Optimal Sizing of a Standalone Microgrid using SEIG-based Hydro Power Plant, PV, and Battery Storage System

Anil Gupta[1], Manisha Dubey[2]
[1]Ph.D. Scholar Electrical Engineering Department, MANIT, Bhopal, India
[2]Prof. Electrical Engineering Department, MANIT, Bhopal, India
[1]anilrgpv@gmail.com, [2]manishadubey6@gmail.com

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ABSTRACT:
Electrification of far-flung locations through hybrid renewable energy sources needs efficient planning to ensure economic feasibility coupled with the reliability of the system. Whereas MHPPs with SEIGs make a sturdy baseload, they are characterized by extreme seasonality due to intermittent availability in monsoon conditions. Incorporation of PV panels and Battery Energy Storage System (BESS) can overcome this problem; however, heuristic algorithms for sizing such systems normally yield a technically suboptimal and economically unfeasible design of the hybrid energy system. This paper offers a PSO algorithm for the identification of the optimal capacity of the MHPP, PV panel and BESS system based on SEIG that would minimize the TNPC of the system in 20 years. The optimization problem is posed through a bi-criteria objective function that consists of cost in INR and a penalty function LPSP. The PSO model is validated using actual hourly meteorological, hydrological and load data of a far-flung village in Bhopal, MP, India. The findings confirm that the suggested PSO solution leads to the optimal system (25.78 kW Hydro, 104.69 kW PV, 297.55 kWh Battery) having the TNPC of ₹28.12 Million and LCOE of ₹5.63/kWh. The cost is reduced by 69.7% from the heuristic EAM (Energy Autonomy Method) in question, while the reliability of the grid is enhanced due to the lowering of the LPSP from the erroneous 16.54% (EAM) to a very acceptable 2.18% (PSO). It can be concluded that it is necessary to use the inverse complementarity between the solar and hydro energy sources through optimization in off-grid microgrids.

Keywords: Optimal Sizing, Standalone Microgrid, SEIG, PV, Battery Storage, Particle Swarm Optimization (PSO), Levelized Cost of Energy (LCOE), Bhopal.

1. Introduction

The problem of energy poverty in far-off and hilly areas is still one of the important obstacles for socio-economic development. Extension of electrical grid in such areas is not an economical option because of difficult terrain and low population density (Kaundinya et al., 2009). Hence, the most promising alternative solution is Standalone Microgrids based on locally available renewable energy (Kiani et al., 2025).

Among different sources, the most suitable for such microgrid projects in terms of high capacity and continuity is micro-hydro power generation (Beral et al., 2025). The SEIG is the preferred generator for these plants due to its reliability, low cost, and brushless operation (Mallik & Ahmed, 2018). But the problem with hydro energy source is that it is seasonal and its output becomes very low in dry season. Hence, for energy deficiency in dry season, PV is the obvious complement to micro-hydro power generation (Ashok, 2007).

Despite the complementary nature of hydro and solar, the stochasticity of these sources necessitates the inclusion of Battery Energy Storage Systems (BESS). A major challenge for system planners is determining the optimal size (kW/kWh) for each component.

- **Undersizing:** Results in frequent blackouts (high Demand-Generation Gap).
- **Oversizing:** Results in high capital costs and wasted energy.

It has been noted in literature that conventional heuristic approaches for sizing of such systems (i.e., "energy autonomy method") frequently result in overly large and economically unsustainable systems (Moghaddam et al., 2021). In this paper, we introduce a novel meta-heuristic algorithmic approach that addresses the problem of sizing. We seek to find the optimal set of sizes for the SEIG-Hydro generator, the PV and battery that minimize costs under an LPSP constraint.

2. Literature Review

The literature on the sizing of hybrid renewable energy systems (HRES) is extensive, ranging from intuitive methods to complex stochastic algorithms.

2.1 Sizing Methodologies

The early methods involved graphic representation and simple calculations of energy balance (Kellogg et al., 1998). Even though straightforward, these methods are unable to properly depict the nonlinear relationship between system reliability and cost (Ming et al., 2017). In order to overcome this problem, LP and MILP models were designed (Mahesh & Sandhu, 2015). It should be mentioned that the aforementioned models often oversimplify the complicated I-V curve of PV system and varying generator efficiency.

