Research is to identify the existing issues for the utility concerning the domestic connected solar PV energy sources and to introduce a economically viable solution through battery energy storage which shall be viable for both the utility and the consumer.

1) INTRODUCTION

With the realization of depleting of fossil fuels in the future, the world is moving ahead of harnessing energy from the renewable energy sources. Among these few of the most predominant renewable energy technologies are mini hydro, Solar and Wind. Sri Lanka being a tropical country receives abundant solar radiation throughout the year. Its potential of harnessing energy has not been fully utilized yet. Solar energy conversion to electrical energy is mainly done by two technologies. They are the use of Photovoltaics (PV) and Concentrated solar thermal power plants.

Photovoltaics, the most popular out of these technologies perform the conversion of light into electricity using semiconducting materials. PV energy production process is a pollution free environmentally friendly process. There are no moving parts and can be installed very easily anywhere where direct sunlight is available.

Earlier PV systems were mainly installed in off grid rural areas. However recently it has been a popular choice even in urban areas to be installed in parallel with grid connected supply. Most rooftops provide an ideal location for residential, commercial and industrial electricity consumers to install PV panels.

The growth of Photovoltaic systems has risen rapidly over the past decade and subsequently costs have decreased immensely. The economics of PV systems is now on the verge of reaching grid parity in many countries. Grid parity is considered when the LCOE of solar PV is comparable with grid electrical prices of conventional technologies and is the industry target for cost-effectiveness. Given the state of the art in the technology and favorable financing terms it is clear that PV has already obtained grid parity in specific locations and as installed costs continues to decline, grid electricity prices continue to escalate, and industry experience increases, PV will become an increasingly economically advantageous source of electricity over expanding geographical regions [1].

1.1 Current Situation

The Net Metering scheme was first introduced to Sri Lanka in 2009. Here electricity customers are given the opportunity to install PV panels to produce electricity which can be absorbed by the grid. This allows consumers the advantage of consuming solar energy generated during day and to provide the excess energy to the grid. In net metering the excess energy rolls over as a net kilowatt credit for the next month, making solar energy generated of a given month to be used in a later month. Therefore on the consumers' point of view the grid acts as a virtual storage for the energy produced by the PV panels.

This has been a boon for high electricity consuming domestic consumers. Since the electricity tariff in Sri Lanka is based on a block tariff, high electricity consumers have to pay higher price per kilowatt hour after a certain block is passed. The tariff authorized from 2014/11/15 onwards by the Public Utilities Commission of Sri Lanka for domestic consumers above 60 units is as presented in table 1.

Consumption per month(kWh)	Energy Charge (LKR/kWh)	Fixed Charge(LKR/month)
0-60	7.85	–
61-90	10.00	90.00
91-120	27.75	480.00
121-180	32.00	480.00
More Than 180	45.00	540.00

Table 1 Domestic tariff rates

Therefore such electricity consumers have been gradually shifting from conventional grid only supplied electricity connections to net metered electricity connections. This has enabled to increase the renewable energy portfolio in the country. As at end of December 2015 the total number of installed Solar power from net metering in Ceylon Electricity Board (CEB) areas was 21.58 MW from 3025 consumers [2].

In order to expedite the growth of renewable energy share the Ministry of Power and Renewable Energy (MOPRE) of Sri Lanka introduced a Programme in September 2016 , named “Battle for Solar” by providing the opportunity for consumers to generate their own electricity from solar power under three schemes of Net metering, Net Accounting and Net plus. The intension of the Programme is to increase the capacity of solar energy to 200 MW by 2020 and 1000MW by 2025 [3].

Under the Net Accounting scheme the consumers are paid back for the excess energy produced at a rate of LKR 22/kWh. In the Net plus scheme the generation and consumption of a consumer is considered independently, where consumption is charged separately while production is supplied at a rate of LKR 22/kWh.

However by introducing these solar power schemes not only have provided merits but also are restricted to several constraints.

1.2 Existing Problems

1.2.1 Intermittency

Solar power is unpredictable mainly due to weather conditions. Passing of clouds can most often result in shading problems causing the power to reduce drastically. By using Maximum power point tracking & bypass diodes the power output can be kept at the maximum possible. However the output varies with time due to the change in solar irradiance fluctuation on panels caused by the passing clouds.

Net metering scheme has been very effective in increasing renewable energy penetration of the power system. Moreover it has aided the Distributed Generation concept which has improved low voltage issues within the distribution network. However there are concerns regarding the actual power quality parameters once the PV is connected to the grid. Although there are inverter standards when connecting to the grid, there is no proper monitoring and evaluation of power quality issues of grid connected PV systems.

Failure to operate the system at its required power quality parameters can disrupt the operation of equipment and might cause disconnection of power sources to prevent damage which could lead power system instability. In order to investigate the prevailing issues on the Domestic PV interconnection, an actual sample data was required to be analyzed.

Therefore actual physical data was measured on a Net metered connection of 3.25 kW installation of a domestic net metered consumer in Piliyandala area. The inverter installed were a GOODWE Inverter of 4kW capacity. Measurements of Voltage, Current, Power, Frequency, Harmonics, Flicker parameters were taken from: 23rd July 2015 to 28th July 2015 using the LEM Power Quality Analyzer. The results were analyzed by using the Topas 1000/19 version 3.3.0.2. 20030708.

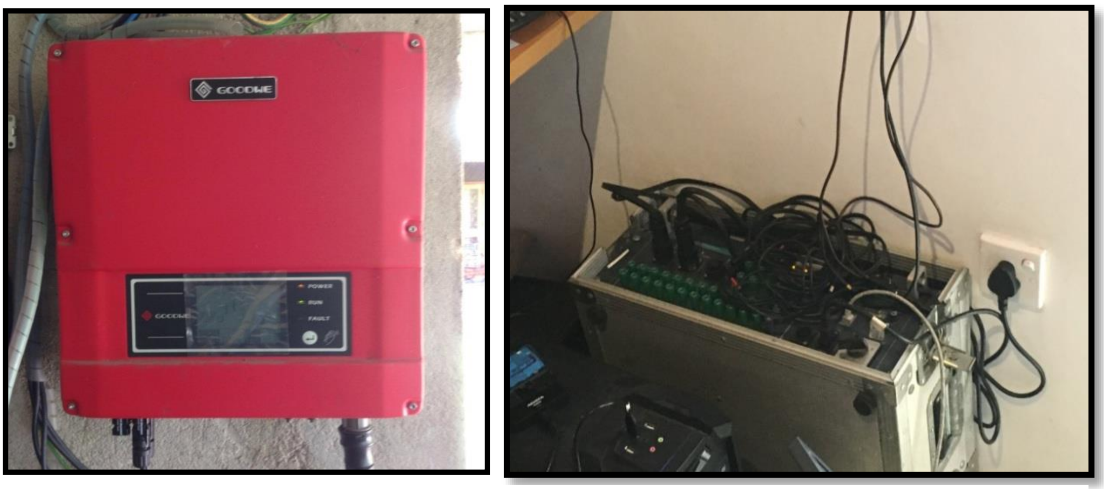


Figure 1 a) GOODWE Inverter b) LEM Power Quality Analyzer

The Power variation pattern and voltage variation pattern were revealed as presented in figure 2 and figure 3 respectively. Solar Power Generation started from 6.30 am to 6.30pm as expected and maximum output is generated in noon. Power fluctuations of 30% of the maximum power can be seen occurring within one minute interval time.

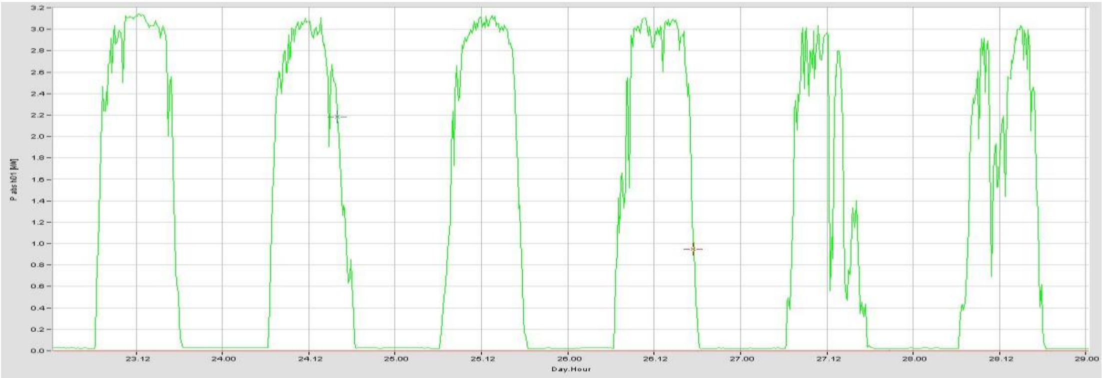


Figure 2 Power variation Pattern of 6 days

Figure 3 Voltage variation of single day

Voltage is a parameter that depends on the point of common coupling to the grid. Hence it does not completely depend on the PV power variation. The results revealed that the voltage tends to fluctuate throughout the day. However it was seen to be within the limits of 6% variation accepted by the Utilities.

Power-line flicker is a visible change in brightness of a lamp due to rapid fluctuations in the voltage of the power supply. Rapid voltage fluctuations result in flicker and the magnitude of light change has an obvious relationship to the perceived annoyance to the observer. Short term flicker index (Pst) is calculated according to a statistical process over a standardized 10-minute observation interval. Long term flicker index (Plt) is calculated to a statistical process over a standardized two-hour period. The IEC 61000-2-2 Standard specifies a compatibility level for Pst as is 1.0 and Plt as 0.8.

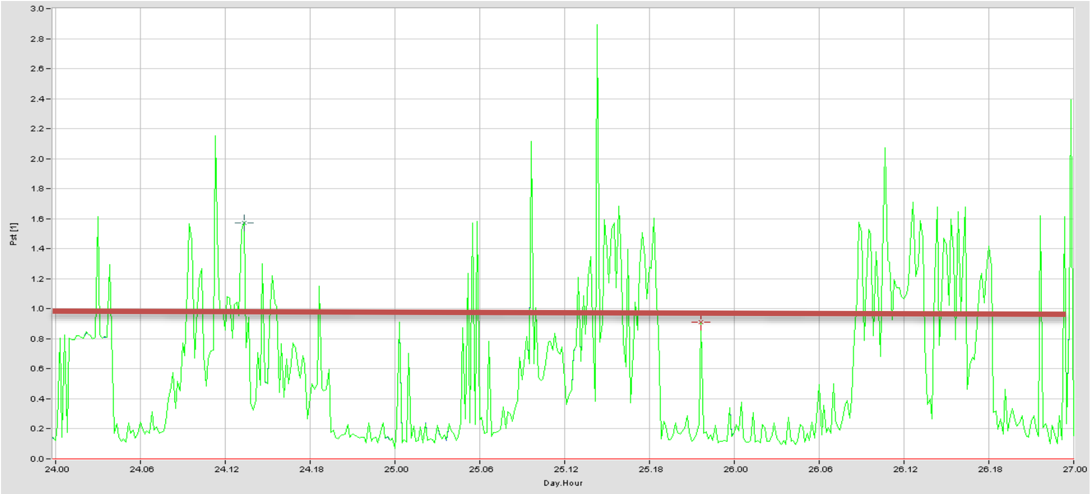


Figure 4 Pst Variation due to Solar Panels

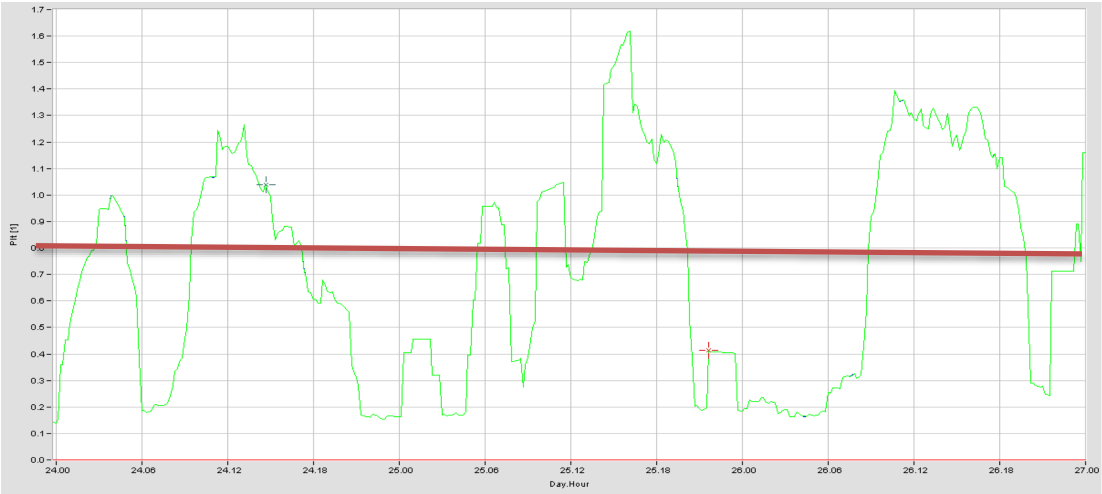


Figure 5 Plt Variation due to Solar Panels

The Short Term Flicker index values and Long Term Flicker index value for three days operation are presented in figure 4 and figure 5 respectively. It is observed that the PV installation violates both the short term flicker index and the Long term flicker index parameters within the time period of generation of solar energy. Pst values ranging from 1.8 to 2 can be witnessed regularly and Plt values of above 1 is also very frequent.

Harmonics are multiples of the fundamental frequency which are caused by nonlinear loads. Harmonics can increase heating in the equipment and conductors, misfiring in variable speed drives and cause power system instability. The Utility has adopted the IEEE standard 519 in which the Total Harmonic Distortion Level must be less than 5 % for any PV installations and the individual harmonics is expected to be less than 3%.

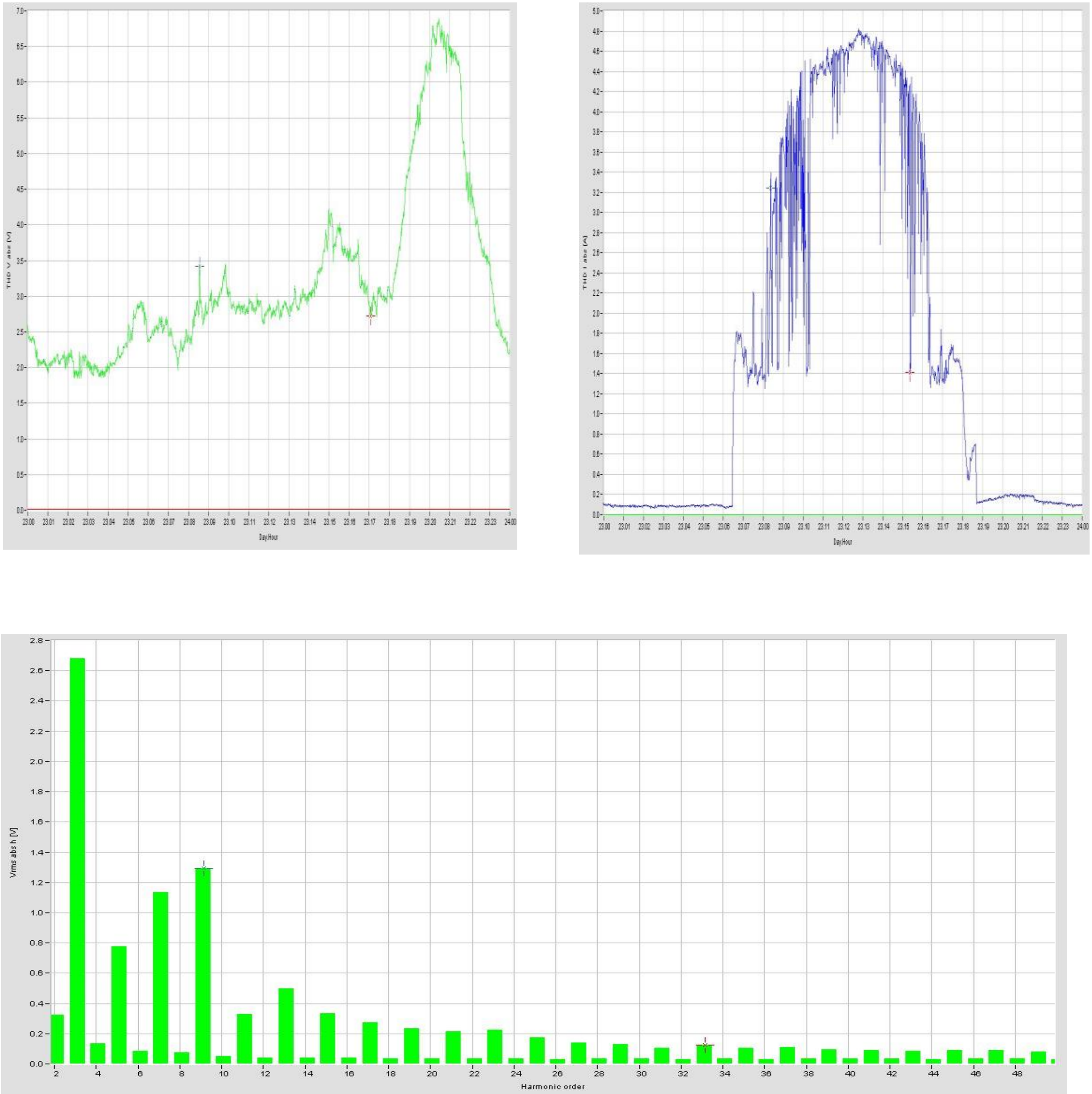


Figure 6 a) Voltage Harmonics b) Current Harmonics C) Harmonic Orders

The harmonic levels of the PV installation are within the acceptable limits as illustrated in figure 6. The individual harmonics are less than 3% and the total current harmonic distortion level is below 5% throughout the whole period of operation. The voltage harmonics are also within standards during the time of PV solar generation.

