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Impact of Extreme Weather Parameters on Optimum Sizing of Solar Photovoltaic-Battery Energy Storage Systems: A Case Study

Gauri Karve[1], Mangesh Thakare[2], and Geetanjali Vaidya[3]

[1]Department of Electrical Engineering, PVG's COET & GKPIOM, Pune, Maharashtra, India; gmk_elect@pvgcoet.ac.in
[2]Department of Electrical Engineering, PVG's COET & GKPIOM, Pune, Maharashtra, India
[3]SAS Powertech Pvt Ltd, Baner, Pune, Maharashtra, India; geetvaidya@gmail.com

***Correspondence:** Gauri M Karve; E-mail: *gmk_elect@pvgcoet.ac.in*

ABSTRACT- The performance of an off-grid solar Photovoltaic (PV) system with Battery Energy Storage (BES) depends on the system's location. Incorporating climatic variables such as solar irradiance, ambient and cell temperatures into the modelling of PV systems helps predict the system's appropriate behaviour. The paper discusses the impact of variations in seasonal irradiance, temperature, and system location on the optimum sizing of a standalone solar PV-BES system for minimum total annual cost using Improved Particle Swarm Optimization. Three locations: Pune (Maharashtra), Ladakh (Jammu and Kashmir), India, and Rafsanjan (Iran) with extreme weather conditions (winter and summer) are identified to analyze the effect for optimum sizing of PV-battery energy systems. In addition, the optimum system sizing is analyzed for lead acid and lithium-ion batteries for both seasons. The results indicate that the system's size and cost are significantly affected due to changes in location, temperature, and seasonal irradiance. Assuming the same load demand in both seasons, the number of lithium-ion batteries required is less than that of lead acid batteries, proving their cost-effectiveness. The study gives a comprehensive techno-economic analysis of the PV-BES system considering climatic variations at three locations for two battery chemistries.

Keywords: Extreme weather parameters, Optimum sizing, Solar photovoltaic, Battery energy storage, Total annual cost.

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1. INTRODUCTION

The global proliferation of "Renewable Energy Resources" (RERs) and "Battery Energy Storage" (BES) systems is expected to reduce concerns about local energy and environmental pollution and improve the energy supply to standalone societies. The intermittent nature of RERs, such as solar Photovoltaic (PV) and Wind Turbines (WT), always causes a mismatch between their power generation and load demand. To alleviate this mismatch, a cost-effective, self-reliant Hybrid Energy System (HES) is deployed and analyzed on different parameters like "Cost Of Energy" (COE), "Loss of Power Supply Probability" (LPSP) and "Total Annual Cost" (TAC) for various locations and with several optimization techniques [1].

The HES's performance depends on its components' optimum size and efficiency. In particular, the efficacy of a PV-BES system is dependent on the duration and intensity of solar irradiance. However, climatic variables such as intermittent solar irradiance, ambient temperature, wind speed, humidity, dirt, tilt angle, etc., affect the duration and intensity of maximum irradiance during a day. The intensity of solar irradiance directly impacts the open circuit voltage and short circuit current of the panel, which decides its output power [2]. This reduces the expected power output from a solar panel and underestimates its required size [3].

A reduction in the intensity of solar irradiance decreases the panel power, and a decrease in temperature increases the panel power. On the other hand, a decrease in temperature decreases BES output and vice versa up to a specific temperature range. This range depends on the battery chemistry [4]. Both these factors play a critical role in PV-BES system operation but have opposite effects on the output power of the PV panel as well as BES [5, 6], impacting their optimum size. Under sizing PV-BES hampers system reliability, while oversizing increases the cost of system operation. Some researchers have determined the optimum sizing of PV-BES systems with several optimization algorithms considering constant meteorological parameters such as cell temperature and ambient temperature [7, 8]. Different types of Particle Swarm Optimization (PSO) techniques are studied to optimize the capacity of a hybrid (PV/WT/BES) system under constant meteorological data [7]. Various heuristic algorithms, such as PSO, simulated annealing, tabu, and harmony search, are compared to determine the best size of the PV/WT/fuel cell/BES system, considering the minimum TAC. However, due to the assumptions of constant meteorological data, the output from solar PV is approximate in these studies. Accurate modelling of PV with temperature effect is necessary to get factual results [8, 9].