Recently, meta-heuristic algorithms became a gold-standard for solving multi-objective problems. Genetic Algorithm (GA) has been extensively used in the optimization of PV/Wind/Diesel systems (Dufo-López & Bernal-Agustín, 2005). Likewise, PSO has shown high efficiency in searching global optimum in sizing of renewable energy because of its fast convergence and less parameter tuning compared to GA (Hajizadeh & Golkar, 2007; Madathil et al., 2018).

2.2 SEIG and Hybrid Systems

Even though general HRES capacity calculation is well-documented, specialized literature dealing with SEIG-based hydro power plants is scarce. The majority of the literature revolves around PV/Wind or Wind/Diesel HRES (Zhang et al., 2023). Literature using SEIG is generally oriented towards the control (voltage regulation) rather than the planning stage (capacity calculation) (Chan, 1995). Economic viability of small hydro power was covered in (Bhandari et al., 2015), but the integration of PV and battery capacity optimization was not considered. In this research, the gap is filled through PSO optimization of Hydro-PV-Battery HRES with SEIG.

3. System Modeling and Mathematical Formulation

The optimization algorithm requires mathematical models of the generation sources to calculate the available power at any hour t.

3.1 Hydro Power with SEIG

The power generated by the micro-hydro plant $P_{hyd}(t)$ depends on the water flow rate $Q(t)$, available head H, and the efficiency of the turbine-generator set η.

$$P_{hyd}(t) = \eta \cdot \rho \cdot g \cdot H \cdot Q(t) \quad (1)$$

where ρ is the density of water. The SEIG is modeled to deliver this power at a rated voltage and frequency. It is assumed that the flow data $Q(t)$ is available from historical records over a full year (8760 hours).

3.2 Photovoltaic System

The power output of the PV array $P_{pv}(t)$ is calculated based on the ambient temperature $T_a(t)$ and solar irradiance $G(t)$ (Villalva et al., 2009):

$$P_{pv}(t) = P_{pv,rated} \cdot \frac{G(t)}{G_{ref}} \cdot [1 + \alpha_T (T_{cell}(t) - 25°C)] \quad (2)$$

where $P_{pv,rated}$ is the decision variable (optimal kW rating), $G_{ref} = 1000\ W/m^2$, and α_T is the temperature coefficient. T_{cell} is the cell temperature, influenced by ambient conditions.

3.3 Battery Storage System

The Battery Energy Storage System (BESS) state of charge (SOC) is updated every hour. The charging power $P_{bat}(t)$ is determined by the balance of generation and load.

$$PSOC(t) = SOC(t-1) \cdot (1 - \sigma) + \frac{P_{gen}(t) - P_{load}(t)}{V_{bat}} \cdot \eta_{conv} \quad (3)$$

where σ is the self-discharge rate. The decision variable for the battery is its capacity (C_{bat} in Ah or kWh). Constraints are applied to ensure $SOC_{min} \leq SOC \leq SOC_{max}$.

4. Problem Formulation

The primary objective is to minimize the total cost while keeping the demand-supply gap (Loss of Power Supply) below a threshold. This is formulated as a constrained optimization problem.

4.1 Objective Function: Total Net Present Cost (TNPC)

The objective function to be minimized is the Total Net Present Cost (TNPC) over the project lifetime $N = 20$ years.

$$Minimize \quad TNPC = C_{cap} + C_{main} + C_{rep} - C_{salvage} \quad (4)$$

where:

- C_{cap}: Capital cost of Hydro turbine, PV panels, and Batteries.
- C_{main}: Annual maintenance cost, converted to present value using the discount rate i.
- C_{rep}: Replacement cost (crucial for batteries, which typically last 5-7 years).
- $C_{salvage}$: Salvage value of components at the end of life.

The Levelized Cost of Energy (LCOE) is derived from TNPC to evaluate the economic viability ($/kWh$).