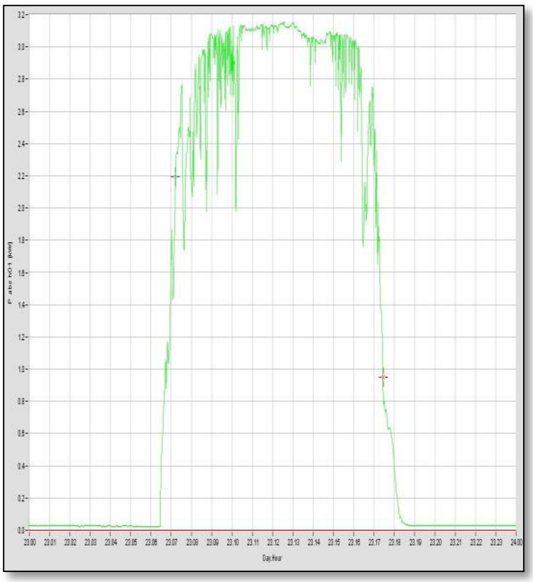
The existing issues are not localized and studies have been conducted worldwide on adopting a strategic solution for the case. A distribution network containing medium and low voltage feeders were extracted from a New South Wales Distribution system in Australia to investigate Rooftop Solar PV Impacts and Evening Peak Support by Managing Available Capacity. [4] The Study reveals that the voltage-rise is reduced by the charging operation of batteries and the voltage fluctuations are reduced by the short-term discharging operation. The voltage profile is improved during the evening peak by the discharging operation; and the voltage dip is partly mitigated by the short-term high discharge operation.

A system currently operating in a solar-coupled mode on 12.47 kV power systems in the Hawaiian Islands, was investigated by a group of scientists at a solar technology testing facility in Colorado for a variety of modes of operation for battery energy storage systems in grid-tied solar applications [5]. The BESS was used to provide voltage stability through dynamic VAr support, and frequency regulation via droop control response. As pointed out, the rapid-response characteristic of the BESS makes storage valuable as a regulation resource and enables it to compensate for the variability of solar PV generation.

As such a similar approach could be adopted in Sri Lanka where battery energy storage is used to capture all the intermittencies and store the power on dynamic charging rates as per requirement. The storage solution should result in reduction of the flicker and other voltage fluctuation related issues prevailing in the current grid.

1.2.2 Demand Supply Mismatch

Solar energy is produced only during the day time. The effective operation of the solar panel can be classified during the period from morning 6am to evening 6 pm. The period and intensity of sunshine are varied on the dry and wet seasons which directly effects on the power and energy output. However the daily pattern of energy production, in most cases can be predicted as presented in figure 7 based on test results. Here the maximum power occurs during the noon. The increase of consumer accounts under any incentive scheme for solar power shall contribute to large amount of solar generation during the day time following the same pattern shown in figure 7.



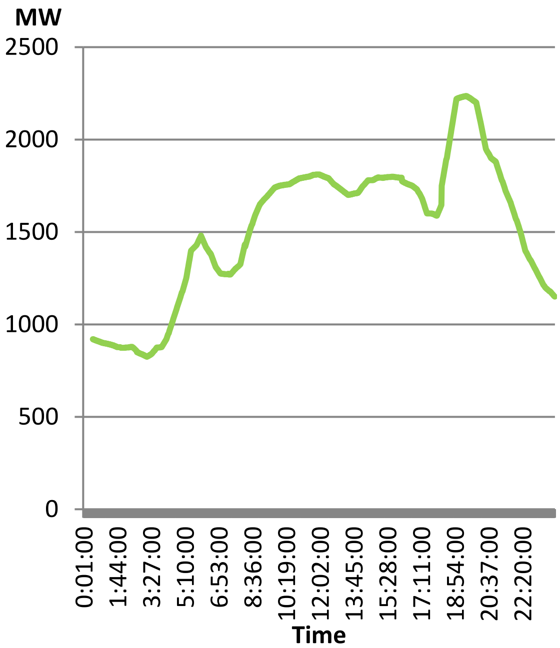


Figure 7 : PV panel Power variation of single day

Figure 8 : Daily Load curve as on 2016-06-06

On the other hand the load curve of Sri Lanka follows a different pattern as illustrated in figure 8. It presents the typical load curve of Sri Lanka as depicted from data on 06th June 2016. Here the maximum demand occurs during the night time from the period around 6.30 pm to 9.30 pm.

As presented in the Long Term Generation Expansion Plan (LTGEP) 2015-2034 of CEB, the load curve pattern has not changed significantly in the last eight years. Thus if the same load pattern is forecasted at the year 2020 for the demand growth of 6.8% as projected in LTGEP 2015-2034 of CEB, the load curve might change as illustrated in Figure 9.

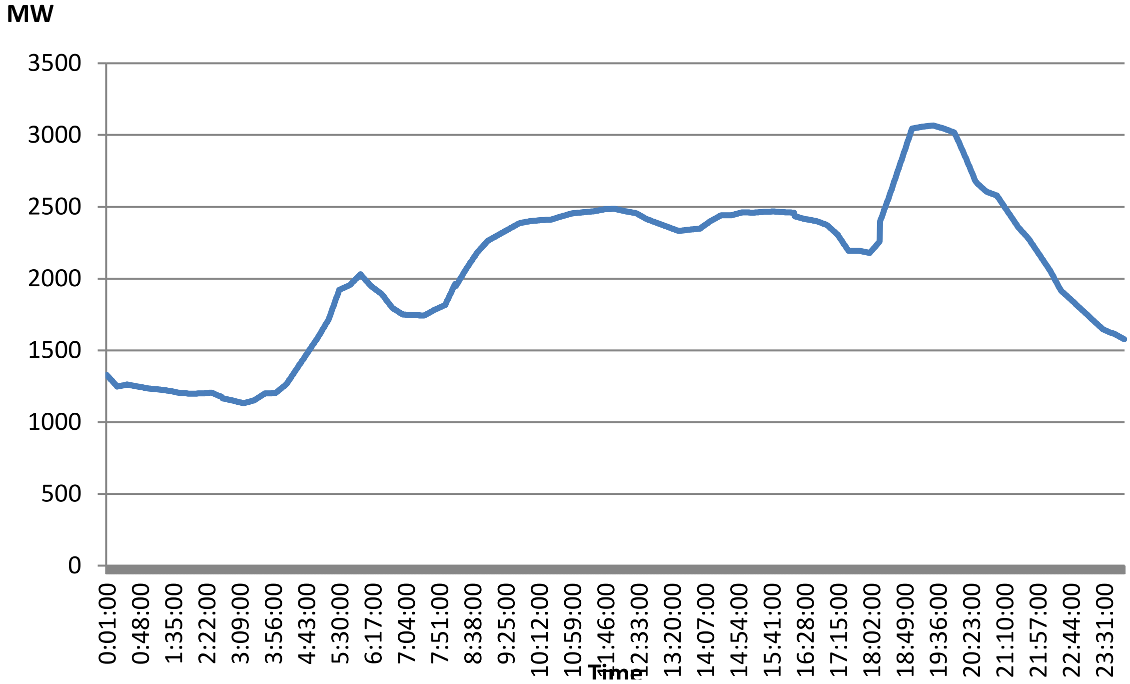


Figure 9 Extrapolated Load Curve Forecast 2020

Under the current Ministry of Power and Renewable Energy (MOPRE) targets, it is expected to introduce 200MW of solar PV to the grid through the “Battle for Solar” Programme. If so, the effect it could have on the load curve has to be investigated. The data taken on the 3kW domestic PV panels are extrapolated to predict the 200MW Solar PV generation pattern. The minor variations of shading effect management as per the scattered distribution of PV plants are neglected herewith. The expected power variation pattern of a single day due to this contribution is depicted in figure 10.

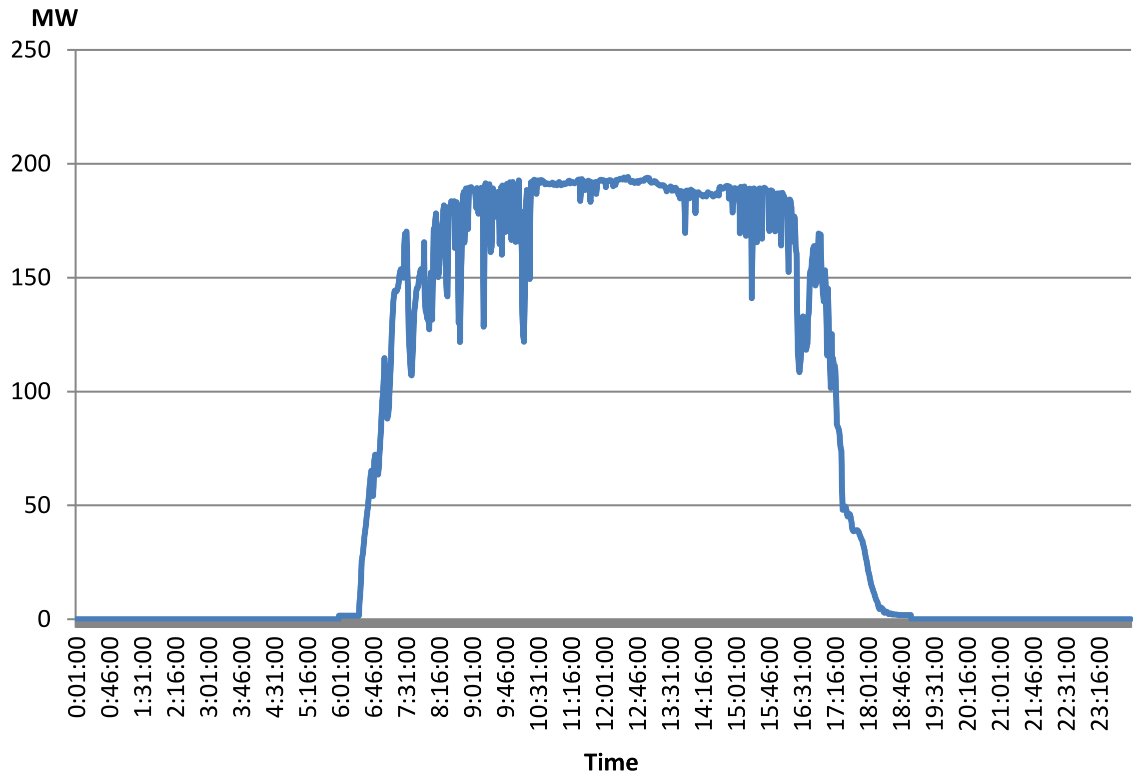


Figure 10 Solar Power Contribution 2020

Incorporating the battle for solar shall give the additional 200MW power during the time from 6am to 6pm as per the pattern. As such the following variation of the typical load curve in 2020 can be expected as presented in Figure 10.

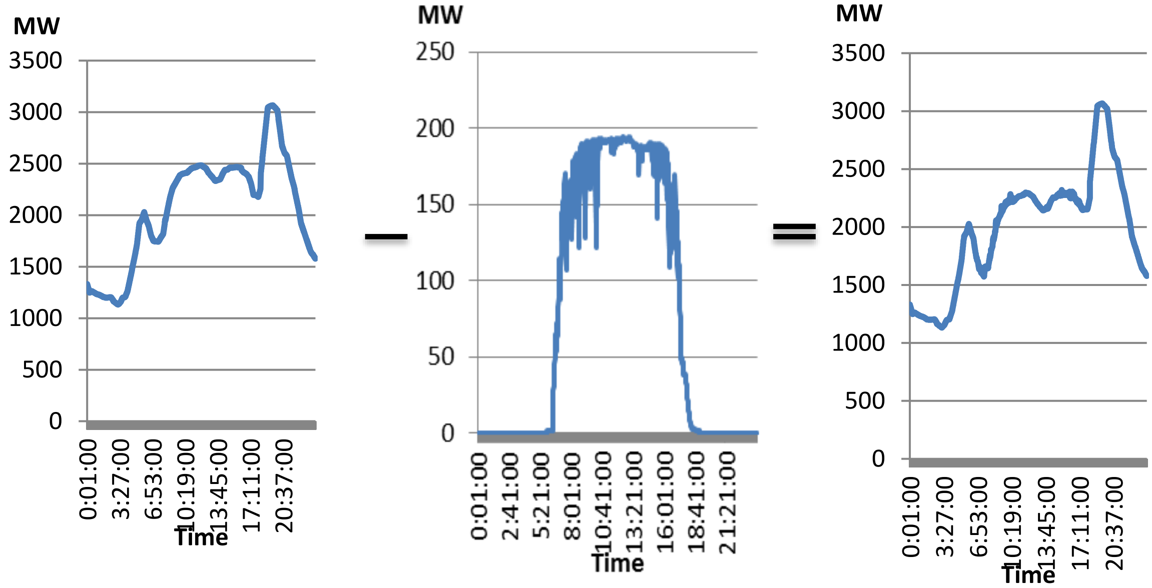


Figure 11 Load curve variation through "Battle for solar" in 2020

There is only a minor deviation from the existing load curve pattern and the load factor shall get reduced furthermore. An alternative is required to be introduced in order to incorporate this additional generation for load factor improvement and to address the matter on reducing the expensive generation during the peak hours.

1.3 Economics of Peak Power

The peak power demand is supplied by fast operating power additions that can regulate the power easily. There are two power options which are used here in Sri Lanka for this purpose. They are Hydro power plants and Gas turbines which are mainly used for peaking purposes. All the other Thermal additions also operate in the peak time while also running during the base load. In some instances the combined cycle plants are also operated at the peak time when the hydro energy is insufficient.

The following table represents the cost component which is incurred by the generation of 1 kWh of energy to the utility as presented in the LTGEP 2015-2034 of CEB [6].

Parameters	GT 16	GT 110	Comb. Cycle Naptha	Diesel Engin e : Man	Diesel Engin e : Pielsti c	Coal Puttala m
Fuel cost (Uscts/Gcal)	8858	8858	8282	6187	6187	1553
Heat rate at full load (kcal/kWh)	4022	2860	1897	2015	2245	2378
Variable O&M($/Mwh)	0.77	5.98	3.23	2.03	6.89	3.49
Fuel rate (Uscts/kWh)	35.63	25.33	15.71	12.47	13.89	3.69
Fuel rate (Rs/kWh)	47.03	33.44	20.74	16.46	18.33	4.87
Variable O&M (Rs/kWh)	0.10	0.79	0.43	0.27	0.91	0.46
Total	47.13	34.23	21.16	16.72	19.24	5.34

Table 2 Generation Cost of Power Sources

Coal Power plant is a base load power plant and is a least cost solution which shall operate on maximum availability independent of peak power requirement. Hydro power plants which have the reservoir storage option are utilized for peak power generation to avoid high cost generation in the night. However the total energy available of the power plant is independent of time of operation. Therefore if solar power is effectively stored and provided in the night time hydro power resource can operate independently without peak power requirement restriction. A proper analysis has not yet been done on forecasting the effective peak price under different seasons of the year. The effective peak price can be a combination of the gas turbine prices combined cycle prices or diesel engine prices which operate at various loads on different days during the peak time. It is assumed that the plants operating cost areas same as on full load efficiency.

Therefore for my analysis I have taken on the assumption of finding the effective price for the worst avoided cost scenario, which is the scenario where gas turbines operate on peak time every day. After identifying the limit in which battery energy storage system becomes cost effective for the worst avoided cost scenario, derivations shall be made for the other power plant configurations on peak time. Thus the following cases are considered on derivations of the worst avoided cost scenario

Gas Turbine Generation Cost	$= C_{GT}$	(Rs/kWh)
Combined Cycle Plant Generation Cost	$= C_{cc}$	(Rs/kWh)
Avoided Generation Cost	$= A_g$	(Rs/kWh)
Avoided Transmission & Distribution Cost	$= A_{T\&D}$	(Rs/kWh)
Annualized Equivalent Total Avoided Cost	$= A_E$	(Rs/kWh)

Case 1: Gas turbine Operates every day to produce electricity in the peak time

$$A_g = C_{GT}$$

Case 2: Gas turbine Operates 90 % of the days in the year while the remaining 10 % of the day's peak is given by Combined Cycle power plants.

$$A_g = 0.9C_{GT} + 0.1C_{CC}$$

Case 3: Gas turbine Operates 80 % of the days in the year while 20% is supplied by the Combined Cycle power plants

$$A_g = 0.8C_{GT} + 0.2C_{CC}$$

Case 4: Gas turbine Operates 70 % of the days in the year while 30% is supplied by the Combined Cycle power plants

$$A_g = 0.7C_{GT} + 0.3C_{CC}$$

In the conventional system power generated is centralized and the power produced is transmitted and distributed through power line carriers. Power transmission and distribution incur losses while delivering the energy. The losses are mainly due to resistive losses in conductors and transformer losses. Therefore the cost of delivering shall include not only the generation cost, but also the transmission cost and distribution cost.