Few authors have considered the impact of temperature and solar irradiance on the output of PV panels and the optimum sizing of HES with different objectives. The authors considered various expressions to find efficiency of PV array as a function of temperature for specific mounting geometry [10]. Different designs with various tilt angles, azimuth angles, and storage days have been proposed for the optimal size of a PV-BES system for the same load at a specific site [11]. The authors have undertaken a similar study of the optimum capacity sizing of a standalone off-grid PV/WT/BES/diesel generator HESs and their optimal combination [12-14]. The peak performance of three PV-BES systems with different azimuth and tilt angles has been analyzed for the summer and winter seasons without considering different battery chemistry [15]. An enhanced Genetic Algorithm has been studied for the optimum capacity sizing of an islanded off-grid PV/WT/BES HESs with a minimum TAC for 20 years [16]. A study determined the minimum TAC for a standalone system comprised of PV/BES/diesel generator using various PSO techniques [17, 18]. The authors presented the optimum capacity sizing of a standalone off-grid PV/WT/BES HESs for minimum TAC for reliability criteria using the Firefly Algorithm with a single type of battery chemistry [19]. On similar lines, the authors minimized the total cost of a PV–BES system using a mixed integer nonlinear programming model to optimize the BES capacity [20]. The experimental validation of the effects of extreme weather conditions on PV systems is carried out in [21], but without system optimization.

The majority of the research is based on the effect of changes in temperature and solar irradiance on the output of a PV system and its optimization, but without battery optimization. In the case of optimizing PV-battery systems, the researchers have assumed constant meteorological data for a specific site and a single type of battery chemistry.

However, the researchers have not considered all these parameters simultaneously for optimum HES sizing. This paper studies the impact of ambient temperature and solar irradiance variations on the PV-BES system for lead-acid and lithium-ion battery chemistries in winter and summer. These two batteries are specifically considered to highlight the importance of the different SOC ranges in determining the optimum sizing and cost of the system components.

The significant contributions of the paper are:

- This paper has analyzed the effect of variations in temperature and solar irradiance on the optimum sizing of a PV-BES system for minimum TAC in the two equatorial regions like Iran & India which have high solar radiations and have geographical different locations with extreme weather conditions: Pune (18.55°N, 73.85°E, Maharashtra), Ladakh (33.95°N, 77.55°E, Jammu and Kashmir, India), and Rafsanjan (31.88°N, 54.28°E, Iran).
- The paper indicates that the location (Pune) with moderate variations in weather conditions (winter and summer) is the best suited for a PV-BES system with the minimum difference in system costs for both seasons compared to locations with extreme weather conditions like Ladakh and Rafsanjan.
- The paper showed that fewer Lithium-Ion (Li-Ion) batteries are required compared to Lead Acid (LA) batteries due to their different SOC ranges across three locations. In addition, using lithium-ion batteries results in lower TAC despite their high cost.

2. MATHEMATICAL MODELLING OF SYSTEM COMPONENTS

The system configuration under study consists of solar PV-BES (*figure 1*) and the load demand of three locations (Pune, Ladakh, and Rafsanjan). The optimum size of system components (N_{PV}, N_{batt}, N_{ci}) for a minimum TAC objective has been determined using the IPSO algorithm.

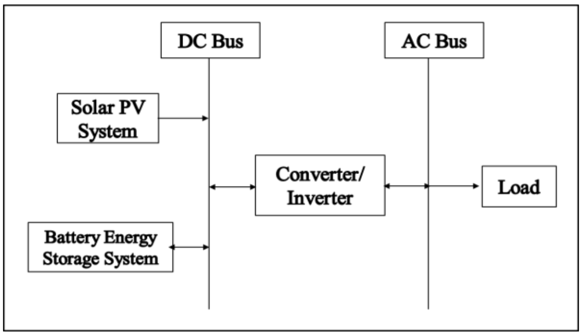

Figure 1. System configuration under study

2.1 Solar PV System

The mathematical modelling of the PV system and its power output with constant weather conditions and radiation at Nominal Operating Cell Temperature (NOCT) is given by *Eqs. (1)* and *(2)*, respectively [9, 14, 22].

