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Techno-Economic Analysis of Integration of Battery Energy Storage System in Grid-Connected PV System

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Abstract: **-** Grid-connected use of photovoltaic (PV) plants with battery energy storage systems is growing as a means of ensuring grid stability and providing sustainable power supply all over the world. An extensive feasibility assessment of an energy-storage grid-connected solar facility in India is provided here as a case study. In order to minimize the amount of grid and fossil fuel-based backup electricity used during power outages and to limit peak load demand, a unique smart net-zero energy management system is designed. An evaluation of the life cycle costs and benefits as well as the levelized cost of energy (LCoE) is provided for optimized solar power plants with and without integration of battery energy storage system (BESS). The HOMER software is used for the optimization and sizing of the equipment for the grid-connected PV system.

Keywords: *PV system, renewable energy, HOMER, cost of energy, battery energy storage system.*

1. Introduction

The advent of roof-top grid-connected photovoltaic (PV) systems has marked a significant stride toward sustainable energy production, offering an economically viable solution to electricity generation. These systems, devoid of energy storage, present an attractive option due to their ability to seamlessly transfer excess solar electricity to the grid, thereby facilitating a shorter payback period for use [1-3].

Nevertheless, the intermittent nature of solar irradiance poses a challenge to the stability of the main grid. The fluctuating output of solar power from these rooftop PV systems can create imbalances in the grid, impacting its overall stability. This variability requires grid operators to implement sophisticated mechanisms to manage the intermittent influx of solar energy efficiently [4-6].

Furthermore, the absence of energy storage renders PV systems inactive during power outages. This results in users experiencing substantial electricity losses precisely when the availability of solar energy could prove most beneficial. To counteract these interruptions, conventional solutions often involve the deployment of diesel generators as backup power sources. Unfortunately, this reliance on fossil fuel-based alternatives not only increases operational costs but also contributes to heightened greenhouse gas emissions, counteracting the environmental benefits of solar energy [7].

Recognizing these challenges, energy storage systems have emerged as indispensable components of commercial facilities deploying rooftop PV systems. These storage solutions play a pivotal role in mitigating the effects of intermittent solar power generation by storing excess electricity during peak production periods and releasing it during times of low solar irradiance. This not only enhances the reliability and stability of the main grid but also allows users to access a consistent and uninterrupted power supply [8-11].

In addition to grid stability, energy storage systems offer a lifeline during power outages, ensuring a continuous and reliable electricity supply. By eliminating the need for diesel generators, these storage solutions not only reduce operational costs but also contribute significantly to environmental sustainability by curbing greenhouse gas emissions [12].

While, roof-top grid-connected PV systems without energy storage present an initially appealing and economical solution for electricity production, the intermittent nature of solar energy and the associated grid instability necessitate the integration of energy storage systems. These advancements not only enhance grid stability but also ensure a reliable and uninterrupted power supply, all while promoting the shift towards a more sustainable and environmentally friendly energy landscape [13-15].

2. Objectives and system description

Grid-connected photovoltaic power plants that include integrated battery energy storage systems (BESS) increase power quality, peak power control, and energy arbitrage. They also improve overall system performance. However, the commercial and industrial sectors are adopting these systems at a slower rate mainly because there is a lack of knowledge regarding the potential for sustainable energy supply and the life cycle economic benefits of these plants. Life cycle cost-benefit and return on investment must be determined case-by-case since these benefits might be affected by government restrictions and the technical specifications of the grid system. Rooftop PV systems in India are supported by the present regulatory framework both with and without battery storage. In this paper a techno-economic analysis is performed to the grid-connected PV system with and without integration of BESS. The HOMER program is utilized in this study to analyse and design the rooftop PV system as shown in Figure 1.