However in a decentralized distributed generation system power is produced at the load center itself. Thus the transmission cost and the distribution cost is negated.

Total Avoided Cost = Avoided Generation Cost + Avoided Transmission & Distribution Cost

$$A_E = A_g + A_{T\&D}$$

The effect of incorporating BESS for peak support is evaluated with the constraints of energy loss on storage. Battery energy storage systems can have a battery efficiency of 80% as depicted in the study of Japanese team of experts on their study of Economic Value of PV Energy Storage Using Batteries of Battery-Switch Stations

[7]. The total energy produced at the daytime derived from the data as presented in Figure 10 is 1869 MWh under the "Battle for solar Programme" in a day on 2020,. This shall yield the opportunity to provide 1495 MWh of energy considering the 20% energy loss. The resultant energy can be supplied as a constant power supply of 373.81 MW for four hours or 498.41 MW for three hours. Region wise coordination on peak power limit can also be introduced for smooth operation.

The expected effect in load curve for a constant 373.81MW PVBESS energy supply during the peak hours from 6pm to 10pm is illustrated in figure 12.

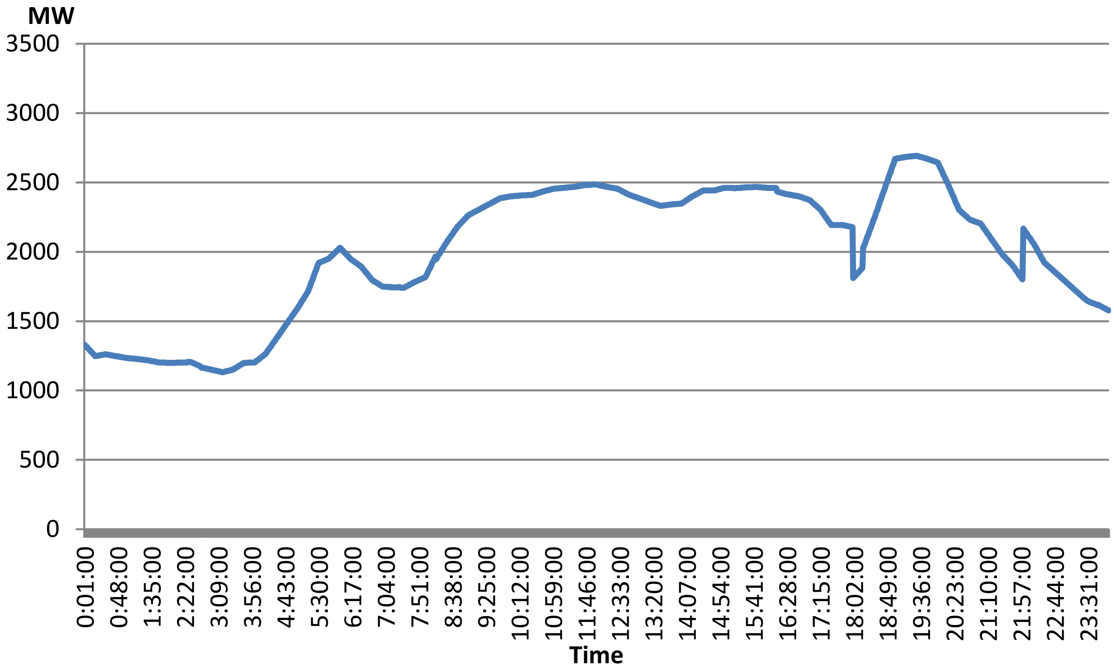


Figure 12 Load curve on 2020 with PVBESS integration

As depicted in the above figure the peak power demand has reduced significantly and the load factor is improved. Thus the commitment of expensive power sources that run on fuel is restricted. In the Sri Lankan context peak power suppliers of Gas turbines or Combined Cycle power plants disconnected or de loaded from the national grid. The Public Utilities Commission of Sri Lanka's approved LTGEP 2015-2034 has identified the introduction of 105MW of Gas turbines to be introduced to the national grid by 2018 and 2019.

It is also possible to replace such addition by alternatively introducing PVBESS. However in this research the capacity benefit is excluded and only the energy benefit is considered when evaluating the avoided cost. Therefore the avoided cost shall compromise of fuel cost and the variable operation and maintenance cost.

This is due to the fact that the Gas turbines not only provide the function of peak energy support but also has the function of reactive power generation while running on syncon mode. It also provides the black start capability in case of blackout.

Even so since the PVBESS electricity supply is decentralized and uncoordinated there is a degree of unpredictability. Hence it could be required to have Gas turbine power plants installed to the national grid as standby power plants. All power plants have a fuel cost, variable Operation & Maintenance cost and a Fixed operation and maintenance cost. Since the gas turbine plant is kept as standby by system the avoided cost shall be the fuel cost and the variable operation and maintenance cost only.

Battery energy storage systems are increasingly being used to help integrate solar power into the grid. These systems are capable of absorbing and delivering both real and reactive power with sub-second response times. With these capabilities, battery energy storage systems can mitigate such issues with solar power generation as ramp rate, frequency, and voltage issues. Beyond these applications focusing on system stability, energy storage control systems can also be integrated with energy markets to make the solar resource more economical [8].

A literature review on PV-battery systems highlights the prevailing European domestic tariff systems and PV installation configurations and emphasizes the German Scenario where their tariff structure not only involves a selling price for the electricity but also a self-consumption fee that is split into two tariffs [9]. It presents a rate of 12.43 €ct/kW h if the self-consumption share is above 30% and a rate of 8.05 €ct/kW h if self-consumption share is below 30%.

2) PVBESS OPERATION TOPOLOGY

Although there are many methods in adopting PVBESS solutions the proposed PVBESS configuration shall be used in such a way that all the energy produced by the PV panel shall be devoted to supply the peak. As such all the power generated shall flow through the charge controller to the Battery.

If the State of charge of the battery is above the maximum state of charge of the battery the charge controller shall stop the battery charging and divert the energy through the inverter to the domestic household usage. If the Power required at housed hold is less than the power of the inverter output the resultant energy shall be passed off to the grid. Meanwhile when discharging the energy during the peak time the battery will discharge its stored energy through the inverter until its maximum allowable depth of discharge is achieved. In order to correctly meter the resulting benefit the energy discharged through the inverter should be measured by the utility. Thusly the consumer is also benefitted on the self-consumption of his own energy units. So in order to divert all the energy that is produced by the panels for peak consumption the ideal battery capacity should be selected.

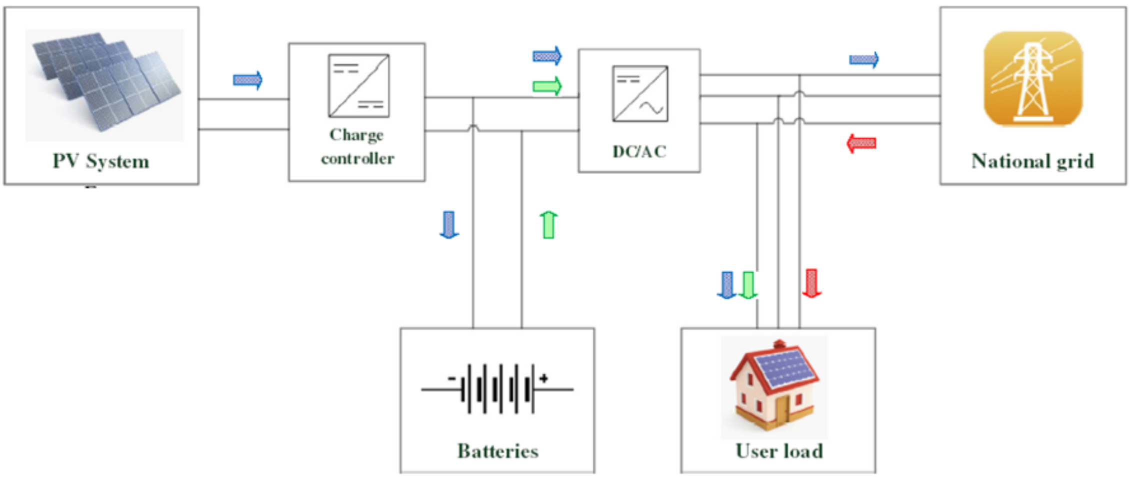


Figure 13 Operation of PVBESS cycle

2.1 PV panels

PV panels are the main equipment of the configuration which converts solar irradiance to electric power. The study conducted by National Renewable Energy Laboratory of Colorado gives a comprehensive analysis on the available solar irradiance potential in Sri Lanka [10]. Accordingly such the geographical map of Annual average daily total solar resources for fixed flat plate collector depicts a Solar Irradiance Index of 4.5- 5.5 kWh/m^2/per day.

Solar Irradiance Index Energy per day	$= E_{IPV}$	(kWh/perday)
Energy produced by the PV panel per day	$= E_{PV}$	(kWh/perday)
PV panel degradation on year T	$= D_T$	(%)

$$E_{PV} = D_T \times E_{IPV}$$

The Efficiency of PV panels do not remain constant throughout the lifetime of the panel. The performance of Solar PV degrades annually. Usually it is an accepted norm by each supplier in which they give a guarantee in which the PV panel will have 90% of the original output in 10 years and 80 % of the original output in 25 years of operation. That is the estimated degradation of 10% in 10 years & 20% in 25 years. It is in line with the Review study which was carried on Photovoltaic Degradation Rates which analyzes data of over 40 years with nearly 2000 degradation rates, measured on individual modules or entire systems. [11]. It presents mean degradation rate of 0.8%/year based on the available data.

However the annual rate of degradation with linearity and the precise impact of climate have not been satisfactorily researched. In this analysis the degradation levels have been taken for the lifetime of 25 years with annul degradation of 0.992 per year compared to the previous year which follows the manufacturers guarantee.

Year of Operation	PV Panel Degradation
0	1
1	0.972
2	0.964224
3	0.956510208
4	0.948858126
5	0.941267261
6	0.933737123
7	0.926267226
8	0.918857088
9	0.911506232
10	0.904214182
11	0.896980468
12	0.889804625
13	0.882686188
14	0.875624698
15	0.868619701
16	0.861670743
17	0.854777377
18	0.847939158
19	0.841155645
20	0.8344264
21	0.827750988
22	0.82112898
23	0.814559949
24	0.808043469
25	0.801579121

Table 3 PV Panel Degradation Rates

2.2 Inverter

The current produced in the solar panel is direct current. However majority of the household operating equipment as well as the grid operate on alternating current. Therefore for every PV installation, an inverter is required to convert the direct current to alternating current. The utility has imposed standards and specifications to be adopted when connecting an inverter for the consumer.

The inverter used to convert the solar panel produced energy may be a uni-directional or bi-directional unit depending on the purpose of the application. Since the viability of charging the battery bank through grid energy has not been considered as economically feasible yet an uni-directional inverter is considered sufficient for a PVBESS installation.

The most important fact to consider is even though the inverter is designed to convert the specific capacity of solar power energy produced over the sunshine period of a day, when considering the peak demand it has to discharge the energy within three or four hours. Hence for a PVBESS installation equivalent inverter capacity of 1.33 times the regular PV only grid connected installation is required.

2.3 Charge Controller

A charge controller is required to ensure that the batteries do not overcharge or discharge beyond the certain level as accepted. The State of Charge (SOC) is the inverse of depth of discharge (DOD) which provides the figure of the available capacity of a battery. Some companies provide inbuilt charge controller in the inverter itself but a separate charge controller is recommended to ensure proper functionality and protection of batteries. The charge controller shall function as follows.

During Daytime of solar power Generation ($E_{pv} > 0$ & 06.30 H< T< 18.30)

If $SOC >= SOC_{(max)}$

Stop charging the battery and supply the energy to the household

Else if $SOC_{(max)} > SOC > SOC_{(max\ DOD)}$

Charge the battery

Else if $SOC < SOC_{(max\ DOD)}$

Charge the battery

During the peak energy time (18.30 H< T< 21.30)

If $SOC > SOC_{(max\ DOD)}$

Discharge the battery

If $SOC < SOC_{(max\ DOD)}$

Stop discharging the battery

2.4 Battery

There are various types of batteries available in the market today. Usually different types of batteries have unique advantages to suit for their applications. Unlike the usual car batteries the renewable energy storing batteries must be selected to have large number of deep cycle discharges.

The most evolved battery technologies are based on Lithium- ion batteries and Lead acid batteries. There are pros and cons for both technologies and number of studies have been carried out on their affectivity [12]. A research conducted in Belgium investigates possibility of PV Battery integrations of different battery technologies under different price variations. It mentions that in 2012 the Li-ion battery is almost as double as expensive as the starter Lead acid battery system and if the electricity prices do not increase by the next 20 years, then only a lead-acid battery system up to 5 kWh is cost-effective. However in 2017 the Li-ion system cost comes almost close to the lead-acid storage system cost. If the electricity price does not increase, then a small battery up to 2 kWh is viable. Conversely it states if the electricity prices would increase substantially batteries will be attractive with discerning sizes.

Although Flooded lead acid batteries are more economical, thye require regular maintenance. On the other hand Sealed batteries are "maintenance free" and will not emit any corrosive fumes as flooded batteries. Valve Regulated Lead Acid battery, more commonly known as a sealed maintenance free batteries provide the competitive edge over other batteries. There is no need to check the level of electrolyte or to top up water lost due to electrolysis. Hence it would be most practicable solution in implementing domestic battery storage solution which relives the burden from the consumer.

The battery bank consists of many batteries connected in a combination series-parallel configuration to provide the desired power and energy capabilities for the application. A Single battery typically has two main parameters which are the voltage per unit and the capacity described in ampere hour (Ah). An Ah is the amount of energy charge in a battery that will allow one ampere of current to flow for one hour. In an ideal battery, the relationship between continuous current and discharge time is stable and absolute. But real batteries don't behave exactly as this simple linear formula would indicate. Although the Voltage of a battery bank varies depends on the state of charge of the unit it is safe to assume it as a constant voltage source. So effectively the total energy shall be estimated based on as an ideal battery which shall be the product of unit voltage and current capacity.

Energy stored in the battery per day	$= E_{BS}$	(kWh/perday)
Energy discharged by the battery per day	$= E_{BD}$	(kWh/perday)
Capacity to store Energy per day	$= C_{BS}$	(kWh/perday)
Depth of Discharge	= DOD	(%)
Charging Efficiency	$= \eta_c$	(%)
Discharging Efficiency	$= \eta_d$	(%)

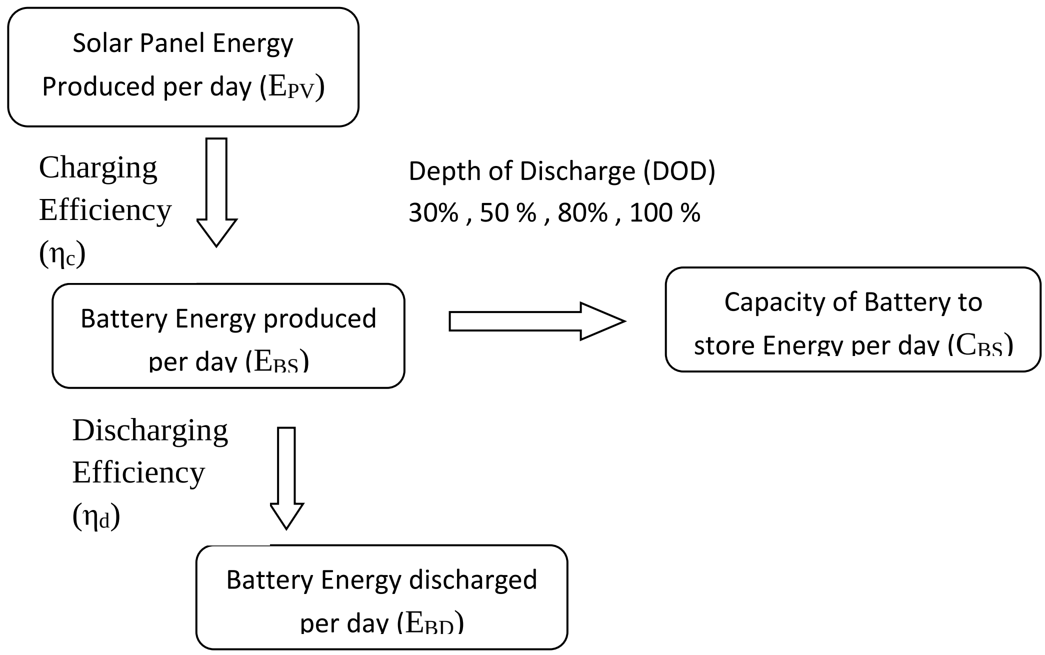


Figure 14 Battery Storage Capacity & Energy Determination

$E_{PV} = E_{IPV} . D$

$E_{BS} = E_{PV} . \eta_c$

$C_{BS} = E_{BS} . (DOD) = E_{PV} . \eta_c . (DOD)$

$E_{BD} = E_{BS} . \eta_d = E_{PV} . \eta_c . \eta_d$

The typical operational flows of the battery energy and capacity values are presented in figure 8. Only a portion of the energy produced by the panel is stored in the battery and even a lesser amount of energy is discharged during the peak. Battery Efficiency is a pivotal concern when it comes to storage solutions. J. Ruggiero & G.T. Heydt, have mentioned that lead-acid batteries can have capacities up to 50 MW and can store up to 200 MWh of energy at an efficiency of 75-85% [12]. On a research conducted in Japan the efficiency of the battery is utilized as 0.81 which consist of a charging efficiency of 0.9 and the discharging efficiency of 0.9 [7]. The same efficiency values are used here in the analysis for integrating PVBESS configurations.