$$p_{PV-Each}(t) = \begin{cases} P_{Rs}\left(\frac{r^2}{R_{SRS}R_{CR}}\right) & \text{if } 0 \leqslant r \leqslant R_{CR} \\ P_{Rs}\left(\frac{r}{R_{SRS}}\right) & \text{if } R_{CR} \leqslant r \leqslant R_{SRS} \\ P_{Rs} & \text{if } R_{SRS} \leqslant r \end{cases} \quad (1)$$

$$P_{pv}(t) = p_{pv-Each}(t) \times N_{pv} \quad (2)$$

Where,

P_{Rs}	Rated PV power (W)
r	Solar irradiance (W/m^2)
R_{CR}	Certain solar irradiance point (W/m^2)
P_{pv}	Total power output of all PV panels (W)
N_{pv}	Number of PV panels
$p_{pv-Each}(t)$	Power rating of a PV panel (W)
R_{SRS}	Solar irradiance with standard environment as 1000 W/m^2

The peak winter season for Pune, Ladakh, and Rafsanjan are December, January, and January, respectively. The peak summer season for Pune, Ladakh, and Rafsanjan are May, July, and July,

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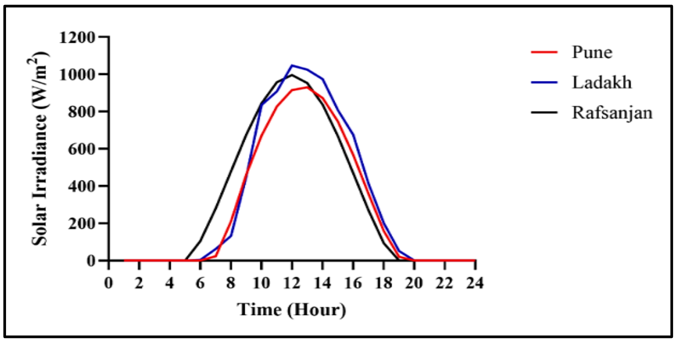
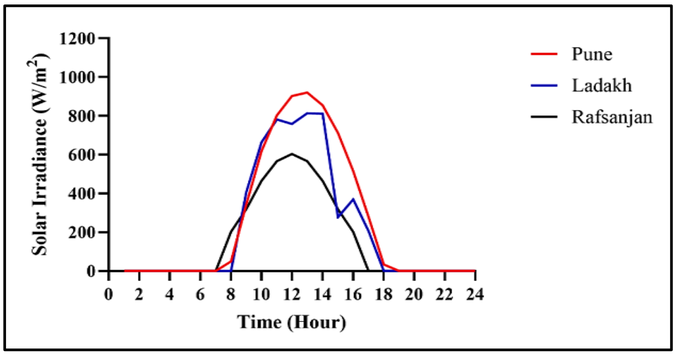
respectively. The solar irradiances at these locations are shown in *figure 2* for peak winter and summer seasons, respectively. The daily solar irradiances are averaged from a month to a week and from a week to a day of that particular month for all three locations [23].



(a)



(b)

Figure 2. Daily solar irradiance (a) Winter; (b) Summer

2.1.1 Mathematical Modelling of Solar PV Considering the Effect of Weather Conditions

The size and output of a standalone PV system change with atmospheric conditions such as solar irradiance, local wind speed, cell material, cell temperature, ambient temperature, etc. All these meteorological variables are mathematically modelled as shown in *eq. (3)* and *eq. (4)*. The power output from each PV panel and that of the complete PV system can be found using *eq. (5)* and *eq. (2)*, respectively [9]. All the following mathematical expressions are referred from [8, 10].