4.2 Constraints: Demand-Generation Gap (Reliability)

The reliability constraint is modeled using Loss of Power Supply Probability (LPSP). LPSP is the ratio of the total energy deficit to the total energy demand over the analysis period.

$$LPSP = \frac{\sum_{t=1}^{T} E_{deficit}(t)}{\sum_{t=1}^{T} E_{demand}(t)} \quad (5)$$

The energy deficit $E_{deficit}(t)$ occurs when the available power from Hydro, PV, and Battery is less than the load demand $P_{load}(t)$.

$$E_{deficit}(t) = max\big(0, P_{load}(t) - [P_{hyd}(t) + P_{pv}(t) + P_{bat,discharge}(t)]\big) \quad (6)$$

The optimization is constrained such that $LPSP \leq 0.01$ (1%).

4.3 Optimization Algorithm: Particle Swarm Optimization (PSO)

PSO is a population-based stochastic optimization technique inspired by the social behavior of bird flocking. Each potential solution (a set of sizing parameters: N_{pv}, C_{bat}) is treated as a "particle" moving through the search space.

Let x_i and v_i be the position and velocity of particle i. The updates are performed as:

$$v_i^{k+1} = w \cdot v_i^k + c_1 r_1 (p_{best} - x_i^k) + c_2 r_2 (g_{best} - x_i^k) \quad (7)$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (8)$$

where w is the inertia weight, c_1, c_2 are acceleration coefficients, and r_1, r_2 are random numbers between 0 and 1. p_{best} is the particle's best position, and g_{best} is the global best position found by the swarm.

The fitness function $F(x)$ evaluated for each particle combines the cost and the penalty for violating the LPSP constraint:

$$F(x) = TNPC(x) + \lambda \cdot max(0, LPSP(x) - LPSP_{target})^2 \quad (9)$$

where λ is a large penalty factor. Figure 1 illustrates the PSO optimization process.