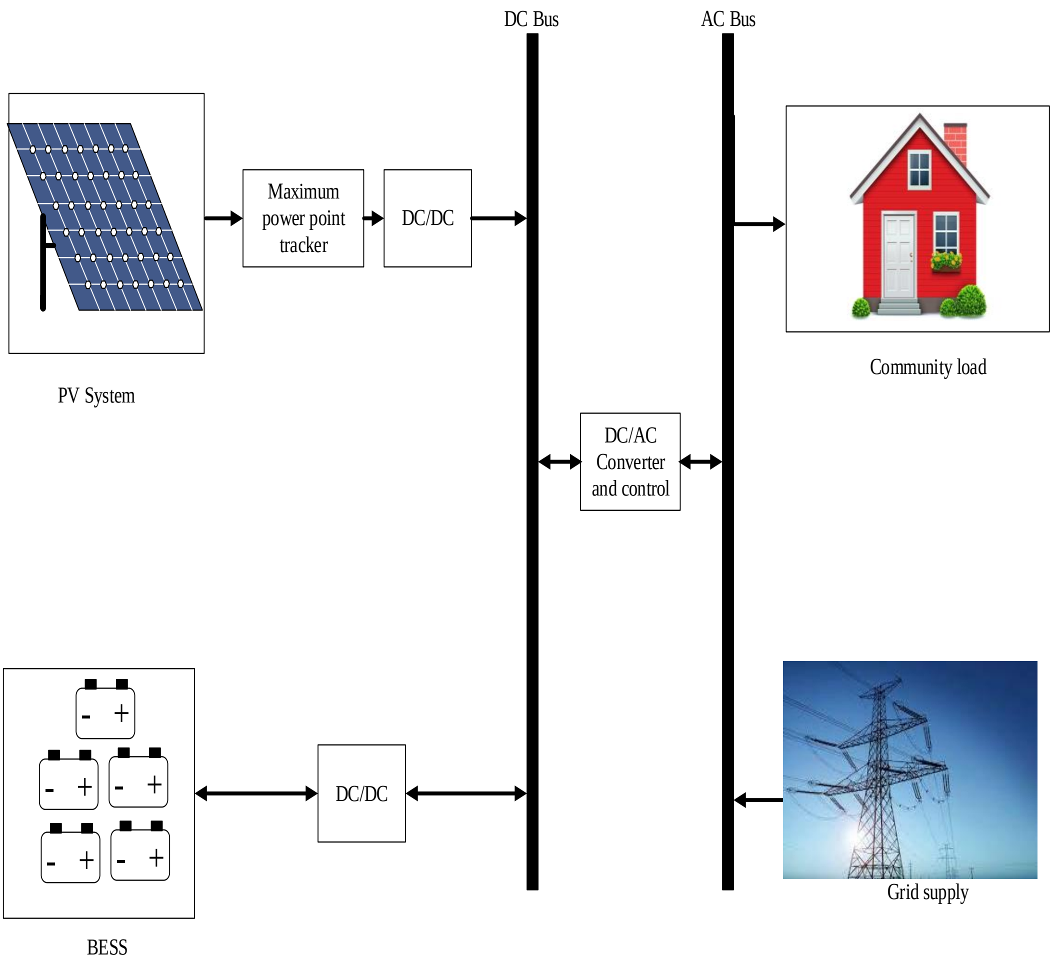


Figure. 1. Proposed grid-connected PV system

As shown in Fig. 1, the BESS is connected to the grid-connected PV system along with the load which is to be served. In this work, the techno-economic analysis is performed with and without integration of BESS. The model of the proposed system is simulated in HOMER software. The National Renewable Energy Laboratory created

HOMER, an optimization tool for microgrid systems [11, 12]. The three main features of the HOMER program are sensitivity analysis, optimization, and imitation. The HOMER system takes into account several factors such as load balancing, load profile, location-specific tools, and system components. It also uses performance indicators including cost of energy (CoE), net present cost (NPC), operating cost (OC), and starting cost.

Here, 1 kWh of electricity production cost is defined as cost of energy (CoE) and is represented as follows:

$$CoE(\$/kWh) = \frac{TAC(\$/year)}{TAEC(kWh/year)} \quad (1)$$

In the equation (1), total annual cost is represented by TAC and total energy consumption in a year is represented by TAEC.

Net present cost (NPC) includes the total investment cost, operation and maintenance cost and all other expenditures subtracted by salvage cost of the project during its overall life span. NPC can be mathematically represented as:

$$NPC(\$/year) = \frac{TAC(\$/year)}{CRF} \quad (2)$$

Where capital recovery factor (CRF) is:

$$CRF(i,n) = \frac{i(1+i)^n}{i(1+i)^n - 1} \quad (3)$$

In the equation (3), annual interest rate is ‘i’ in %, total life span is n year.

1. PV modules

Solar energy, one of the most abundant renewable energy resources (RER) in India, is a key component of Hybrid Renewable Energy Systems (HRES). Photovoltaic (PV) modules convert solar energy into direct current (DC) electricity, with the output directly proportional to the available solar radiation at a specific location and time. To maximize solar energy extraction, a Solar Maximum Power Point Tracking (MPPT) system is employed, adjusting the angle of solar panels based on the sun's direction. This study utilizes flat plate PV modules with an installation cost of $857/kW [21], incorporating a continuous adjustment MPPT system with a horizontal axis. The operational and maintenance (O&M) cost for the PV system is minimal, estimated at $10/kW/year. Given the negligible salvage value, the replacement cost equals the installation cost. Table 1 provides technical details of the PV system.