Unlike normal PV system operation, the lifetime of a battery bank system will depend on various factors. One of the main characteristics is the battery charge and discharge cycle. As per the requirement of providing peak support the domestic PVBESS system shall typically charge and discharge energy every day. Thus one life cycle shall be equal to a single day. The charging cycle shall vary between 6am to 6pm every day and the discharging cycle shall lie between 6.30pm to 9.30pm.

The Depth of Discharge (DOD) has a huge impact on the battery lifetime. If the battery bank operates at a higher DOD the lifetime of a battery bank will be lesser. All reputed battery manufactures supply the DOD vs. Lifecycle graph on their manufacturing sheet. The battery lifecycle graph provided by Weida on VRLA batteries is utilized for this research [13].

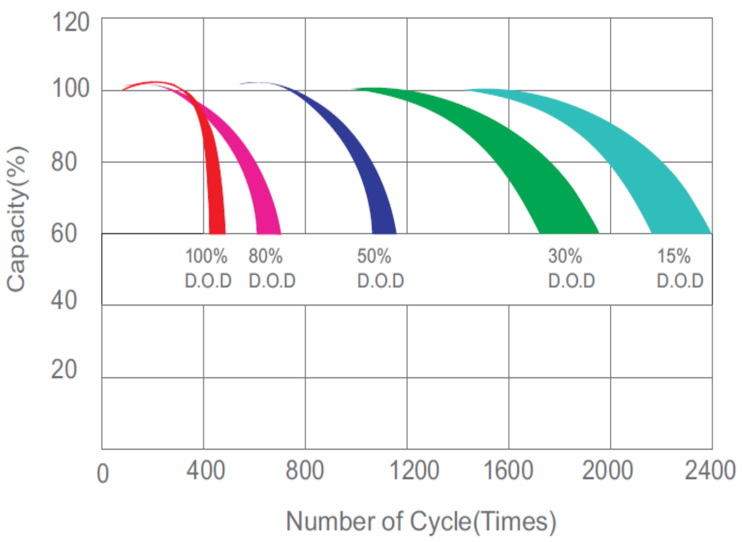


Figure 15 Life Cycle Characteristics of a Battery

The 100% DOD cycle has 420 life cycles which shall cause battery replacements once every year. The 80% DOD cycle has on average 420 life cycles which shall cause battery replacements once every two years. Similarly 50% DOD and 30 % DOD systems will have lifecycles of 1200 and 1800. Thus they would have to be replaced once every three and five years respectively. For example for a 30% DOD BESS, in order to store and discharge 3kWh per day having storage of 10kWh would be required. Although it may be apparent having the minimum DOD yields the maximum lifetime having excess reserve capacity may not be economical and could also be result in space restrictions.

3) ECONOMICS OF PVBESS

3.1 Levelized Cost of Energy

The Levelized cost of Electricity (LCOE) is a measurement of the net present value of the unit cost of electricity over the operating lifetime of the asset. The LCOE can be calculated through the following formula.

$$LCOE = \frac{Net\ Present\ Value\ of\ Total\ Cost\ incured\ during\ lifetime\ opertion}{Net\ Present\ Value\ of\ Total\ Energy\ Produced\ during\ operting\ lifetime}$$

Not only it aggregates the lifetime cost of the system it also incorporates the time value of money. In today’s point of view energy produced in the current year does not have the same economic value as energy produced in the next year. Hence not only cash flows have to discounted but also the energy units have to be discounted.

The lifetime operation and cost of a solar PV is simple as only the initial investment is high and no regular expenses are incurred on fuel or maintenance. Therefore in order for proper analysis the LCOE needs to be evaluated. The LCOE for solar power is high compared to other energy sources, but the price is gradually decreasing.

The following price configuration is utilized as per the availed data from Solar Panel suppliers of Jlanka Technologies (pvt) Ltd and Lanka Shakthi Technologies (Pvt) Ltd. Similar prices are also available with many other online panel suppliers.

PV Configuration kW	PV panel (Rs.)	Inverter (Rs.)	Charge Controller (Rs.)	Installation (Rs.)
1	112000	75000	16000	34000
1.5	165000	80000	16000	34000
2	221000	102000	24000	34000
3	330000	148000	34000	64000
4	435000	195000	40000	64000
5	535000	220000	77750	64000

Table 4 Price Catalogue of PV equipment

The Battery price rates can be variant based on technology and manufacturer. Since VRLA batteries were chosen based on their deep cycle operation and the corresponding prices provided by J Lanka was chosen for the analysis. The price of a 12V 200AH battery is classified as Rs.35000 each and battery capacities required for each configuration was calculated separately and presented as below.

PVBESS Configuration	Batter Energy Storage Cost (Rs.)
1	78750
1.5	110250
2	149625
3	220500
4	299250
5	370125

Table 5 Initial Price of Battery Storage

Operation and maintenance cost is taken as Rs.2000 per year based on for cleaning and inspection of PVBESS mechanism. The LCOE for different grid connected PV system capacities were evaluated for justification of the results. As per the available data from J Lanka Technologies and Lanka Shakthi Technologies, the LCOE for 1kW to 5 kW are summarized below. The discount rate which represents the opportunity cost of investment funds is taken as 10% which is the same value used in the LTGEP of CEB was used.

PV System Capacity	LCOE (Rs./kWh)
1 kW	16.42
1.5 kW	13.32
2 kW	12.63
3 kW	12.53
4 kW	12.00
5 kW	11.22

Table 6 LCOE of PV only grid connected system

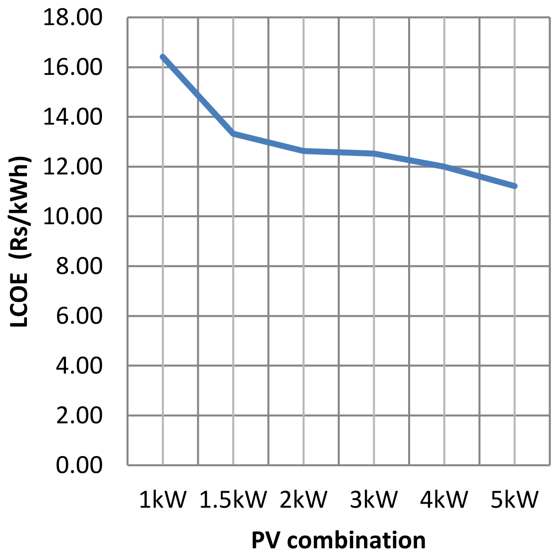


Figure 16 LCOE of PV only grid connected system

It is observed that as the system size grows the LCOE shall decrease. Thus optimum utilization of domestic user rooftop area is required to yield the maximum benefit. However in this study the main emphasis is on analyzing the economic viability of PVBESS on domestic consumers. Therefore in order to have consistency the same data is used while introducing battery energy system data to calculate the LCOE of PVBESS. Due to the effect of PV panel degradation, the number of units produced per day shall decrease annually. Thus the same BESS capacity which is installed at the beginning of the same PV configuration is not required when replacing the BESS system at the end of its lifetime. The reduction of required AH of battery rating is corrected to the closest available battery capacity which can fully store and supply the produced PV energy at the given DOD. The BESS additions with respective capacity were calculated for the PVBESS configurations from 1kW to 5kW for 12V battery bank.

Year	Degradation of PV	PV UNITS PER YEAR	Current Capacity required for 1kw solar PV with 12V BESS							
			30 % DOD		50% DOD		80% DOD		100% DOD	
			R (Ah)	C (Ah)	R (Ah)	C (Ah)	R (Ah)	C (Ah)	R (Ah)	C (Ah)
0	1.000	1825	1241.8	1250	745.8	750	466.1	500	372.9	400
1	0.972	1774	1207.0		724.9		453.0		362.4	400
2	0.964	1760	1197.3		719.1		449.4	450	359.5	
3	0.957	1746	1187.8		713.4	750	445.8		356.7	400
4	0.949	1732	1178.3		707.6		442.3	450	353.8	400
5	0.941	1718	1168.8	1200	702.0		438.7		351.0	
6	0.934	1704	1159.5		696.4	700	435.2	450	348.2	350
7	0.926	1690	1150.2		690.8		431.7		345.4	350
8	0.919	1677	1141.0		685.3		428.3	450	342.6	
9	0.912	1663	1131.9		679.8	700	424.8		339.9	350
10	0.904	1650	1122.8	1150	674.3		421.5	450	337.2	350
11	0.897	1637	1113.8		669.0		418.1		334.5	
12	0.890	1624	1104.9		663.6		414.7	450	331.8	350

13	0.883	1611	1096.1		658.3	700	411.4		329.1	350
14	0.876	1598	1087.3		653.0		408.1	450	326.5	
15	0.869	1585	1078.6	1100	647.8		404.9		323.9	350
16	0.862	1573	1070.0		642.6	650	401.6	450	321.3	350
17	0.855	1560	1061.4		637.5		398.4		318.7	
18	0.848	1547	1052.9		632.4		395.2	400	316.2	350
19	0.841	1535	1044.5		627.3	650	392.1		313.6	350
20	0.834	1523	1036.2	1050	622.3		388.9	400	311.1	
21	0.828	1511	1027.9		617.3		385.8		308.6	350
22	0.821	1499	1019.6		612.4	650	382.7	400	306.2	350
23	0.815	1487	1011.5		607.5		379.7		303.7	
24	0.808	1475	1003.4		602.6		376.6	400	301.3	350
25	0.802	1463	995.4		597.8		373.6		298.9	300

Table 7 Lifetime BESS replacements

In order to identify the best combination which results in the least cost for lifetime operation the LCOE under different DOD were calculated.

Solar PV + BESS	LCOE (Rs./kWh)			
	30% DOD	50% DOD	80% DOD	100% DOD
1kW	59.51	55.36	53.59	56.41
1.5kW	55.06	50.67	48.64	50.81
2kW	53.75	49.44	47.33	49.40
3kW	53.33	48.83	46.72	48.75
4kW	52.36	48.09	45.85	47.61
5kW	51.80	47.36	44.28	47.04

Table 8 LCOE of PVBESS Configuration –CI

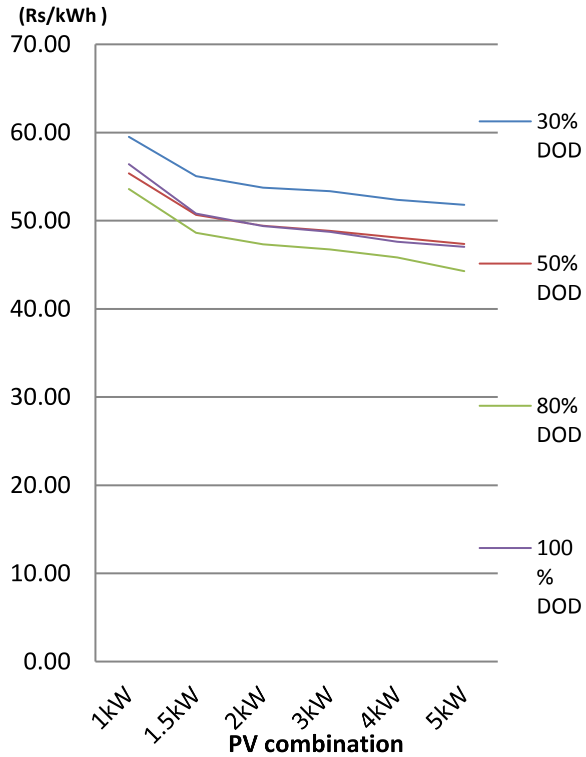


Figure 17 LCOE of PVBESS Configuration –CI

As in the previous case the discount factor of 10% was utilized and the associated lifetime was taken as 25 years of operation of the solar panel.

It can be seen that the PVBESS are much more expensive compared to the PV only grid connected systems. In most cases the LCOE is nearly four times higher than the typical PV only solution. This is mainly due to the replacement and reinstallation cost associated with batteries. The results indicate the LCOE reduces as the PVBESS configuration capacity increases under all DOD scenarios. Thus for any consumer who has abundant space available in their rooftops should utilize the maximum available space when installing a PVBESS system subjected to the capital investment constraints.

Furthermore the most interesting fact is the effect of DOD percentage to the LCOE. Under all PVBESS configurations the 30% DOD indicates a higher LCOE. This means investing in large capacity of battery banks to increase the lifecycles is not beneficial. The 50% & 100 % DOD percentages have resulted in a comparatively less LCOE while the most optimum least cost configuration has been seen when utilizing an 80% DOD. Even though investing on exact capacity shall limit its lifetime a balance in lifetime and initial cost is achieved by operating it at a 80% DOD. Therefore the most feasible configuration is a 5kW PVBESS configuration at 80% DOD.

3.2 Capital Investment Scenarios

3.2.1 Consumer capital investment Scenario

In this scenario the consumer will purchase the PV panel system, inverter and the battery storage system and will own the complete system. The consumer has the responsibility of maintaining and replacing the battery energy storage systems periodically at the end of the life cycles.

When evaluating the economical cost of the system it is vital to consider the time as well as value of money and analyze the net present value of incurred cost during its life time. The Discount Rate is the interest rate used to convert benefits and costs occurring at different times to equivalent values at a common time. The cumulative net present value of costs distribution depicts the lifetime investment costs of the PVBESS system.

Annual Cost = Investment cost on PV + Inverter + Battery + Charge Controller + O&M cost + Installation cost

Investment cost on PV panels	= C_{PV}
Inverter cost	= C_{INV}
Battery Energy storage system cost	= C_{BESS}
Charge Controller cost	= C_{CC}
Operation & Maintenance cost	= C_{OM}
Installation cost	= C_{OI}
Discount factor	= d
Cumulative Net Present value of costs	=CNPV

$$CNPV = \sum_{t=0}^{25} \frac{C_{pv}^{t} + C_{inv}^{t} + C_{cc}^{t} + C_{BESS}^{t} + C_{OM}^{t} + C_{OI}^{t}}{(1+d)^{t}}$$

The CNPV of PVBESS cost over the lifespan of 25 years of different system configurations operating on DOD level of 80% is calculated as per the formula. The distribution is as depicted in figure 18.

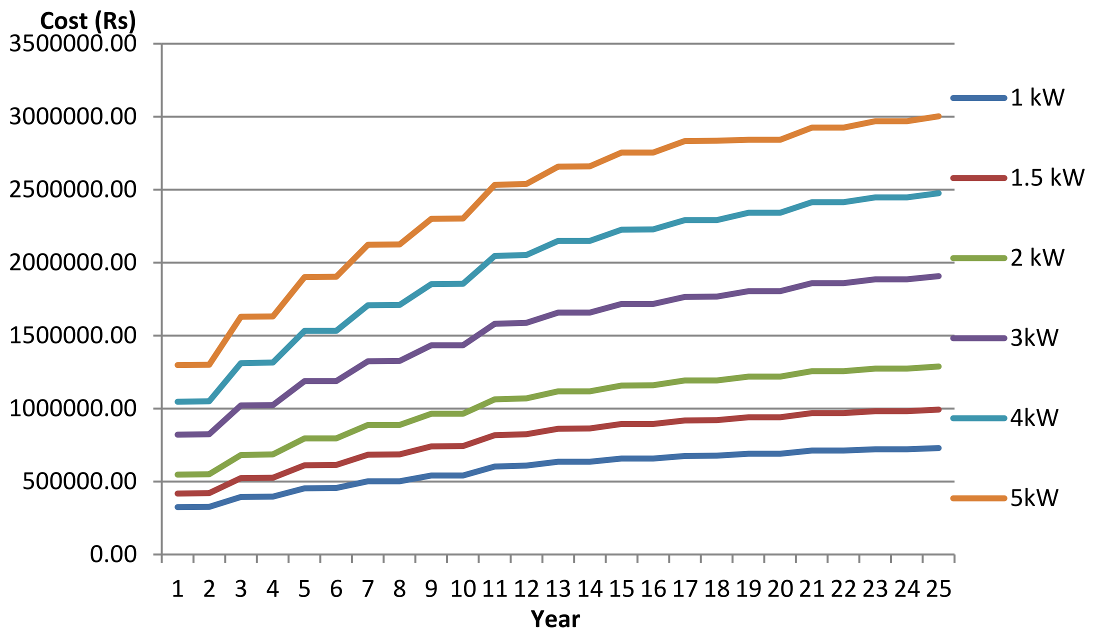


Figure 18 CNPV Distribution of System Cost of PVBESS Configurations

The CNPV distribution depicts the initial capital investment and periodic investments on battery storage throughout the lifespan of the system to be borne by the consumer. In order to justify the investment the consumer must be provided a tariff satisfactory to recover the costs and gain financial benefit.