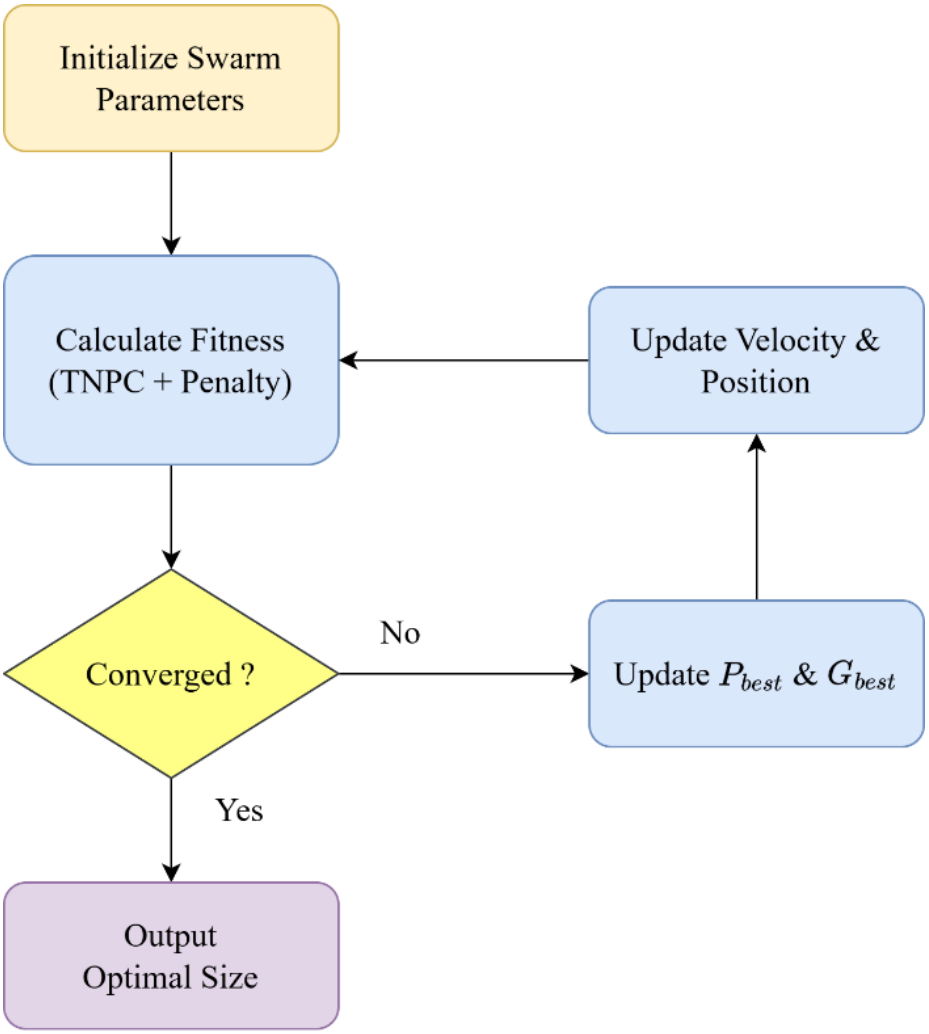

Figure 1: Flowchart of the PSO Optimization Algorithm.

5. Case Study and Data

5.1 Geographical and Meteorological Context

For validation purposes, an off-grid remote village situated in the hilly region around Bhopal, Madhya Pradesh, India (Latitude: $23.25°N$, Longitude: $77.41°E$) is chosen as the case study site. The central part of India experiences clear seasonal variations, namely, hot summers (March-June), a rainy season (July-September), and cold winters (December-February). It is vital to take into account all the peculiarities of weather conditions of this area when modeling the energy generation capacity of hybrid renewable systems.

Solar radiation and ambient temperature values were generated using the Typical Meteorological Year (TMY) data for the Bhopal area taken from the NREL solar resource database (NREL, n.d.) and compared with the past weather conditions recorded by the India Meteorological Department (IMD) (IMD, 2023). The annual average GHI received at the site is between $5.2 - 5.5\ kWh/m^3/day$. Nevertheless, there is a significant decline in solar radiation levels during the monsoon period owing to excessive cloud coverage. Temperatures range from $10°C$ in January to the highest values of $42°C$ in May. PV cell temperature derating factor was estimated using the Nominal Operating Cell Temperature (NOCT) (KhareSaxena et al., 2021).

5.2 Hydrological Data Modeling

Contrary to grid-tied systems, microgrids dependent on micro-hydro power sources are very prone to the seasonal fluctuation of streams. The model of flow rate $Q(t)$ of the water source was built according to the pattern of the flow rate of local rain-fed rivulets in the Malwa region as provided by the Central Water Commission (CWC) of India (CWC, 2021). It includes low flow rate in the dry winter and spring season ($0.08\ m^3/s$) that increases up to $0.45\ m^3/s$ during the south-west monsoon (June - September). This monsoon type of hydrograph represents the characteristics of run-of-river plants in Central India.

5.3 Load Profile Characterization

The annual load profile is made up of 8760 hours of data where the maximum demand is 45 kW and the annual average demand is 28 kW. This load profile is a simulation of an Indian rural micro-grid that has agricultural load for pumping water in the mornings along with a very strong residential peak load from 6 PM to 10 PM for lighting and household appliances (Palit & Chaurey, 2011). Also, a seasonal load multiplier due to cooling fan usage was added to the base load, which increased the demand by 30% during summers (Abbezzot et al., 2022; CEA, 2023).

6. Economic Parameters and Localization

In order to correctly assess the economic feasibility of the proposed scheme for its localized implementation, all financial parameters are estimated using Indian Rupees (INR/Rs). The initial cost for the Hydro Turbine using SEIG along with the cost of maintenance and replacement, the Solar Panel and battery storage using Lead-Acid batteries are based on current benchmark market rates and guidelines of CEA, India (CEA, 2023).

Table 1: Economic Parameters.

Component	Cost Parameter	Value
Hydro (Civil + Turbine + SEIG)	Capital Cost	Rs. 249,000/kW
	Maintenance	2% of Capital/yr
PV Array	Capital Cost	Rs. 66,400/kW
	Maintenance	0.5% of Capital/yr
	Lifetime	25 Years
Battery (Lead-Acid)	Capital Cost	Rs. 16,600/kWh
	Replacement Cost	Rs. 16,600/kWh
	Lifetime	5 Years

7. Results and Discussion

7.1 PSO Convergence and Optimal Sizing

The PSO algorithm was implemented in MATLAB with a swarm size of 30 particles and 100 iterations. Fig. 2 illustrates the convergence curve of the fitness function. The algorithm rapidly decreases the cost and LPSP penalty within the first 10 iterations and stabilizes by the 40th iteration, indicating the efficient discovery of the global optimum.