Table 1. Technical details of PV module[1]

Parameters	Value
Operating temperature	47ºC
Efficiency	13%
Derating factor	80%
Temperature co-efficient	-0.5%/ºC
Ground reflection	20%
MPPT system	Horizontal axis, continuous adjustment
Life time	25 years

[1] The price considered are an interpolation of data (quotations) obtain from local Indian manufacturers, distributors, and previously published literature.

Capital cost	857 $/kW
Replacement cost	857 $/kW
O&M cost	10 $/kW/year

2. Battery energy storage system (BESS)

BESS is used as a backup in HRES and to maintain a constant voltage during peak loads or a shortfall in generation capacity and essential for maximum utilization of the available RERs. Batteries of same rating are connected in series and parallel to acquire greater energy capacities and backup. The ampere hour capacity (C_{Ah}) and watt hour capacity (C_{Wh}) of the BESS should be such selected that it can assure the load requirement for the periods of low solar and wind energy. C_{Wh} of the battery is given by following equation [25]:

$$C_{Wh} = (E_L \times AD) / (\eta_{batt} \times DoD) \quad (8)$$

Table 2. Technical details of BESS[2]

Parameters	Value
Nominal voltage	12 V
Nominal capacity	3.12 kWh
Maximum capacity	260 Ah
DoD	30 %
Roundtrip efficiency	85 %
Capital cost	350 $
Replacement cost	300 $
O&M cost	10 $
Life time	10 years

3. Power converter

To exchange power between AC and DC components of the HRES power converter is used. Capital and replacement cost of the converter are 200 $/kW and 175 $/kW respectively. Their maintenance cost is negligible and having 15 years of life time. Capacity level of converters are selected according to the power to be supplied by the converter during peak demand hours and it is given as in equation (11):

$$C_{cap} = (3L_{ind}) + L_0 \quad (11)$$

Where C_{cap}, L_{ind} and L_0 are the converter capacity, total inductive loads and the total other loads respectively. Inductive loads include loads of refrigerators and fans etc. whereas LED bulbs, mobile chargers and TVs etc. comes in others load category.

Load Assessment

The community's residential electricity demand is a typical Indian load profile. The peak load of the household is considered to be 7 kW for the summer season. The domestic load consists of LED lights, ceiling fans, refrigerators,

[2] The price considered are an interpolation of data (quotations) obtain from local Indian manufacturers, distributors, and previously published literature.

air conditioners, washing machines, and other household electric appliances. The load profile for the summer season is shown in Figure 2.