The CNPV value of Avoided Cost Distribution under case 1 scenario for the utility of different PVBESS configurations is represented in figure 19.

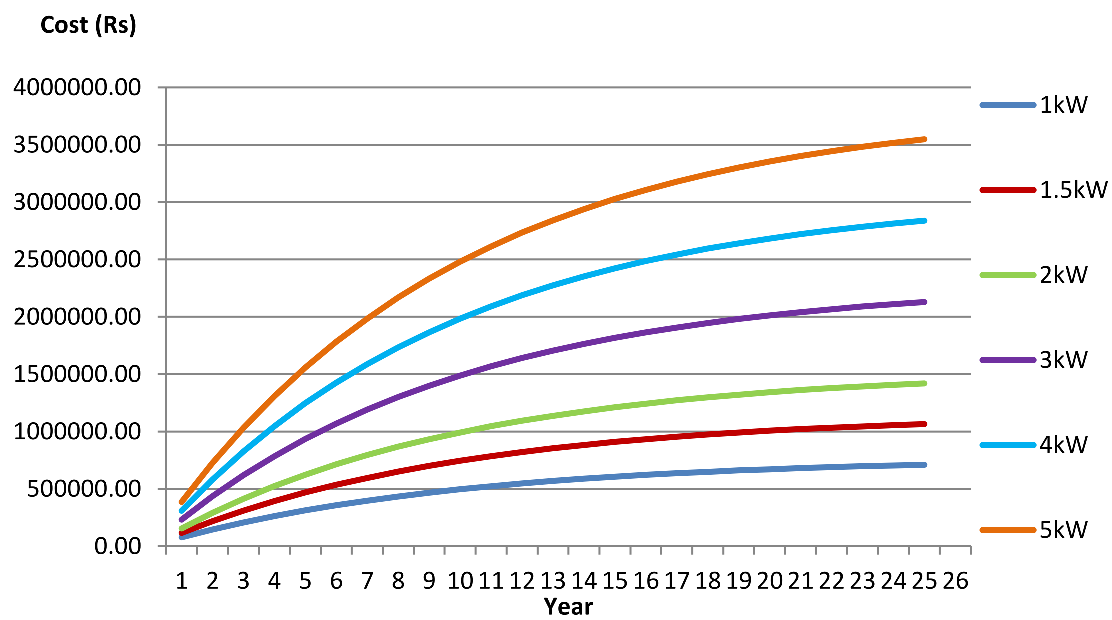


Figure 19 CNPV Distribution of Avoided cost of PVBESS Configurations

The tariff benefit to the consumer shall be a cost for the utility. Therefore in order to justify incorporating PVBESS to the national grid requires utility benefit in reduction of peak power cost. As such the Avoided cost for inclusion of single consumer PVBESS configuration needs to be compared. The methodology used here is to compare the CNPV of Avoided Cost Distribution for the utility with the CNPV of System cost distribution of the consumer.

In order to equalize the advantage of implementing the proposed system, it is suggested to split the savings 50:50 between the consumer and the utility. As such the 50:50 balance margin curve is drawn for the each PVBESS configuration. For illustration the 3kW PVBESS is represented with the CNPV values of system cost and the corresponding avoided cost plotted with the 50:50 balance margin.

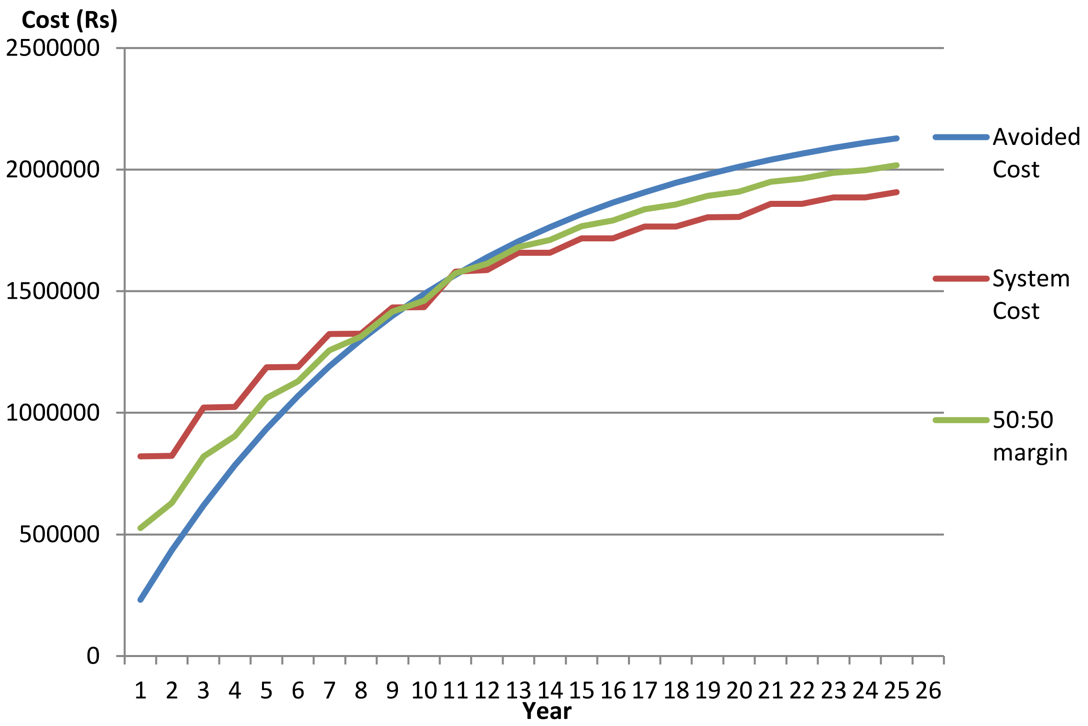


Figure 20 Cost Distribution of 3kW of PVBESS Configuration–CI

All the Cost distribution curves of all PVBESS configurations follow the same pattern and the point of intersection of the two curves is the breakeven point. As illustrated here for the 3kW PVBESS the minimum period of payback achievable is 11 years.

Once the cost distribution graphs are plotted on all PVBESS configurations the calculations are done for all possible tariff combinations and plotted. The plot which follows most compatibly with the 50:50 margin curve shall be derived as the candidate rates. The flat rate tariff scheme is initially utilized for identifying the viable margins.

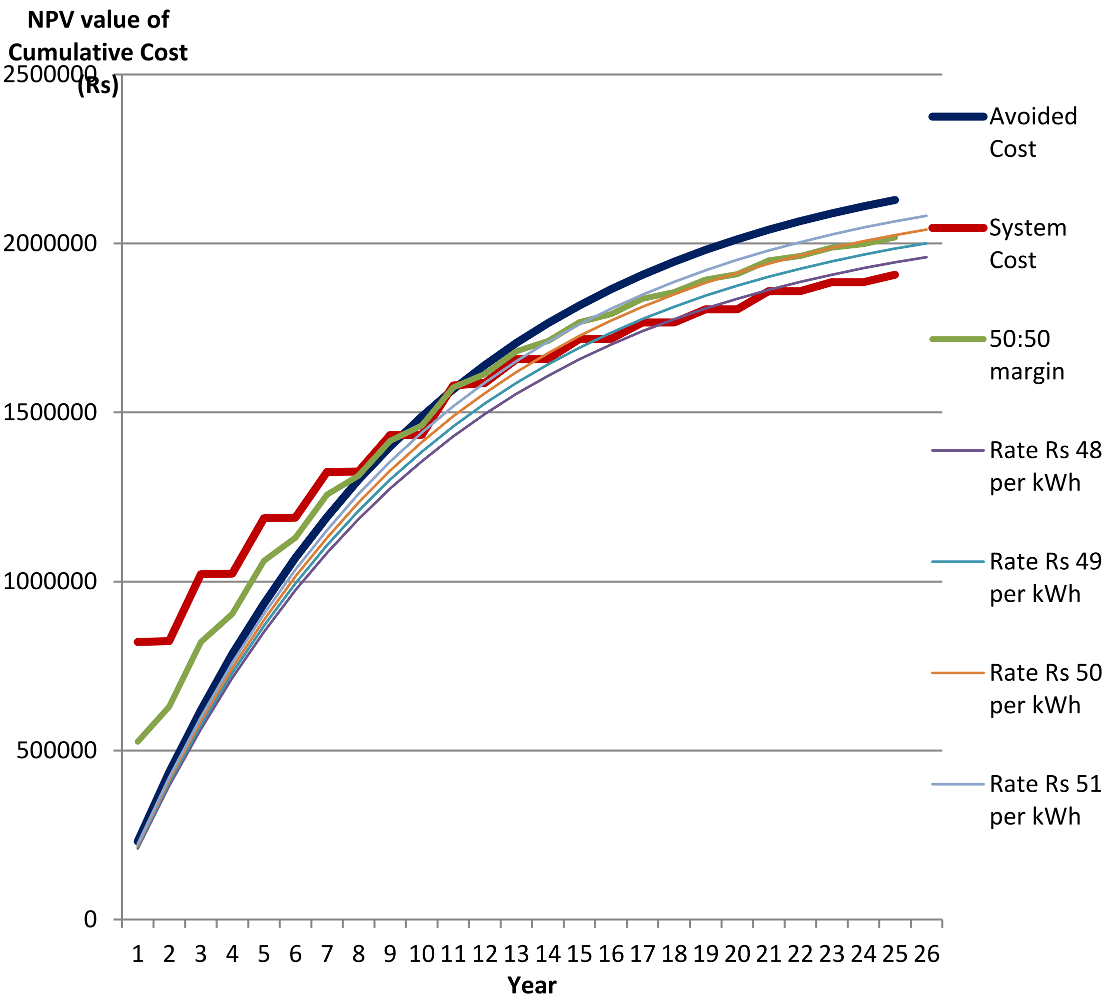


Figure 21 Screening curves for flat rate tariff on 3kW PVBESS–CI

Its identified that the only viable tariff rates which are capable of recovering the PVBESS lifetime cost were starting at a very high value of Rs.48/kWh. The degree of variation is also limited as such a higher rate above Rs.52/kWh shall incur a loss to the utility through the lifetime operation of the power plant. Thus the rates from 48 to 51 were checked with the economic parameters of internal rate of return (IRR), payback period, consumer's Net present value of profit and Utility Net present Value of profit at end of the lifespan of 25 years. The Project IRR is used for comparison since all investments are assumed to be financed by equity. None of the investments are expected to be debt financed. Therefore the equity IRR shall be as same as the Project IRR of implementing a PVBESS system. In order for a system to be viable the IRR must be higher than the discount factor. The results are as tabulated below.

Rate	1 kW solar PV + BESS				1.5 kW solar PV + BESS				2 kW solar PV + BESS			
	IRR (%)	Payback (Years)	C. NPV Rs. ,000	U. NPV Rs. ,000	IRR (%)	Payback (Years)	C. NPV Rs. ,000	U. NPV Rs. ,000	IRR (%)	Payback (Years)	C. NPV Rs. ,000	U. NPV Rs. ,000
48	4	-	-81	61	9	-	-20	92	10	25	7.8	123
49	5	-	-67	48	10	-	-0.5	72	11	17	-4	96
50	6	-	-54	34	11	17	20	52	13	15	61	69
51	7	-	-40	21	12	15	39	32	14	13	88	42

Rate	3 kW solar PV + BESS				4 kW solar PV + BESS				5 kW solar PV + BESS			
	IRR (%)	Payback (Years)	C. NPV Rs. ,000	U.NPV Rs. ,000	IRR (%)	Payback (Years)	C. NPV Rs. ,000	U.NPV Rs. ,000	IRR (%)	Payback (Years)	C. NPV Rs. ,000	U.NPV Rs. ,000
48	11	17	36	184	13	15	116	246	14	15	237	308
49	12	15	77	145	14	13	170	192	15	13	304	241
50	13	15	118	103	15	11	224	138	16	11	372	173
51	14	13	158	63	16	11	278	84	17	11	440	105

Table 9 Economic Parameters of PVBESS Configurations flat rate -CI

The 1kW PVBESSS configuration does not become viable at any tariff rate thus proving ineffective and unviable. The 1.5kW & 2kW PVBESS configuration only receives payback at a rate higher than Rs.50/kWh but that also is after more than 15 years. For PVBESS above 3kW all the validated rates give marginal benefit with minimum payback in 11 years. The most compatible with the plotted 50:50 Balance margin curve is PVBESS systems above 3kw at a rate of Rs.50/kwh.

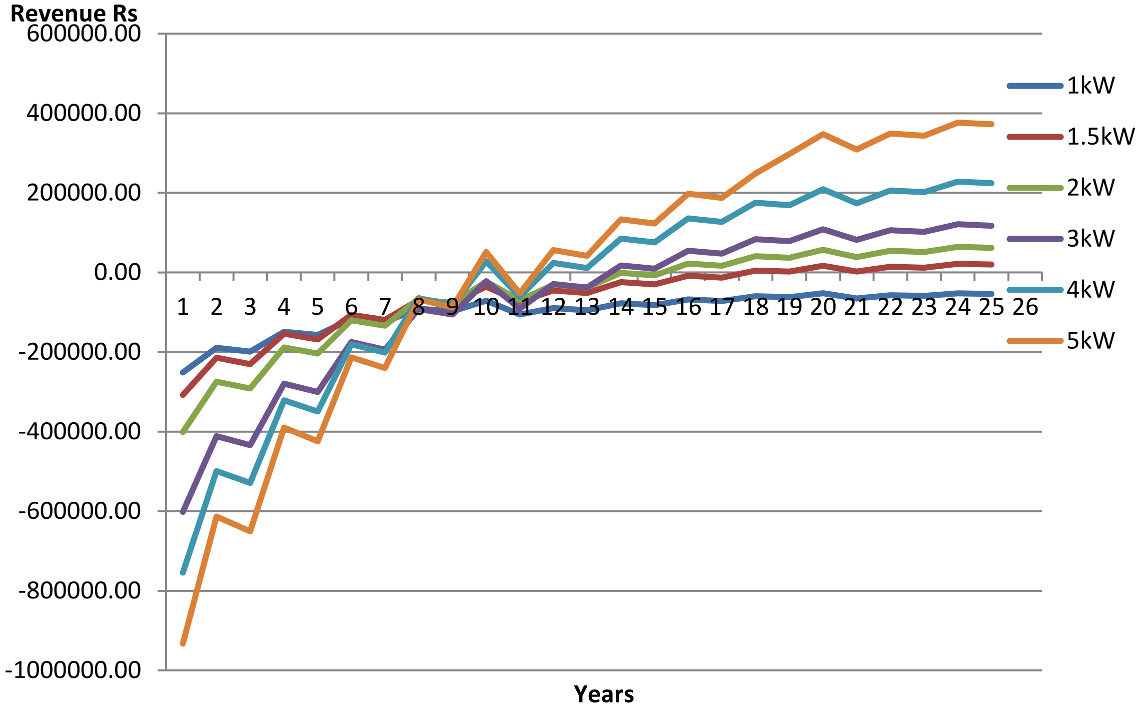


Figure 22 Lifetime Consumer Profit of PVBESS at rate of Rs.50.kWh

The effective lifetime of the system is expected to be 25 years. Therefore the tariff must be developed such that the consumer is capable of recovering his investment fast as possible while earning enough profit for the rest of the lifespan. For the utility prospective it must keep on benefitting consciously from the grid connected system throughout the full lifetime.

Under all flat rate tariff schemes the payback period is too high to consider the investment. Thus in order to encourage the consumer for a PVBESS scheme a two tier should be proposed. Initial higher rate is given as an incentive to recover the capital cost incurred for the project. However next few blocks are comparatively less and is more beneficial for the utility.

Following methodology is adopted when selecting a suitable two tier tariff for the proposed PVBESS configurations.

1. The fastest point of breakeven without incurring a loss to the utility could only occur at the point where the CNPV of avoided cost distribution shall equal to the CNPV of the system cost.

2. After fastest possible breakeven is incurred the rest of the operating lifetime should ideally follow the 50:50 balance margin curve.