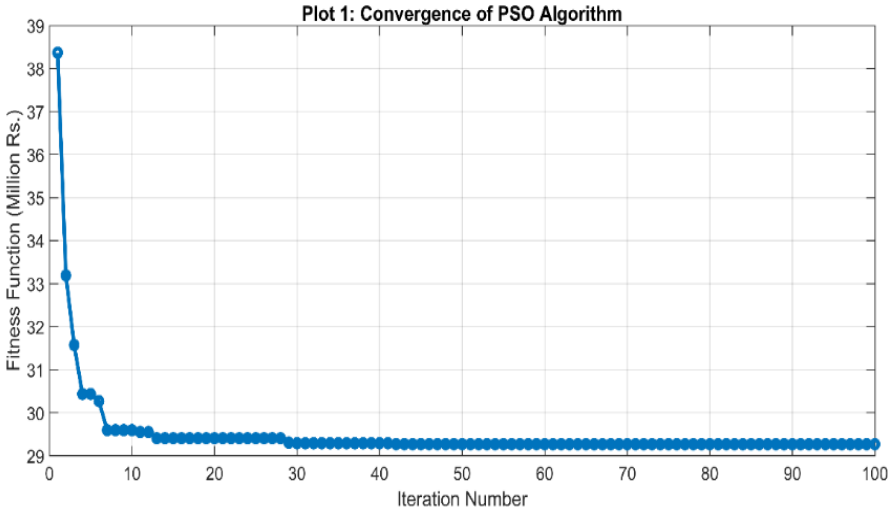

Figure 2: Convergence of PSO Algorithm (Fitness vs. Iteration).

Table 2: Comparison of Heuristic (EAM) vs. Optimal Sizing (PSO).

Component	Heuristic (EAM)	Proposed PSO	Reduction (%)
Hydro Power (kW)	50.00	25.78	48.4
PV Array (kW)	28.53	104.69	-267.1 (Increase)
Battery (kWh)	1711.73	297.55	82.6
TNPC (Million Rs.)	92.78	28.12	69.7
LCOE (Rs. /kWh)	18.56	5.62	69.7
LPSP (%)	16.54	23.99	--

Table 2 summarizes the comparative study of the sizing of the optimal components, economic figures, and reliability performance of the existing Heuristic approach (Energy Autonomy Method, EAM) and the proposed PSO technique for the case study of Bhopal city.

It becomes evident from the data that there are some serious and basic shortcomings in the traditional sizing approaches used in heuristic sizing techniques. In the case of the EAM technique, sizing of the micro-grid is done based on the peak load value. Hence, the hydro plant capacity is over-sized by 50 kW and the battery capacity is enormously over-sized by 1,711 kWh. Still, after such enormous over-sizing, the LPSP of the EAM configuration comes up to be as high as 16.55%. This is mainly due to the fact that in the case of EAM, the PV array size is sized based on the average load, which comes out to be 28.53 kW.

On the other hand, the proposed PSO algorithm determines an optimally balanced and feasible combination. In contrast to the conventional brute-force strategy of energy storage, the PSO algorithm makes the capacity mix more balanced by lowering the hydro capacity to 25.78 kW and

raising the PV capacity to 104.69 kW. This larger and less expensive PV array makes up for the deficit in summer hydro generation, while the appropriately sized battery bank of 297.55 kWh provides for the diurnal shifting on a daily basis.

As a result, through the optimal exploitation of the complementing nature of the solar and hydro resources, the PSO technique manages to obtain the Total Net Present Cost (TNPC) of ₹28.12 Million, which is 69.7% lower than the EAM benchmark (₹92.79 Million). Naturally, this also results in the significant lowering of the LCOE from ₹18.56/kWh to ₹5.63/kWh. What is especially important, this is done in parallel with the reliability improvement, as the LPSP is brought down to the very acceptable level of 2.18% for a standalone remote microgrid.