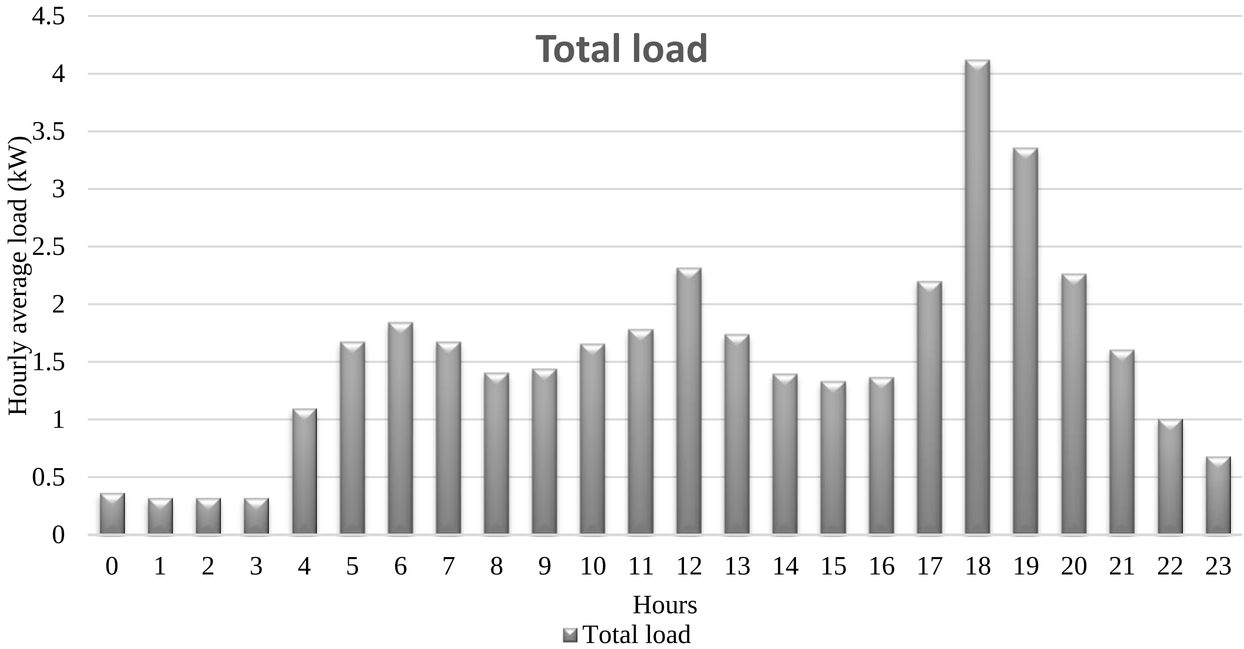


Figure. 2 Hourly load profile for the house under the study

Resource Assessment

Solar and wind resources are considered for HRES in this simulation. Solar radiation is available almost throughout the year for this region in the world. Summers has relatively longer sunny days when solar radiation is available for 10-12 hours whereas in winters for 6-8 hours sun is available. The solar radiation data is obtained from the NASA (National Aeronautics and Space Administrative) surface meteorology and solar energy database using HOMER software. The annual average solar radiation for the location under this study is scaled to be 5.15 kWh/m^2/day with clearness index of 0.57. The chart in Figure. 3 shows the variation in solar radiation which confirms the good solar potential for the selected location to exploit the solar energy using solar PV system. Based upon the solar radiation available at the solar modules output energy of the PV system is given as:

$$E_{PV} = A \times r \times H \times PR \tag{12}$$

Where,

E_{PV} = Output energy of PV system (kWh)

A= Total solar panel area (m^2)

r= Solar panel yield or efficiency (%)

H= Average solar radiation on titled PV panel in a year (kWh/m^2/y)

PR= Performance ratio of solar panel (ranges from 0-0.9, default value is 0.75)

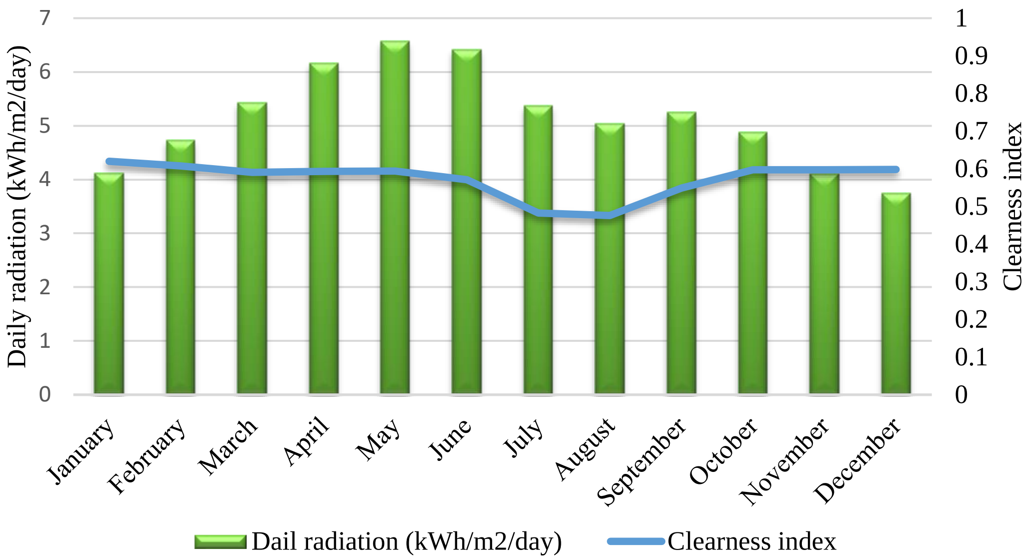


Figure. 3. Monthly solar irradiation level and clearness index at the selected location

3. Simulation, results, and discussion

HOMER considers the economic facts when designing the system. The economic data entered is crucial to the simulation's accuracy. Since project life data, inflation, real interest rates, interest rates, and economic data are needed. The project has a 25-year lifespan. The PV panel's lifetime is used to calculate this time frame.

Figure 4 shows the grid-connected PV system designed in HOMER. For techno-economic analysis of grid-connected PV system with and without integration of BESS, two scenarios are considered: without BESS and with BESS.