$$\beta_{ref} = \frac{1}{(T_o - T_{ref})} \quad (3)$$

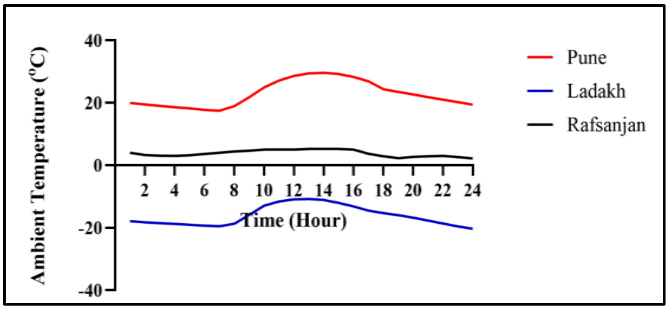
$$\eta_{PV} = \eta_{T_{ref}}\left[1 - \beta_{ref}(T_a - T_{ref}) + \frac{(T_{NOCT} - T_a)r(t)}{r(t)_{NOCT}}\right] \quad (4)$$

$$p_{pv}(t) = r(t) \times A \times \eta_{pv} \quad (5)$$

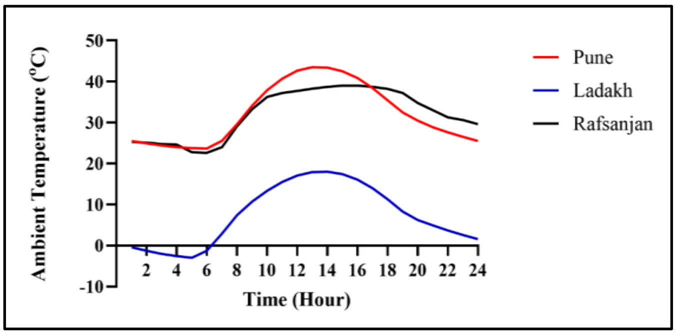
Where,

β_{ref}	Temperature coefficient
t	Particular instant
$p_{pv}(t)$	Power rating of PV panel (W)
r(t)	Solar irradiance (W/m^2) at 't'
η_{PV}	Efficiency of PV panel (%)
$P_{pv}(t)$	Total power output of PV panels (W)
A	Area of PV panel (m^2)
η_{Tref}	Reference efficiency of PV panel (%)
Ta	Ambient temperature (°C)
Tref	Reference temperature (°C)
T_o	Temperature when PV module's electrical efficiency is zero
T_{NOCT}	Temperature at Nominal Operating Cell Temperature (NOCT) (°C)
$r(t)_{NOCT}$	Radiation at instant 't' for NOCT (°C) (Generally considered as 800 W/m^2, Air temperature as 293.16 K (20°C)

Figure 3 describes the daily ambient temperatures at Pune, Ladakh, and Rafsanjan locations during peak winter and summer seasons. The ambient temperatures for extreme winter and extreme summer seasons are averaged from a month to a week and from a week to a day of that particular month for all three locations [23].



(a)



(b)

Figure 3. Daily ambient temperature (a) Winter; (b) Summer

2.2 Battery Energy Storage System (BESS)

Eqs. (6) and *(7)* depict mathematical modelling of BES considering energy output from solar PV, depth of discharge, converter/inverter losses, self-discharge rate, and efficiency of BES [9, 14, 22]. During periods of excess power generation, the BES system will store the surplus energy. Conversely, when the demand for power exceeds the generated amount, the BES will discharge the stored energy to meet the demand. In this study, lead-acid and lithium-ion battery chemistries are considered. Lead-acid batteries have been popular in PV-BES, being mature technology with low cost. On the other hand, lithium-ion batteries are more efficient, having high energy and power density and a high power-to-weight ratio and power-to-volume ratio, but are more expensive than lead-acid batteries.

Charging mode

$$E_{batt(t)} = E_{batt(t-1)} \times (1-\rho) + \left[E_{PV(t)} - \left(\frac{E_{load(t)}}{\eta_{ci}}\right)\right] \times \eta_{batt} \quad (6)$$

Discharging mode

$$E_{batt(t)} = E_{batt(t-1)} \times (1-\rho) + \left[\left(\frac{E_{load(t)}}{\eta_{ci}}\right) - E_{PV(t)}\right] \times \eta_{batt} \quad (7)$$

Where,

$E_{PV}(t)$	Energy generated by SPV (kWh)
$E_{load}(t)$	Energy required by load (kWh)
$E_{batt}(t)$	Energy stored in battery (kWh)
ρ	Rate of self-discharge of battery
η_{ci}	Efficiency of converter/inverter (%)
η_{batt}	Efficiency of battery