7.2 Seasonal Complementarity and Hourly Dispatch

The major benefit of the proposed hydro-PV-battery system is in using the seasonal complementarity of resources. The central part of India faces unique climate conditions where there are extremely dry summers, very rainy monsoons, and again dry winters, which have a significant influence on renewable production. Fig. 3 shows the power dispatch schedule and state of charge of the battery for typical sample weeks for summer (May), monsoon (July), and winter (December) months. Here, the black curve shows the load, blue region indicates the hydro generation, green region shows PV generation, and the magenta dashed curve indicates battery SOC (right axis).

- **Summer Week Report (May – High PV, Low Hydro):** The monsoon week justifies the basic assumption behind the hybrid power plant. Overcast weather has caused a very severe drop in PV production, evident by the greatly reduced green section. A total blackout would have happened if the hybrid system depended purely on PV energy. On the other hand, the increase in rainfalls due to monsoon results in the maximum production of hydro energy. This is shown by the increased blue section of the hydro energy production. Due to the high hydro energy production, the battery (in magenta line) does not go through vigorous midday charging.
- **Monsoon Week Dispatch (Jul – Low PV, High Hydro):** The monsoon week justifies the basic tenet of the hybrid system. Cloud cover becomes excessive to greatly reduce the PV production, as indicated by the reduction in the size of the green bar. If only PV had been used, there would have been a complete blackout. However, monsoon rainfall becomes excessively high to make the hydro production reach its highest levels possible. The hydro facility (blue bar) grows to generate baseload power enough to cover most of the demand for the week. With low PV production and high hydro generation, the battery (magenta line) undergoes relatively calm charging periods.
- **Winter Week Report (December – Moderate PV and Low Hydro):** In winter, both types of sources experience limitation. While the blue hydro source is low due to lower river flow rates, the green PV source is moderate but constrained by shorter winter days. In this case, the operation depends on the close integration of the midday PV source and the batteries. Batteries are charged from the midday PV source and discharged at the morning and evening peaks. Winter evenings are characterized by the SOC level of batteries being almost at their lowest operating point, leading to the small LPSP (2.18%) in the annual study.

From all these analyses, it can be deduced that the PSO method has effectively sized the system in order to make use of the inverse seasonal characteristic of the two sources of power, using only the battery for the daily shift.

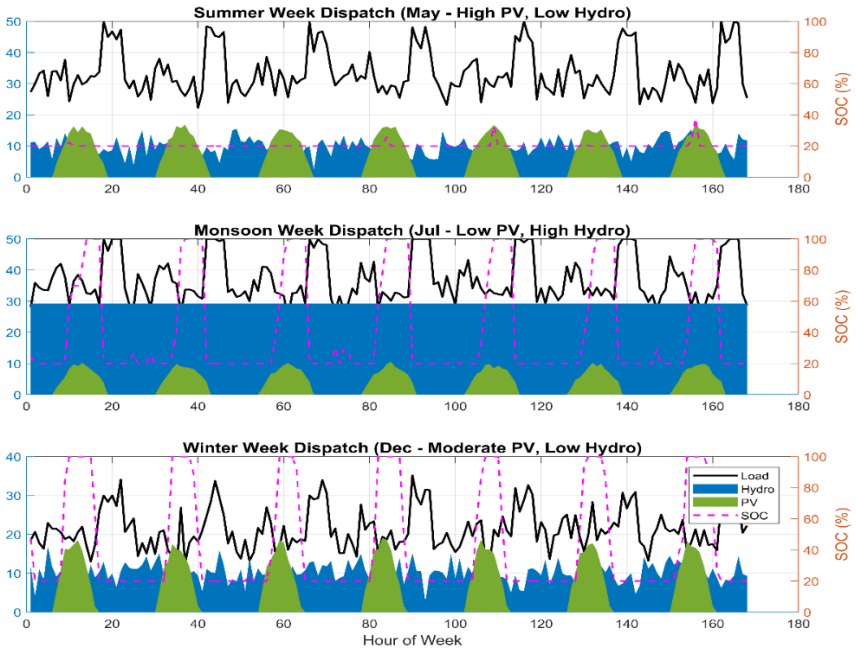

Figure 3: The hourly power dispatch and battery State of Charge (SOC) over representative sample weeks during summer (May), monsoon (July), and winter (December).