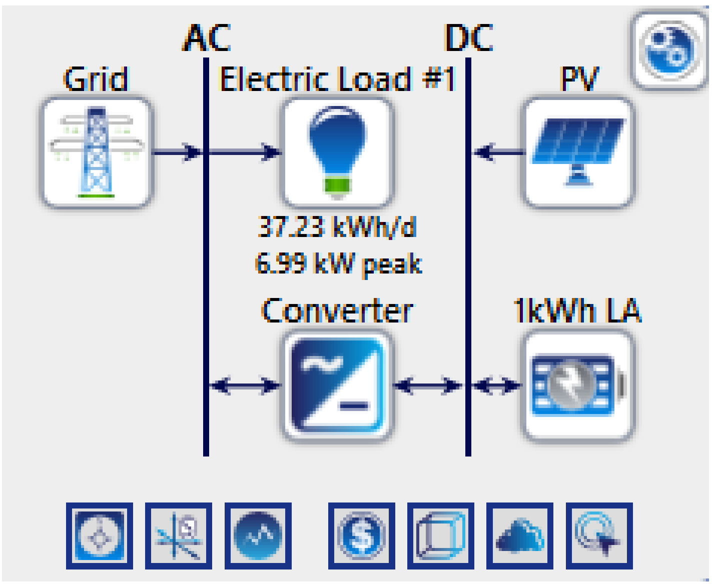


Figure. 4. Proposed system in HOMER

When BESS is not considered in the simulation the simulation results is shown in Figure 5. The CoE for Grid-PV configuration is $0.0391 and for grid-PV-BESS configuration is $0.0415. Here, the cost of production of one kW of electricity is slightly more in case of Grid-PV-BESS configuration. The NPC is also more in Grid-PV-BESS configuration i.e. 0.0118 $M as compared to 0.0104 $M in Grid-PV system. Initial investment is also more in Grid-PV-BESS system as shown in Figure 5.

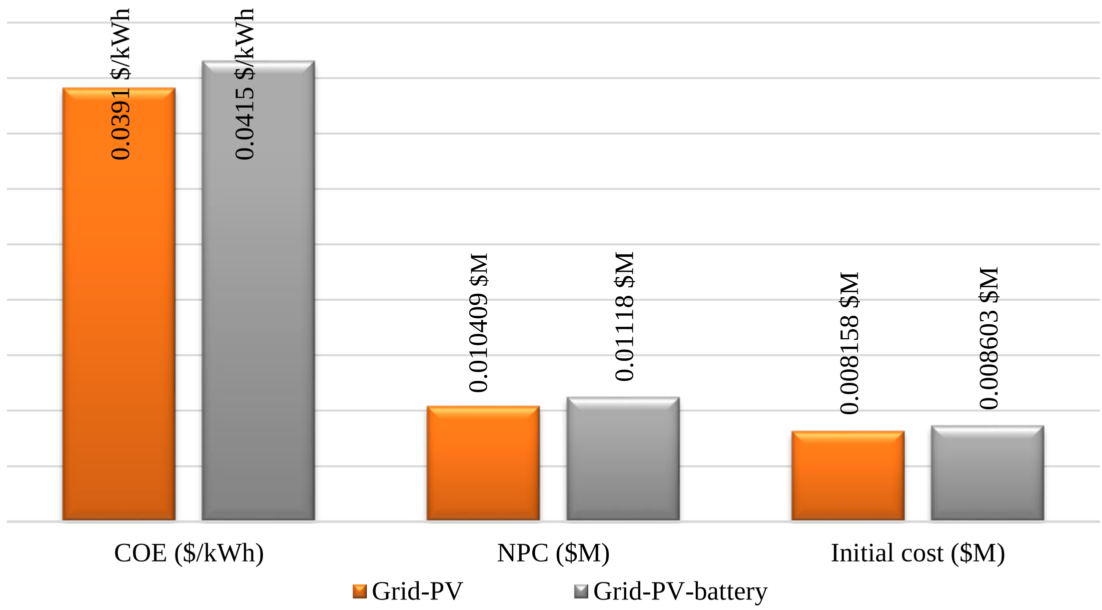
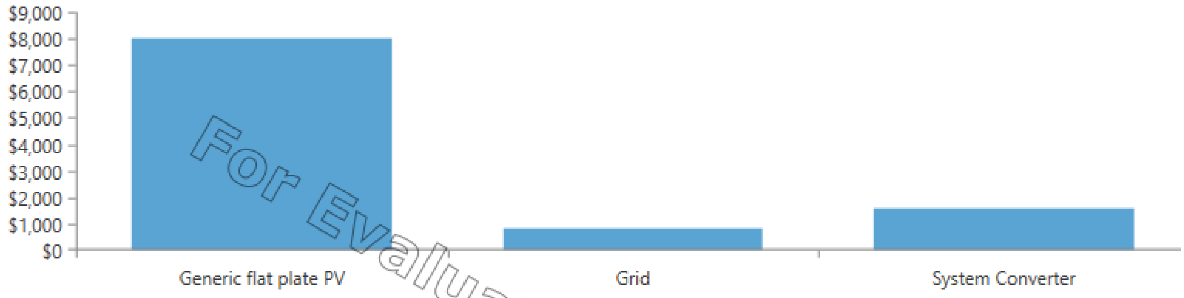