2.3 Converter/Inverter

A converter/inverter is an electronic device designed to transform Direct Current (DC) power into Alternating Current (AC) power. The output of a solar PV system and a BESS are DC in nature; therefore, they need to be connected to the AC load through a converter/an inverter. In the system under consideration, the number of converters/inverters can be found using *eq. (8)*.

$$N_{ci} = \frac{E_{PV\_Peak}}{E_{ci}} \quad (8)$$

Where,

N_{ci}	Number of converters/inverters
E_{PV_Peak}	Installed capacity of PV system (kWp)
E_{ci}	Capacity of unit converters/inverters (kVA)

2.4 Electrical Load Demand

Figure 4 shows real data of electrical load demand for a specific location (Rafsanjan) by averaging load data from one year to 24 hours [14]. For all system components, the load curve is assumed to be the same across all three locations for optimum sizing. The specifications of system components are considered from [17] and mentioned in *table 1*.

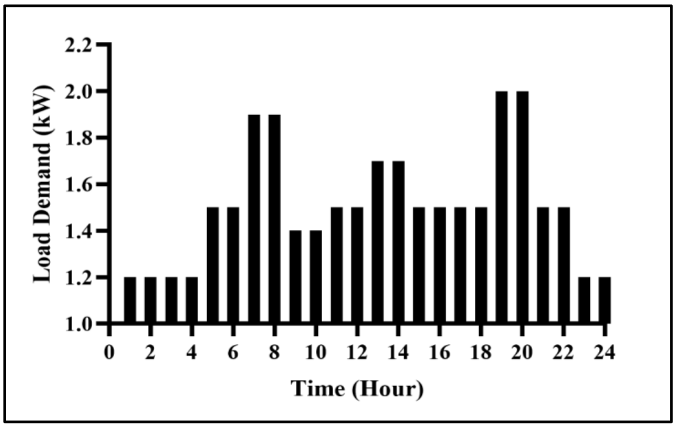


Figure 4. Load demand for 24 hours

Table 1. Specifications of System Components [17]

Rated power of a single solar panel	260 W
Price of a single solar panel	$ 200
Maintenance cost of PV panel	$12 per year
Area of PV panel	1.64 m^2
Rating of single battery	2.1 kWh
Voltage of single battery	12 V
Price of a single LA battery	$600
Price of a single Li-Ion battery	$1169
Charging efficiency of battery	85%
Discharging efficiency of battery	100%
Self-discharge rate of LA battery	0.02% per hour
Self-discharge rate of Li-Ion battery	0.02% per hour
Rated power of single converter/inverter	1.5 kW
Price of a single converter/inverter	$314
Efficiency of converter/inverter	80%

3. OBJECTIVE FUNCTION AND CONSTRAINTS

The primary objective is to minimize the TAC of the system components by reducing both their capital cost (C_{Cpt}) and maintenance cost (C_{Mtn}). The following equations are referred from [22].

$$\text{Total Annual Cost (TAC)} = (C_{Cpt} + C_{Mtn}) \quad (9)$$

$$C_{Cpt} = [(C_{PV} + C_{batt})] = [(N_{PV} \times C_{PV}) + (N_{batt} \times C_{batt}) + (N_{ci} \times C_{ci})] \quad (10)$$

$$C_{Mtn} = [(C_{PV} + C_{batt} + C_{ci})] \quad (11)$$

The C_{Cpt} and C_{Mtn} of system components depend on the lifetime of the project (*n*) and the interest rate of the system (*j*). The relationship between these parameters is given by the "Capital Recovery Factor" (CRF).

CRF is the ratio of a constant annuity to the present value of receiving that annuity for the project's lifetime. Using an interest rate *j*, the CRF can be calculated using *eq. (12)*.

$$CRF = \frac{A}{P} = \frac{j(1+j)^n}{(1+j)^n - 1} \quad (12)$$

Where,

n	Lifetime of the project
j	Interest rate of the system

The installments will differ based on the interest rate and CRF.