Thus such the tariff rate for block 1 should be at the rate of the avoided cost for the utility which is Rs.52 as per the case 1 avoided cost scenario. The time period shall vary depending on the system size and configuration. For standardization the 3kW PVBESS is taken as the cutoff point which became marginally beneficial for the flat rate tariff schemes and analyze the variation on other configurations based on derived rates.

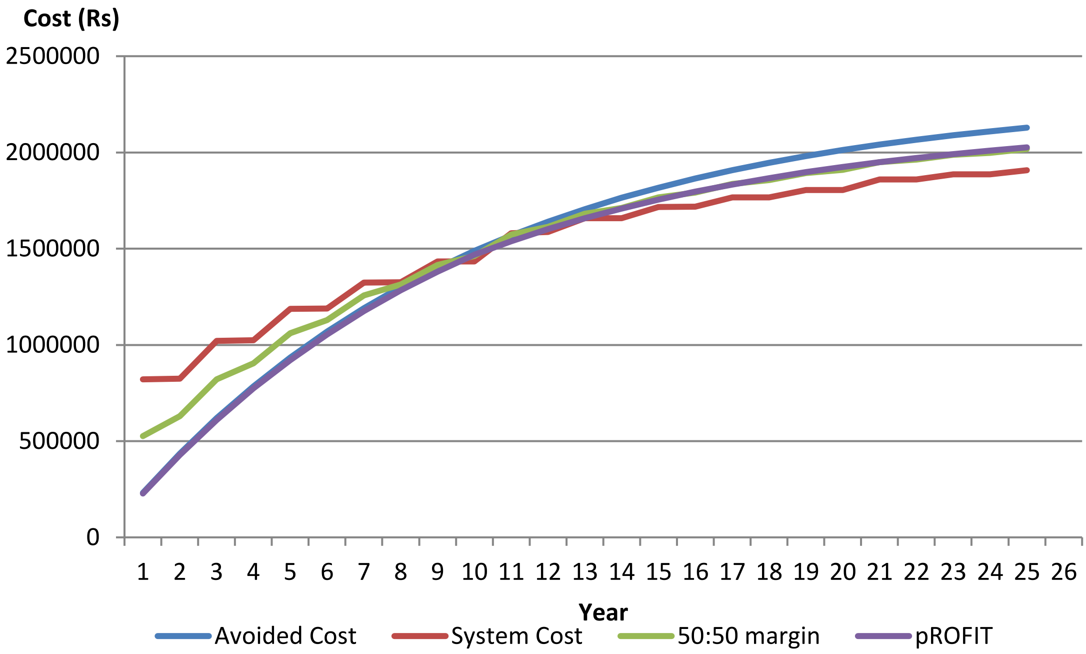


Figure 23 Cost Distribution of 3kW of PVBESS Configuration Two tier logic–CI

By plotting different rates for second tier after the point of breakeven it's seen that the rate at Rs.45/kWh best correlates with the 50:50 balance margin curve. Therefore based on the 3kW PVBESS configuration the Two tiers are defined at 52 Rs./kWh for 10 years as block 1 and Rs.45.5 for next 15 years as block 2.

The corresponding PVBESS configurations are analyzed for the proposed tariff rate and the variation is plotted as below.

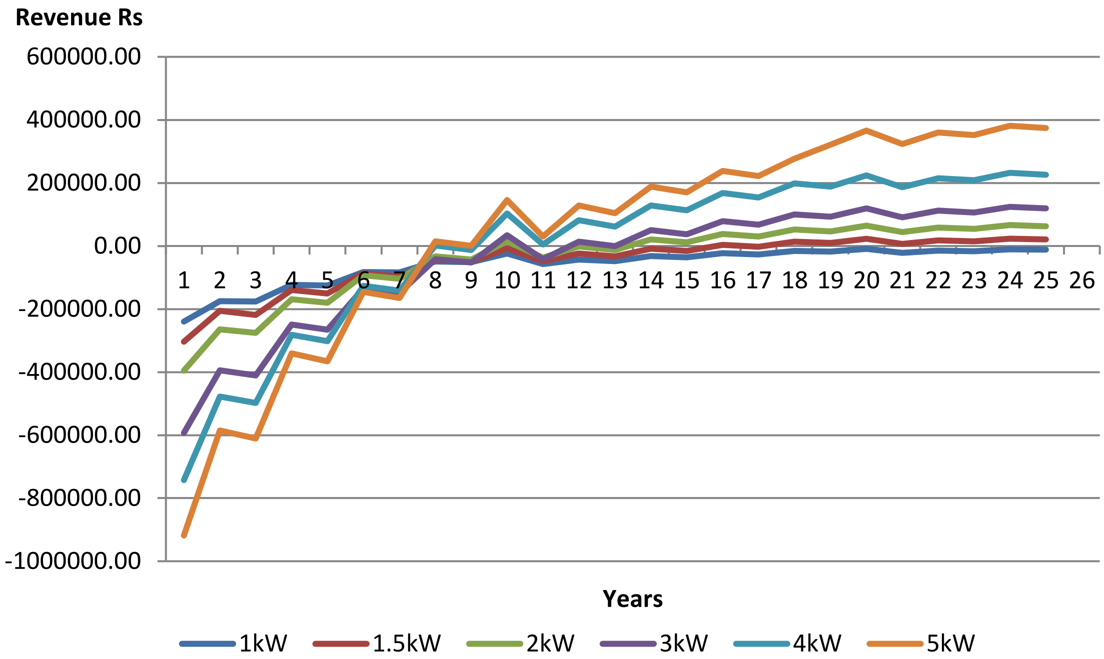


Figure 24 Lifetime Consumer Profit of PVBESS at Two tier tariff–CI

The economic parameters of internal rate of return (IRR), payback period, consumer's Net present value of profit and Utility Net present Value of profit at end of the lifespan of 25 years are as tabulated below.

PVBESS configuration	IRR (%)	Payback (Years)	C. NPV Rs. ,000	U.NPV Rs. ,000
1kW	9	-	-11	34
1.5kW	11	17	20	51
2kW	13	13	62	68
3kW	14	9	118	102
4kW	16	8.5	226	136
5kW	17	7.5	374	170

Table 10 Economic Parameters of PVBESS Configurations Two tier -CI

3.2.2 Consumer + Utility capital investment scenario

In this scenario the consumer will invest in PV panel system and inverter systems. However the Utility will invest for the battery storage systems. This means the under 80% DOD of BESS the utility will have to invest on replacement of batteries every 2 years.

The burden of battery replacement is herewith released from the consumer and falls under the responsibility of the utility. This requires proper monitoring and maintenance from the utility. The extra advantage of this scheme is the bulk order quantity discount. Since the utility directly orders and installs batteries, they are required to have a large stock of battery systems to cater the consumer installations. The bulk order discount can vary depending on quantity size, supplier and the market availability but for analysis it can be safe to use a minimum of 10% discount on each product.

The utility also possess the capability of benefitting from tax exemptions from the government. If proper policies are adopted, the cost of battery prices could further decrease. Based on Bulk order quantity discount of 10%, the LCOE of all PVBESS configurations were reanalyzed.

PVBESS Configuration	CI LCOE (Rs/kWh)	CUI LCOE (Rs/kWh)
1kW	53.59	50.50
1.5kW	48.64	45.59
2kW	47.33	44.32
3kW	46.72	43.74
4kW	45.85	42.86
5kW	44.28	42.14

Table 11 LCOE of PVBESS Configuration – CUI

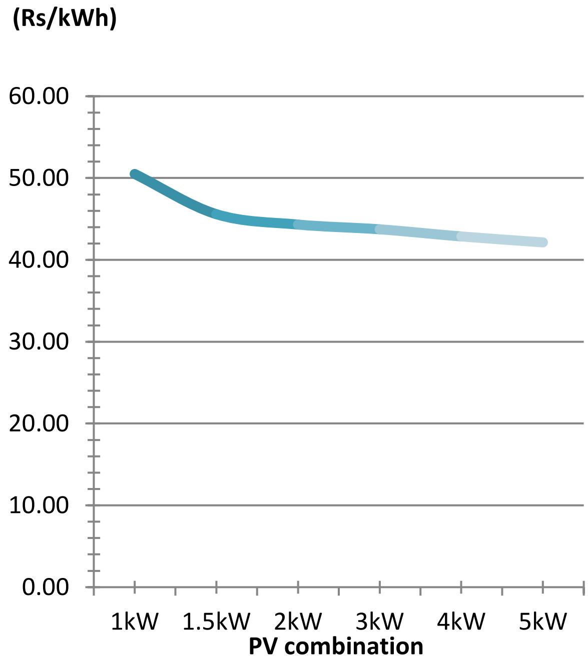


Figure 25 LCOE of PVBESS Configuration – CUI

The LCOE is nearly 6% less for the Consumer and utility investment compared to the Consumer only investment. The corresponding CNPV for the consumer cost and the CNPV value for the Utility avoided cost were also plotted. The actual avoided cost for the utility shall be the difference of investment cost for the BESS and the Annualized Equivalent Total Avoided Cost. The cost function distribution for the consumer and utility follows the pattern as presented in figure 26a and figure 26b respectively for the 3kW PVBESS configuration.

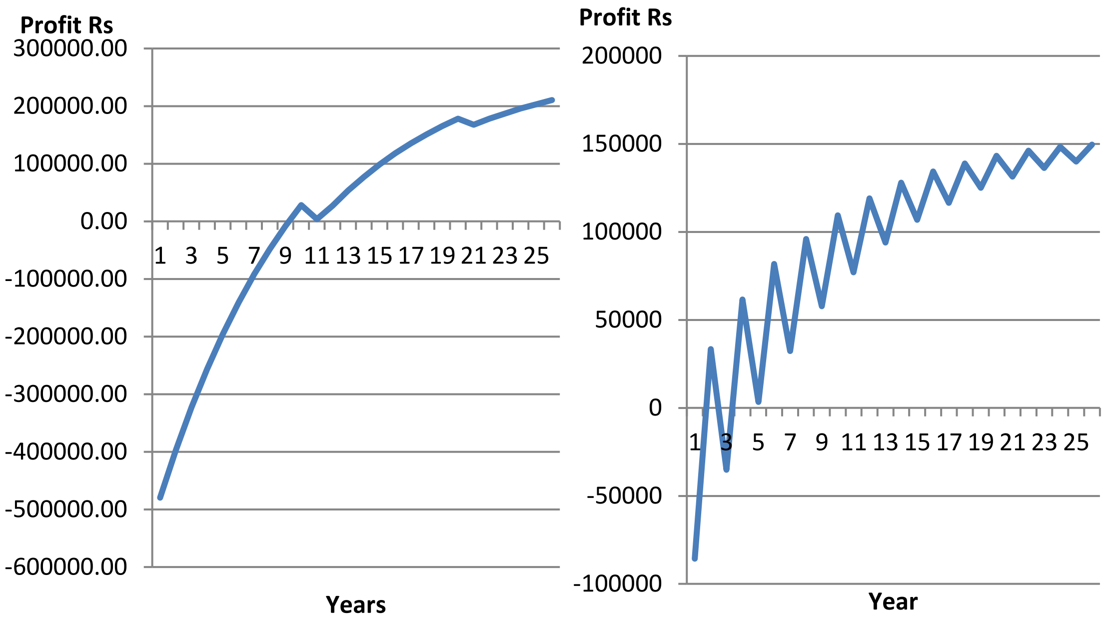
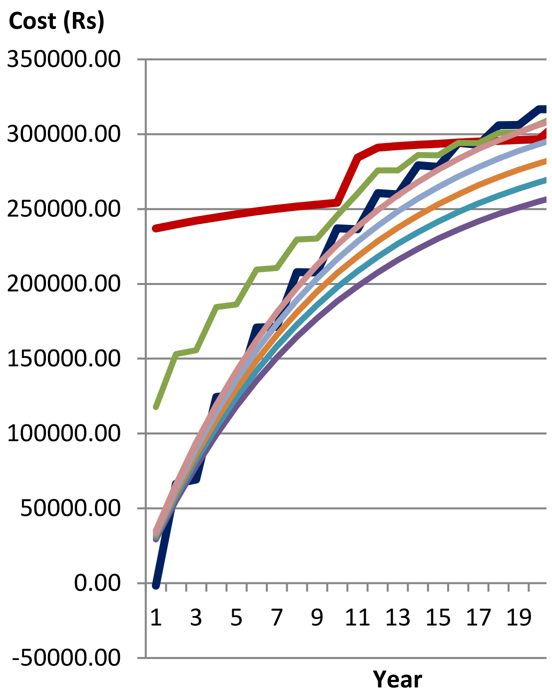
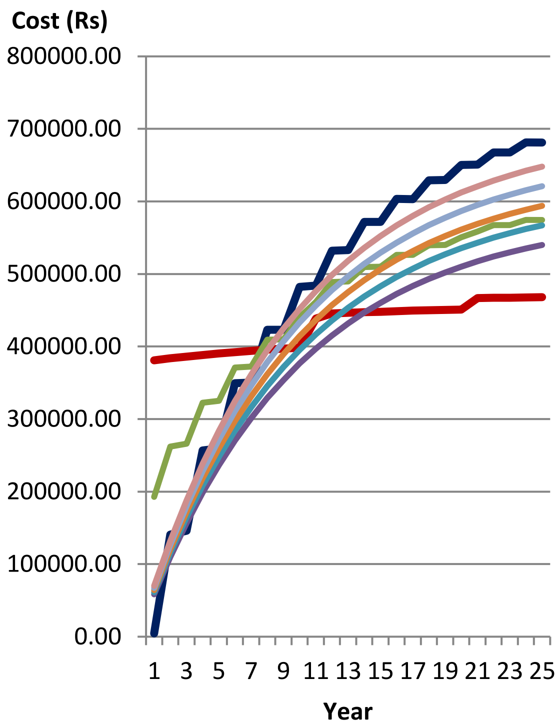


Figure 26 a) Consumer Profit distribution b) Utility Profit distribution for 3kW PVBESS- CUI

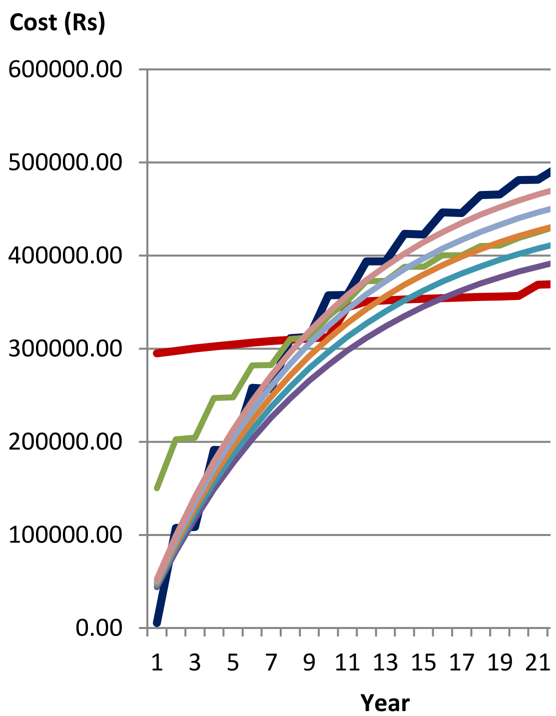
The same methodology is adopted here where all PVBESS configurations CNPV of system cost and CNPV of utility avoided cost are plotted with the corresponding 50:50 balance margin curve. Then suitable tariff rates at flat rate are plotted to check which rates coincide better with the 50:50 balance margin curve. The results for the all PVBESS configurations are illustrated in separate plots in figures 27.