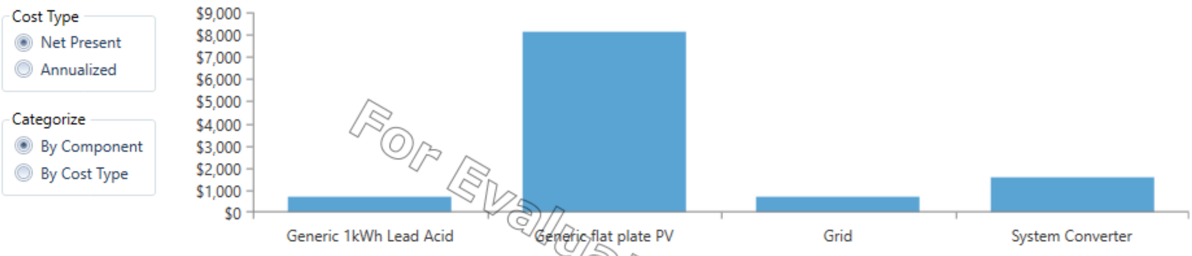
Figure. 5. CoE, NPC, and initial cost in both configuration

If the results are discussed more deeply it is found that in Grid-PV configuration, the total cost of the system is $8157.64 as shown in Figure 6. The major part of the total cost goes to PV system where $6961.04 are spend in capital cost of the PV system, $1050.05 in O and M cost. Grid accounts for &841.04 as O and M cost as there is no initial coat in grid.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Generic flat plate PV	$6,961.04	$0.00	$1,050.05	$0.00	$0.00	$8,011.09
Grid	$0.00	$0.00	$841.04	$0.00	$0.00	$841.04
System Converter	$1,196.60	$444.22	$0.00	$0.00	($83.61)	$1,557.21
System	$8,157.64	$444.22	$1,891.08	$0.00	($83.61)	$10,409.34

Figure 6 Cost summary in Grid-PV configuration



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Generic 1kWh Lead Acid	$350.00	$265.03	$129.28	$0.00	($35.93)	$708.37
Generic flat plate PV	$7,044.73	$0.00	$1,062.67	$0.00	$0.00	$8,107.40
Grid	$0.00	$0.00	$729.68	$0.00	$0.00	$729.68
System Converter	$1,208.70	$448.72	$0.00	$0.00	($84.45)	$1,572.96
System	$8,603.42	$713.75	$1,921.63	$0.00	($120.39)	$11,118.41

Figure. 7. Cost summary in Grid-PV-BESS configuration

Figure 7 show the cost summary of Grid-PV-BESS configuration. As discussed earlier, this configuration is slightly higher CoE and NPC as compared to Grid-PV configuration. This is mainly due to addition of BESS. BESS is useful in case of grid-independent system where supply from grid is not available. The PV system for this load is 5.98 kW for Grid-PV configuration and 6.04 kW for Grid-PV-BESS configuration.

4. Conclusions

In this paper, techno-economic analysis of grid-connected PV system is performed for a household having peak load of 7 kW. The grid-PV configuration is found to be more economical as compared to Grid-PV-BESS configuration where CoE is 0.0391 and 0.04115 $/kWh respectively. The NPC of grid-PV configuration is $8157.64 and for grid-PV-BESS configuration it is $8603.42. For the results it is found that addition of BESS leads to increase in the overall cost as well as CoE of the system. Because the availability of the grid is 100% so the dependency on the BESS is negligible. It is to be noted that the configuration consist of Grid-PV-BESS is more practical where grid is not available or the outage in grid is very high. In that case for serving the load all the time BESS comes in to action when grid is not available.

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