C_{Cpt} = CRF [(C_{PV} + C_{batt} + C_{ci})] =

$$C_{Cpt} = CRF\,[(N_{PV} \times C_{PV}) + (N_{batt} \times C_{batt}) + (N_{ci} \times C_{ci})] \quad (13)$$

$$C_{Mtn} = CRF\,[(C_{PV} + C_{batt} + C_{ci})] \quad (14)$$

$$C_{ManT} = CRF\,\{[C_{Mnt} \times \textstyle\sum_{t=1}^{24} P_{PV} \times \Delta t] \times 365] + [F_{ci} X C_{ci}/n] + [C_{Mntbatt} \times N_{batt} \times P_{batt}/n]\} \quad (15)$$

The difference between the load demand and PV power over (ΔP) over 24 hours should be greater than or equal to zero.

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$$\Delta P = \sum_{t=1}^{24} E_{PV}(t) - \sum_{t=1}^{24} E_L(t) \geqslant 0 \quad (16)$$

With - Inequality Constraint as – $\Delta P \geqslant 0$

$(N_{PV})min \leqslant N_{PV} \leqslant (N_{PV})max$

$(N_{batt})min \leqslant N_{batt} \leqslant (N_{batt})max$

$(N_{ci})min \leqslant N_{ci} \leqslant (N_{ci})max$

4. SIZE OPTIMIZATION OF SOLAR PV AND BES SYSTEM

The improved Particle Swarm Optimization (IPSO) algorithm optimizes complex problems with multivariable objective functions. It can be applied to minimize or maximize the objective functions to yield optimal results. It is implemented for this problem being suitable for such type of optimization problem [24-26] and its ability of fast convergence without getting stuck up at local minima.

It is executed to determine the optimum size of system components (N_{PV}, N_{batt}, N_{ci}) for a minimum TAC. The IPSO algorithm has been configured with 50 populations and 100 iterations. Through optimization over 10 runs, the system has been refined to yield consistent and dependable results.

4.1 Procedure for implementing IPSO for optimization problem

The flowchart in *figure 5* indicates the procedure for implementing IPSO to find the system components for minimum TAC.

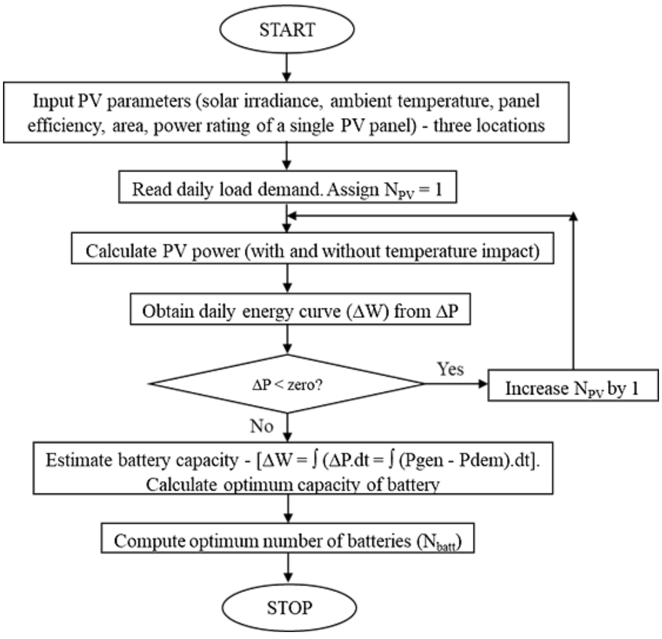


Figure 5. Flow chart of IPSO for optimum system components for minimum TAC

The results obtained following the steps in the flow chart are discussed in the next section and presented in *table 2.*

5. RESULTS AND DISCUSSION

This section shows the impact of ambient temperature and solar irradiance variations on the optimum N_{PV}, N_{batt}, and N_{ci} of a standalone solar PV-BES system. This effect is observed in three locations, Pune (India), Ladakh (India), and Rafsanjan (Iran) - all of which experience extreme weather conditions and share the same load curve.