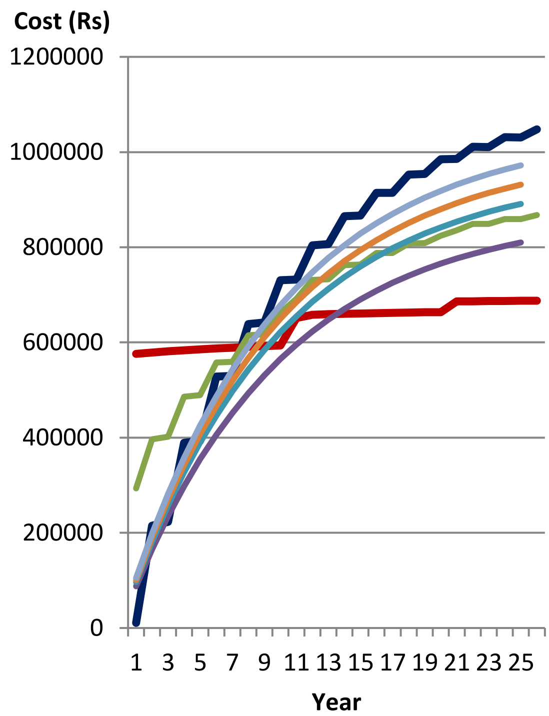
a) Screening curves of 1kW PVBESS



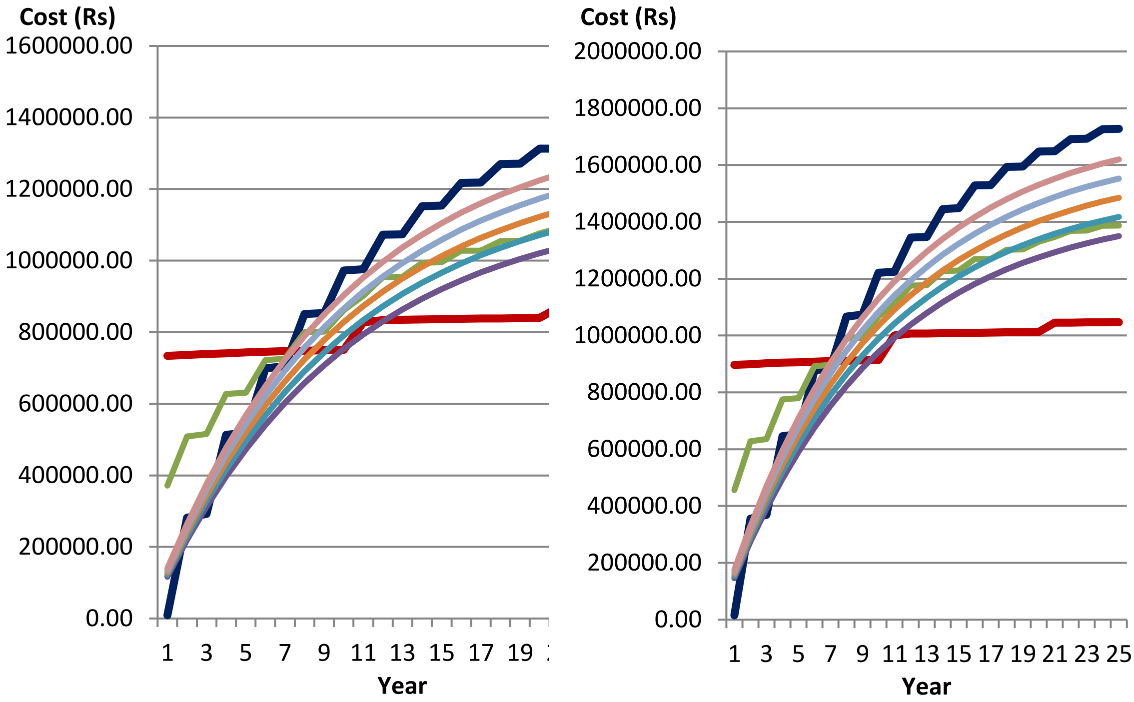
c) Screening curves of 2kW PVBESS



b) Screening curves of 1.5 kW PVBESS



d) Screening curves of 3kW PVBESS



e) Screening curves Cost of 4kW PVBESS

f) Screening curves of 5kW PVBESS

Figure 27 Screening curves for PVBESS Configurations on CUI

The flat rate tariff margins which fit in the profitable margin for both the utility and the consumer are from Rs20-24/kWh. The figure shows that the rates at Rs.22/kWh or Rs.23/kWh correlate more with the 50:50 balance margin

As earlier in the consumer investment only scenario the 1kW PVBESS configuration does not payback during its lifetime. The 1.5kW PVBESS configuration only gives a marginal benefit.

The economic parameters for all the configurations are checked for all the possible tariff rates in the profitable area for both the utility and the consumer. The results are tabulated in sections of Table 12

Rate Rs. /kwh	1 kW solar PV + BESS					
	Consumer			Utility		
	IRR (%)	Payback (Years)	C. NPV Rs. ,000	IRR (%)	Payback (Years)	C. NPV Rs. ,000
20	7	-	-37	60	3	65
21	8	-	-23	49	3	51
22	9	-	-10	38	5	38
23	10	25	3	23	7	24
24	11	20	16	18	11	12

Flat rate for 1kW PVBESS - CUI

Rate Rs. /kwh	3 kW solar PV + BESS					
	Consumer			Utility		
	IRR (%)	Payback (Years)	C. NPV Rs. ,000	IRR (%)	Payback (Years)	C. NPV Rs. ,000
20	14	13	128	65	3	231
21	15	12	169	51	3	190
22	16	9	210	38	3	149
23	17	8	251	27	5	108
24	19	8	292	16	7	68

Flat rate for 3kW PVBESS - CUI

Rate Rs. /kwh	1.5 kW solar PV + BESS					
	Consumer			Utility		
	IRR (%)	Payback (Years)	C. NPV Rs. ,000	IRR (%)	Payback (Years)	C. NPV Rs. ,000
20	12	16	38	59	3	104
21	13	13	58	45	3	83
22	15	12	78	33	5	63
23	16	11	99	21	7	43
24	17	8	120	11	11	23

Flat rate for 1.5kW PVBESS – CUI

Rate Rs. /kwh	4 kW solar PV + BESS					
	Consumer			Utility		
	IRR (%)	Payback (Years)	C. NPV Rs. ,000	IRR (%)	Payback (Years)	C. NPV Rs. ,000
20	15	12	218	75	3	310
21	16	11	272	61	3	255
22	18	8	326	49	3	200
23	19	7	381	37	5	146
24	20	7	435	27	7	91

Flat rate for 4kW PVBESS – CUI

Rate Rs. /kwh	2 kW solar PV + BESS					
	Consumer			Utility		
	IRR (%)	Payback (Years)	C. NPV Rs. ,000	IRR (%)	Payback (Years)	C. NPV Rs. ,000
20	13	14	76	59	3	148
21	15	12	103	46	3	120
22	16	11	130	35	5	93
23	17	8	158	24	5	66
24	18	8	185	14	9	39

Flat rate for 2kW PVBESS - CUI

Rate Rs. /kwh	5 kW solar PV + BESS					
	Consumer			Utility		
	IRR (%)	Payback (Years)	C. NPV Rs. ,000	IRR (%)	Payback (Years)	C. NPV Rs. ,000
20	16	11	314	63	3	395
21	17	8	381	49	3	326
22	18	8	450	37	3	258
23	20	7	518	26	5	190
24	21	6.5	586	17	7	173

Flat rate for 5kW PVBESS - CUI

Table 12 Econometric Parameters on flat rate for all PVBESS - CUI

The lifetime CNPV of cost and revenue for the consumer is plotted for all PVBESS configurations for the most correlated tariff rate of Rs21/kwh.

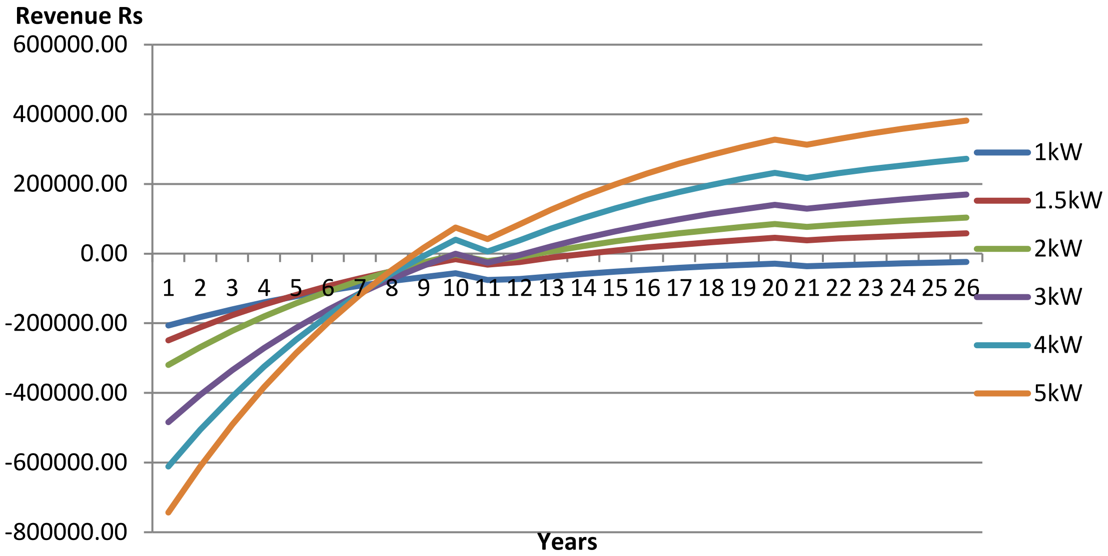


Figure 28 Lifetime Cost & Revenue for the Consumer at Rs21/kWh

The Utility also needs to keep track of their CNPV of avoided cost, since unlike the consumer only investment scenario, the utility initiates with a negative cash flow at certain years.

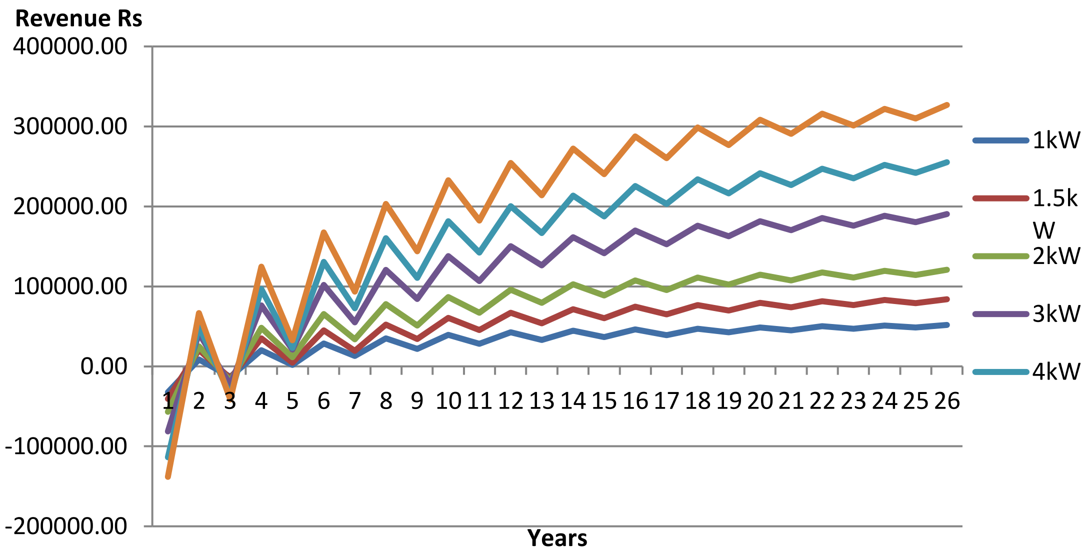


Figure 29 Lifetime Cost & Revenue for the Utility at Rs 21/kWh

It is observed a minimum of 8 years payback period is incurred for the consumer in all configurations. On the other hand even with utility investments on battery storage the return on investment for the utility is acceptable. It is observed that under all PVBESS configurations, investment is recovered within 3 years.

Since the period of payback is far better for the utility than the consumer, a requirement may arise to equalize the benefit during the same period of paybacks for both parties. As such the only possible method to do so would be to break up the tariff rates to different blocks.

1. The intersection of CNPV system cost and CNPV avoided cost distribution occurs within the region of 7 years for all PVBESS configurations. Therefore the earliest possible tariff rates to recover costs in 7 years are plotted.

2. After the point of breakeven the rates which follow the 50:50 balance margin curves most are considered and evaluated for second block tariff rate.

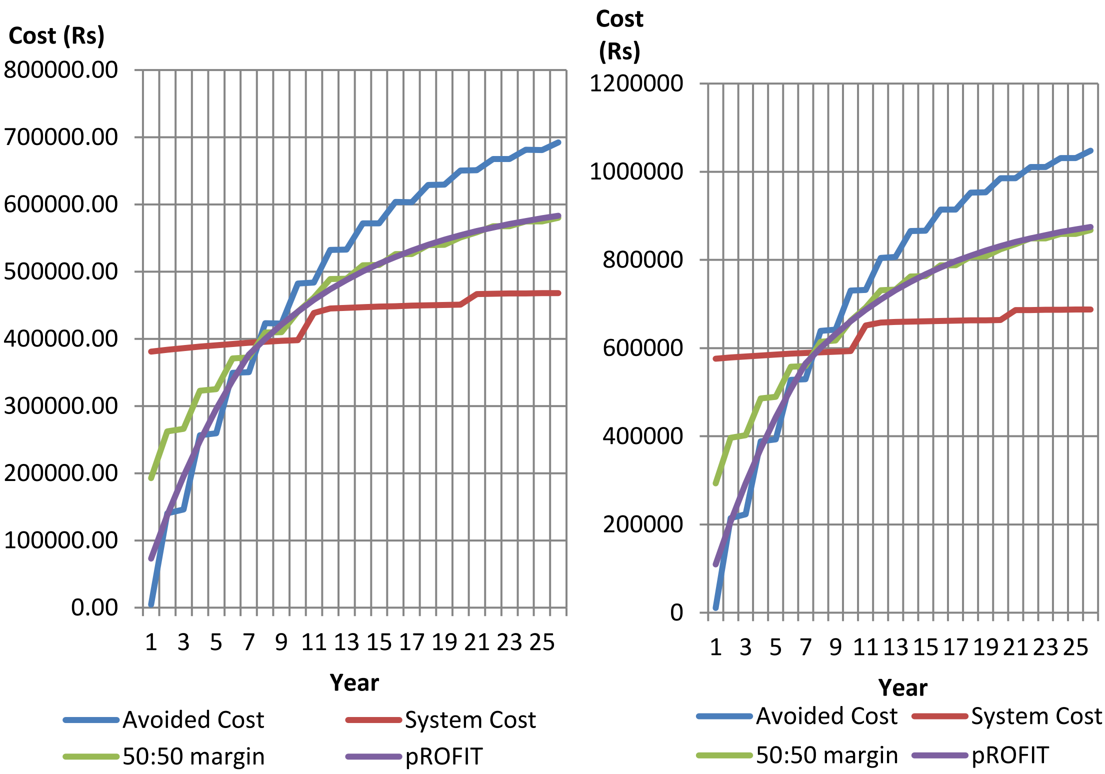


Figure 30 a) 2kW b) 3kW PVBESS Cost Distribution

rates of Rs.25/ kWh for the first 7 years as block 1 and Rs.17/ kWh for the period of 18 years as block 2 is suggested as it correlates more with the above requirements.

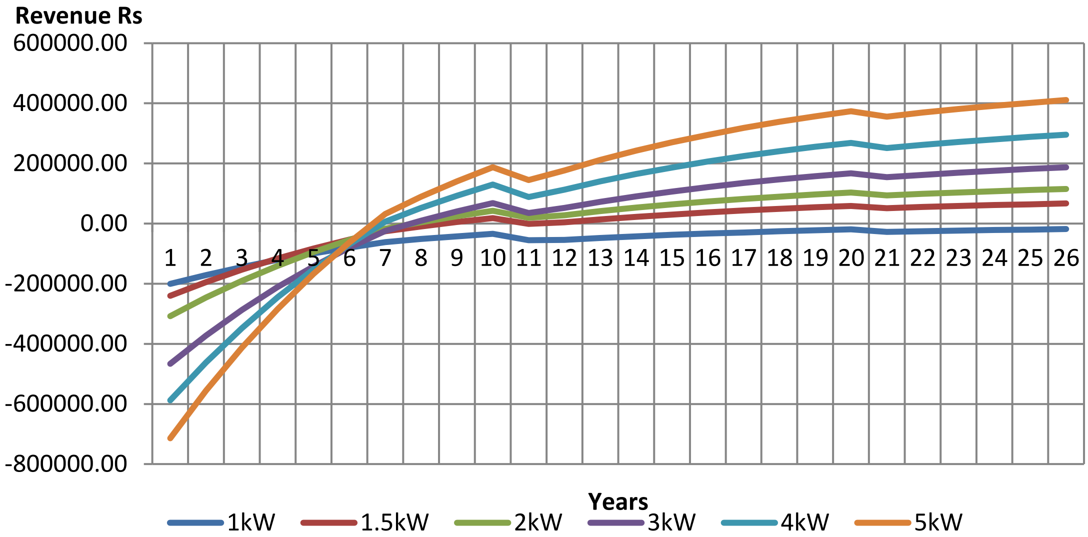


Figure 31 Lifetime cost & revenue to consumer at Two Tier rate - CUI

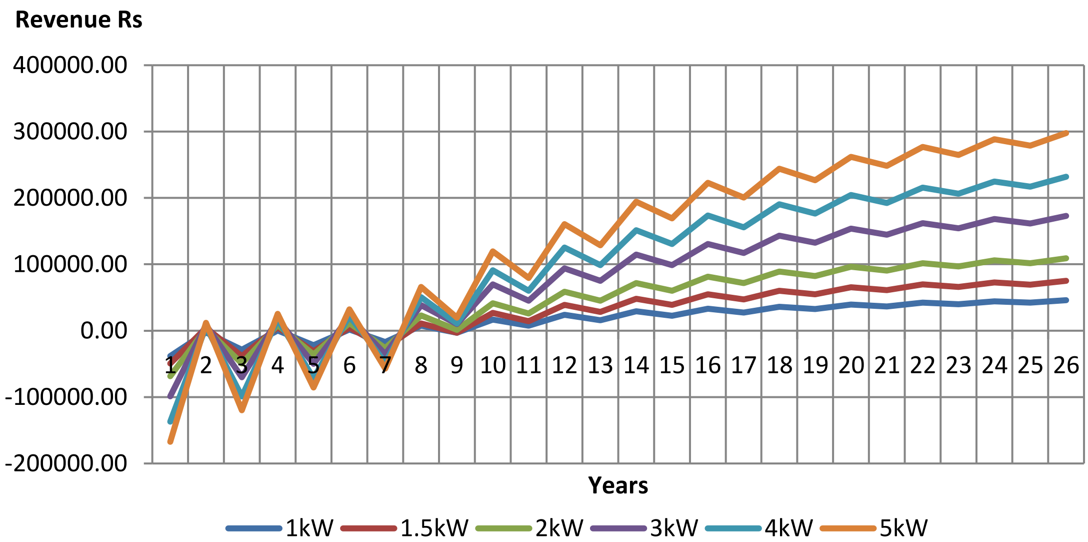


Figure 32 Lifetime cost & revenue to utility at Two Tier rate – CUI

PVBESS configuration	Consumer			Utility		
	IRR (%)	Payback (Years)	C. NPV Rs. ,000	IRR (%)	Payback (Years)	C. NPV Rs. ,000
1kW	8	-	-18	24	9	46
1.5kW	15	11	67	15	9	75
2kW	16	7	115	17	7	109
3kW	17	7	187	18	7	172
4kW	18	7	295	29	7	231
5kW	20	6	411	18	7	297

Table 13 Economic Parameters of PVBESS Configurations Two tier -CUI

When considering the two tier tariff the limit capacity also restricted to 1.5kW PVBESS configuration and similar pattern of lifetime payback can be seen compared to the flat rate tariff. Either of the Flat rate tariff or the two tier tariff rates can be adopted by the regulatory commission depending on the requirement.