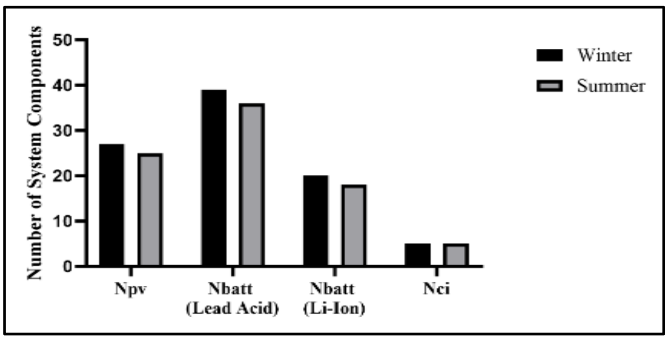
Variations in the intensity and duration of solar irradiance can lead the same PV system to generate up to twice as much electricity in summer compared to winter. Consequently, the required N_{PV}, N_{batt}, and N_{ci} are lower in summer than in winter, as illustrated in *table 2.*

Due to changes in the intensity and duration of solar irradiance, the same PV system may generate twice as much electricity in summer than in winter. As a result, N_{PV}, N_{batt}, and N_{ci} required are less in summer than in winter, as seen in *table 2.*

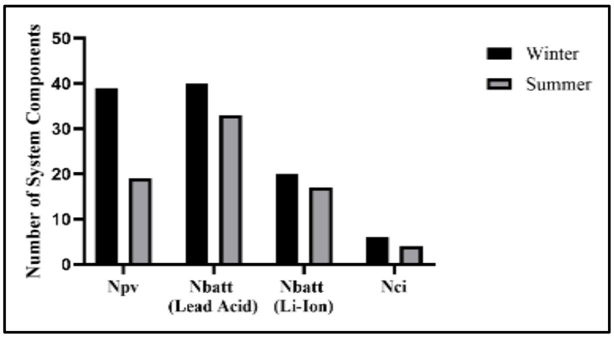
Table 2. System components for Pune, Ladakh, and Rafsanjan using IPSO

Number of System Components	Pune (India)		Ladakh (India)		Rafsanjan (Iran)	
	Winter	Summer	Winter	Summer	Winter	Summer
N_{PV}	27	25	39	19	29	20
N_{batt} (LA)	39	36	40	33	35	32
N_{batt} (Li-Ion)	20	18	20	17	18	16
Nci	5	5	6	4	4	4
TAC ($) - LA battery	19026.2	17876.2	23036.2	14694.9	18234.9	14844.9
TAC ($) - Li-Ion battery	15796.2	14816.2	19636.2	11974.9	15344.9	12124.9

Figure 6 graphically presents the results in *table 2.* The X-axis displays N_{PV}, N_{batt}, and N_{ci} for both winter and summer, while the Y-axis indicates the corresponding values of components. *Figure 7* shows the convergence curve of the IPSO algorithm for minimum TAC.



(a)



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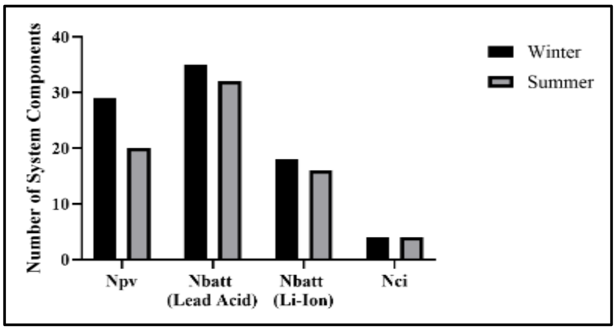

(c)

Figure 6. System components (a) Pune (b) Ladakh (c) Rafsanjan

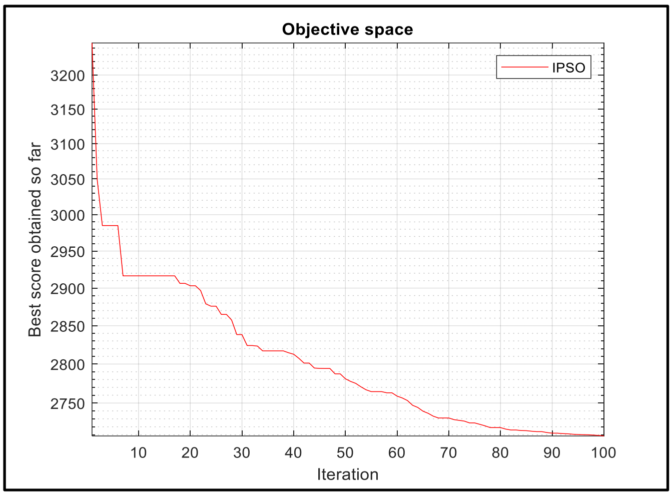

Figure 7. Convergence of IPSO

Table 2 and *figure 6* show that the number of Li-Ion batteries required is less than the LA batteries to meet the same load demand in both seasons. This may be due to the fact that lithium-ion batteries have a greater SOC range (20% to 100%) than lead-acid batteries (50% to 100%). *Table 2* indicates that the Total Annual Cost (TAC) for lithium-ion batteries is significantly lower than that for lead-acid batteries. This suggests that, despite their higher initial cost, Li-Ion batteries are cost-effective overall compared to LA batteries.

Table 2 shows that the location with moderate variation in temperature and irradiance throughout the year (Pune) gives the minimum difference in TAC with an optimum size of system components (N_{PV}, N_{batt}, and N_{ci}) compared to locations with extreme weather conditions like Ladakh and Rafsanjan.

6. CONCLUSION AND FUTURE SCOPE

This work analyses the impact of location, variations in temperature, and seasonal irradiance on the optimum sizing of a standalone solar PV-BES system using IPSO. It focuses on three geographically extreme specific locations - Pune (India), Ladakh (India), and Rafsanjan (Iran) - from two countries characterized by extreme weather conditions to achieve the optimum Total Annual Cost (TAC). The size of components required for the PV-BES system is lesser in summer than in winter due to higher intensity and longer duration of solar irradiance compared to the winter season. Locations with moderate weather variations are more suitable for PV-BES installations, as they tend to have lower overall system costs compared to those in extreme climates, reflecting a smaller difference in TAC between seasons. At all three locations, fewer lithium-ion batteries are required than lead acid batteries to fulfill the same load due to their different SOC ranges, leading to lower TAC. The study gives a comprehensive techno-economic analysis of the PV-BES system considering climatic variations at three locations for two battery chemistries. The work gives an insight into climatic study for the system engineers before installing the PV-BES system at any particular location.

Even though, the study is simulation-based, the results can be evaluated/validated using experimental work in future. The study can be expanded to include various energy sources, such as wind-BES and PV-wind-BES systems, utilizing any battery chemistry. This analysis will be beneficial, as these components also impact the overall cost of the system.

Table of Acronyms

R_{CR}	Certain solar irradiance point (W/m^2)	P_{Rs}	Rated PV power (W)
$P_{PV-Each}(t)$	Power rating of a PV panel (W)	r(t)	Solar irradiance (W/m^2) at 't'
R_{SRS}	Solar irradiance with standard environment (W/m2)	β_{ref}	Temperature coefficient
$P_{PV}(t)$	Total power output of all PV panels (W)	N_{PV}	Number of PV panels
T_{ref}	Reference temperature (ºC)	t	Particular instant
η_{Tref}	Reference efficiency of PV panel at Tref (%)	A	Area of PV panel (m^2)
$r(t)_{NOCT}$:	Solar irradiance at instant 't' for NOCT (ºC)	η_{PV}	Efficiency of PV panel (%)
$E_{PV}(t)$	Energy generated by PV panel (kWh)	T_a	Ambient temperature (ºC)
$E_{load}(t)$	Energy required by load (kWh)	ρ	Rate of self-discharge of battery
$E_{batt}(t)$	Energy stored in battery (kWh)	η_{batt}	Efficiency of battery (%)
η_{ci}	Efficiency of converters/inverters (%)	N_{batt}	Number of batteries
C_{Cpt}	Capital cost of system components ($)	N_{ci}	Number of converters/inverters
C_{Mtn}	Maintenance cost of system components ($)		
T_{NOCT}: Temperature at Nominal Operating Cell Temperature (NOCT) (ºC)			
T_o: Temperature when PV module's electrical efficiency is zero			

Author Contributions:
Gauri M. Karve: Conceptualization, Methodology, Software, Data curation, Writing Original draft
Mangesh S. Thakare: Reviewing, Editing, Visualization, Supervision
Geetanjali A. Vaidya: Reviewing, Editing, Visualization, Supervision.

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