4) SENSITIVITY ANALYSIS

For the analysis we will take the 3kw Solar panel and Battery Energy storage system for comparison with the base case scenario.

The Parameters to consider are evaluated in 6 separate cases. Results are compared to the two tier tariff for the 2kW PVBESS configuration which is the cut off margin for a profitable operation for both consumer & Utility.

4.1 Case 1: Battery Prices Decrease By 10 %

Higher Market penetration can cause Economies of scale in manufacturing. Thus it can be assumed the cost shall fall by 10% due to increase in demand. The forecast for Lead acid battery price reduction has not been properly presented in any literature.

	Base Case Value	Case 1 Value	Change (%)
Levelized Cost of Energy (Rs./kWh)	44.32	41.04	7.4 % ↓
Consumer IRR (%)	16	16	-
Consumer Payback Period (years)	7	7	-
Consumer NPV value of lifetime profit (Rs.’000)	115	115	-
Utility IRR (%)	17	40	129 % ↑
Utility Payback Period (years)	7	5	28 % ↓
Utility NPV value of lifetime profit (Rs.’000)	109	182	67 % ↑

Table 14 Economic Parameters of Sensitivity Case 1 for CUI

Battery price has a strong correlation to the overall parameters of the PVBESS system while price reduction benefit is passed to the utility under the consumer & utility investment scenario.

4.2 Case 2: Life Cycle of Batteries are Improved By 10% at Same Price

One of the main constraints in battery storage systems is the periodic replacements. However in this hypothetical case the battery technology shall improve such that a larger amount of life cycles are possible at the same DOD than as current availability. The emergency of technology is assumed to have no effect on the base price. As such on a hypothetical case of 10% increase in lifecycle shall endeavor a lifetime equal to 2.1 years at 80% DOD.

	Base Case Value	Case 1 Value	Change (%)
Levelized Cost of Energy (Rs./kWh)	44.32	43.13	2.68 % ↓
Consumer IRR (%)	16	16	-
Consumer Payback Period (years)	7	7	-
Consumer NPV value of lifetime profit (Rs.'000)	115	115	-
Utility IRR (%)	17	18	5 % ↑
Utility Payback Period (years)	7	7	-
Utility NPV value of lifetime profit (Rs.'000)	109	162	48% ↑

Table 15 Economic Parameters of Sensitivity Case 2 for CUI

The effect is only marginal increase from the utility benefit based on a 10% lifecycle increase. A substantial increase in lifetime is required for it to have a considerable impact on the existing viability of battery energy storage.

4.3 Case 3: Prices of Gas Turbine Energy increase or decrease by 10 %

The base case considers the operation of gas turbines during peak hours. However the Oil price can change with time and such price variations can cause the peak energy price also to vary. Two subcases are considered in this sensitivity case in such which the peak price increase by 10% and the peak price is decreased by 10 %.

	Base Case Value	Case 3a Value	Change (%)	Case 3b Value	Change (%)
Levelized Cost of Energy (Rs./kWh)	44.32	44.32	-	44.32	-
Consumer IRR (%)	16	16	-	16	-
Consumer Payback Period (years)	7	7	-	7	-
Consumer NPV value of lifetime profit (Rs.'000)	115	115	-	115	-
Utility IRR (%)	17	64	276 % ↑	-	∞
Utility Payback Period (years)	7	3	57	-	∞
Utility NPV value of lifetime profit (Rs.'000)	109	252	119 % ↑	- 33	130 % ↓

Table 16 Economic Parameters of Sensitivity Case 3 for CUI

The variation in peak price in either way has a large impact on the operational profitability to the utility. The PVBESS introduction to the grid can be a massive boon at a time where the peak price increases. Similarly it will also be an unprofitable investment in the case where future peak prices are reduced to a level of 10 %.

4.4 Case 4: Solar Panel Prices Decrease By 10 %

The Solar PV price has decreased immensely during the past decade and will continue to do so in future as well. A reference case is investigated when panel prices decrease by 10% of the current prices.

	Base Case Value	Case 4 Value	Change (%)
Levelized Cost of Energy (Rs./kWh)	44.32	43.50	1.85 ↓
Consumer IRR (%)	16	18	12.5 % ↑
Consumer Payback Period (years)	7	6.5	7 % ↓
Consumer NPV value of lifetime profit (Rs.'000)	115	137	19 % ↑
Utility IRR (%)	17	17	-
Utility Payback Period (years)	7	7	-
Utility NPV value of lifetime profit (Rs.'000)	109	109	-

Table 17 Economic Parameters of Sensitivity Case 4 for CUI

Solar Panel Price reduction also has a very minimal effect on changing the viability of PVBESS as only a marginal benefit change is incurred for the consumer. Since the PV panels is only a one time investment at the beginning and only a fraction of the total cost of PVBESS huge variations are not expected on the viability of PVBESS introduction.

4.5 Case 5: Carbon Credit Mechanism is Functional at 13.61$/ CO_2 tonne

Gas turbine emits 464 Tons of carbon dioxide equivalent for every GWh of electricity produced [14]. Even though the Carbon trading values in the global market is going in the decreasing trend there still exists the possibility for integrating carbon funding mechanisms for such projects. The average value of the past five years of carbon based on the California Carbon Dashboard is 13.61$/ CO_2 Ton. This figure is in line with the values utilized in the LTGEP of CEB.

	Base Case Value	Case 5 Value	Change (%)
Levelized Cost of Energy (Rs./kWh)	44.32	44.32	-
Consumer IRR (%)	16	16	-
Consumer Payback Period (years)	7	7	-
Consumer NPV value of lifetime profit (Rs.'000)	115	115	-
Utility IRR (%)	17	22	29 % ↑
Utility Payback Period (years)	7	7	-
Utility NPV value of lifetime profit (Rs.'000)	109	131	13 % ↑

Table 18 Economic Parameters of Sensitivity Case 5 for CUI

It was assumed that the Carbon credit benefit shall be fully passed on to the utility as it has invested on absorption of inherently intermittent energy sources .Even so as seen in the analysis a inception of carbon credit mechanism does not create a huge variation on the benefits for the Utility.

4.6 Case 6: Transmission & Distribution Losses Decrease by 1 %

The Transmission & distribution losses were calculated based on the LTGEP 2015-2034 for the base case analysis. However through accelerated development scenario the T&D losses can be further reduced as seen in previous years. As such a sensitivity case on the effect to the consumer and the utility for integrating a PVBESS at further T&D loss decrease of 1 % is evaluated.

	Base Case Value	Case 6 Value	Change (%)
Levelized Cost of Energy (Rs./kWh)	44.32	44.32	-
Consumer IRR (%)	16	16	-
Consumer Payback Period (years)	7	7	-
Consumer NPV value of lifetime profit (Rs.'000)	115	115	-
Utility IRR (%)	17	14	17 % ↓
Utility Payback Period (years)	7	7	-
Utility NPV value of lifetime profit (Rs.'000)	109	93	23 % ↓

Table 19 Economic Parameters of Sensitivity Case 6 for CUI

The development of T&D infrastructure is a beneficial to the utility. The effect on the T&D losses decrease, only provides a minor deviation to benefit to the utility based on the identified PVBESS tariff rates.

As such it can be recognized that the battery price change and the peak energy price change are the most predominant factors to consider when moving forward with such a configuration. Fluctuations in either of these parameters affect the viability of the systems and dynamic alternations are required with the time.

4.7 Profit sharing percentage changed to investment basis

The equal profit sharing basis is changed to a profit sharing basis percentage based on individual lifetime capital investment of both the consumer and the utility. Hence the all PVBESS configurations are analyzed on the share of consumer discounted lifetime investment and utility discounted lifetime investment as depicted in table 20. The average of investment share basis for all PVBESS configurations is considered as the profit sharing basis of both the consumer and the utility.

PVBESS Configuration	Consumer Discounted Lifetime Investment Share Percentage	Utility Discounted Lifetime Investment t Share Percentage
1 kW	45.1 %	54.9 %
1.5 kW	39.8 %	60.2 %
2 kW	38.8 %	61.2 %
3 kW	38.5 %	61.5 %
4 kW	37.3 %	62.7 %
5 kW	36.5 %	63.5 %
Average	39.3 %	60.7 %

Table 20 : Consumer & Utility Investment Percentages of different PVBESS Configurations

Once the profit sharing basis is changed the margin curve varies for all PVBESS configuration lifetime cost plots. Hence the earlier identified curves for flat rate tariffs and two tier tariffs are required to be adjusted to match the investment based profit sharing curve.

The most compatible flat rate tariff which shall follow the investment based profit sharing curve is at rate of Rs20.5/kwh. The resulting economic parameters are tabulated in table 21. The breakeven period however increases for the consumer while the breakeven point is utility decreases for all PVBESS configurations compared with the equal profit sharing basis.

PVBESS Configuration	Consumer			Utility		
	Payback Period (years)	IRR (%)	CPNV (Rs. ,000)	Payback Period (years)	IRR (%)	CPNV (Rs. ,000)
1 kW	-	8	-30	3	54	58
1.5 kW	15	13	48	3	52	94
2 kW	13	14	89	3	52	134
3 kW	12	14	149	3	58	210
4 kW	11	16	245	3	68	282
5 kW	9	16	347	3	56	360

Table 21 Economic Parameters of investment share profit sharing basis flat rate

For the Two Tier tariff system the initial block tariff rate remains unchanged since the earliest possible breakeven point of consumer cumulative cost and utility cumulative cost does not change. However the second block tariff was adjusted to Rs15/kWh to closely correlate with the investment based profit share curve. The comparison with the base case scenario of equal profit sharing of 2kW PVBESS configuration is illustrated in table 22.

	Base Case Value	Investment share profit sharing basis Value	Change (%)
Consumer IRR (%)	16	15	6.25 % ↓
Consumer Payback Period (years)	7	7	-
Consumer NPV value of lifetime profit (Rs.'000)	115	90	21.7 % ↓
Utility IRR (%)	17	18	5.88 % ↑
Utility Payback Period (years)	7	7	-
Utility NPV value of lifetime profit (Rs.'000)	109	133	22 % ↑

Table 22 : Economic Parameters of Investment share profit sharing basis two tier

4.8 Reflect on Avoided Cost Sensitivity

As the peak energy mix is a major concern on the suitability of PVBESS integration, different combinations of avoided generation cost were compared to the worst case of 100% utilization of the available gas turbines during the peak time through the year. Although combined cycle power plants are base load power plants, they are the next most expensive power plants which operate during the peak time. On days where gas turbines need not to be dispatched, the corresponding expensive peak energy contribution will be through combined cycle plants. The avoided costs by deloading these plants are concerned herewith in this study. As such cases are considered on the number of days which the gas turbine operates for the peak energy supply and the number of days combined cycle shall operate as the most expensive peak energy supplying source.

Based on the same logic corresponding consumer system cost curves and utility avoided cost curves were plotted while identifying the equal benefit curves. If the avoided cost reduces the corresponding tariff needs to be revised to validate the utility absorbing battery storage power in the peak. However the reduction should be closely monitored as such it does not affect the consumers benefit for return on their investment. The Viable Minimum PVBESS Capacity for lifetime breakeven and the viable flat rate for such equal benefit which shall ensure the same internal rate of return for the consumer as tabulated in Table 20.

Avoided Cost Combination		Viable Minimum PVBESS Capacity	Viable flat rate for equal benefit (Rs.kWh)	Consumer IRR	Utility IRR
Gas turbine (%)	Combined Cycle (%)				
100	0	1.5	21	13	45
90	10	2	20	13	25
80	20	4	18	13	24
70	30	-	-		

Table 23 Sensitivity on Peak Energy Mix

Results indicate if the gas turbine energy share is dropped below 80% even the 5kW PVBESS configuration shall not overlap or intersect which proves the implementation to be uneconomical. Furthermore the tariff has to be revised on other avoided cost combinations as the equal margin curve alters as well as the viable PVBESS combination.

5) CONCLUSION AND RECOMMENDATION

The Solar Energy has great potential to supply energy for increasing demand but its full potential is not yet harnessed. The domestic and commercial consumers of electricity are allowed several schemes where they can generate and provide energy to the utility from Solar PV panels for energy credit or revenue. The inherent intermittency and time dependency of the solar resource itself has been an issue of concern of power utilities and planners. Incorporating Battery Energy Storage systems to the Solar PV to the energy mix is described as a solution to prevailing difficulties.

The introductions of PVBESS to the consumer side where they are given incentive to produce store and provide energy during the peak hours of demand were analyzed. The Levelized cost of Energy for PVBESS systems are nearly four times higher than the existing PV only grid connected systems. However this cost tend to decrease for large PVBESS configurations

It is seen that the consumer only investment scenario has very limited margin of flexibility for variation in tariff to gain benefit for both the consumer and the utility. The PVBESS configurations under 2kW do not payback and systems also require a flat rate tariff above Rs.50/kwh for consumer profitability. The flat rate Rs.50/kWh achieves equal profitability for consumer and utility but the payback period for the consumer is high. As an alternative a two tier tariff can be proposed where the consumers investment cost is recovered earlier with the same level of equal share of profits for both the consumer and the utility. A rate at Rs52.kWh for the first 10 years and Rs 45.5.kWh for the remaining 15 years is seen as a viable rate for present price of resources. However these prices are not cost competitive, subjected to the variation of peak price and would require further incentive to be feasible.

On the other hand if the utility combines the investment with the consumer the systems cost reduces even more. The utility shall own the responsibility for investing in storage while consumer shall provide the space and other necessary investments similar to a PV only grid connected system. For a Bulk Order Quantity Discount of

10%, the LCOE of such PVBESS configuration of 5kW shall be at Rs.42.14/kWh. Similar to consumer only investment scenario the PVBESS of 1kW does not achieve profitability for the consumer and system higher than 1.5kW are viable for investment. A flat rate tariff of Rs.21/Kwh is found to be viable for equal benefit for utility and consumer under a PVBESS scheme. However the payback period is on the high end for the consumer and in order to equalize the period of payback for both parties a two tier tariff was identified. A rate of Rs.25.kWh for first 7 years and Rs.17.kWh for the remaining 18 years provides equal benefit and equal payback close to 7 years for both parties.

However all these rates are comparatively high and viability is highly dependent on the peak energy price of gas turbines. The avoided costs during peak hours are subjected to the power plant mix in future. A 10% increase shall cater a 119% increase of amount of money saved while a 10% decrease in peak price shall cause to incur a loss of 130% compared to the base case of promoting PVBESS scheme.

On a reference basis the avoided cost were rearranged to measure the viability under a different peak energy mix. In a mix of different energy sources the tariff rate should be regenerated based on the same logic of equal beneficiary for both utility and consumer. As such a different 50:50 margin curve shall be adjusted and corresponding tariff rate is required. If the gas turbine energy share during the peak time is less than 80% of the total number of days in the year even a 5kW PVBESS shall not become viable. The cumulative avoided cost and system cost shall not overlap or intersect as such no proper tariff could be developed in order to gain equal benefit for both utility and consumer for such low gas turbine energy share. Thus, even though the utility shall be compensated by reduction of avoided cost the consumer will not be benefitted at all. Therefore this study gives an understanding on the maximum limit possible for a tariff corresponding to a PVBESS integration which has to be reviewed dynamically depending on the scheduled peak energy sources dispatching order.

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