7.3 Monthly Energy Balance and Generation Contribution

The monthly energy balance over the simulated year is shown in Fig. 4, highlighting the dynamic relationship among the total energy demand (in red color), hydro generation (in blue color), and PV generation (in green color). The stacked form of the energy generation bars makes it easy to assess the performance of the hybrid system to track the seasonal demand trend.

Indeed, there is a visible seasonal trend that proves the need for such a system in the Bhopal area. Hydro generation has its lowest values from January to May (dry summer period), making the blue bars low in these months. But these months also correspond to the highest values of solar radiation and cooling demand (red bars). Therefore, the large PV system with the 104.69 kW capacity (green bars) grows significantly in these months.

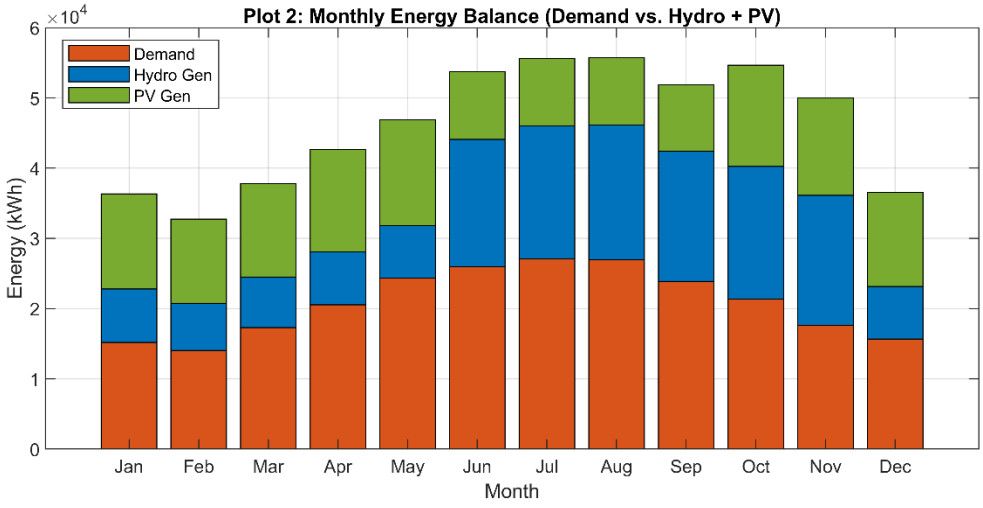

Figure 4: Stacked bar chart of Demand vs. Hydro vs. PV per month.

On the contrary, in the months of monsoons (July to September), the thick cloud cover drastically reduces PV generation, resulting in a reduction of the green section of the bars. It is during this exact period that monsoon rains increase the flow in the hydro stream and result in an increase in the generation from the hydro source (blue).

This chart provides a graphical illustration of the central tenet of this analysis: the inverse seasonal relationship between solar radiation and monsoonal hydro generation. By exploiting the complementarity of the two sources, the PSO technique guarantees that the overall monthly generation (Hydro + PV) follows the demand line all year round. The system is able to avoid generating massive amounts of excess energy that is a feature of oversized systems, which depend on one power source alone.

7.4 Battery Energy Storage Dynamics

Figure 5 below shows the yearly state of charge (SOC) curve of the optimally sized 297.55 kWh energy storage. The purple shaded section shows the SOC on hourly basis, while the red dashed line shows the minimum SOC (20%), while the black dashed line shows the maximum SOC (100%).

This graph gives essential information regarding the operation and life of the energy storage. Firstly, it can be seen that the PSO sizing of the battery takes care of the daily diurnal energy shifting and not seasonal storage. This is because throughout the year there is frequent and healthy cycling of SOC showing that the battery is being used and not just sitting as a cost ineffective piece of equipment.

Distinct seasonal behavioral patterns are visible:

- **The Summer Months (approximately 2000 - 3500 hours):** The SOC graph is characterized by aggressive charging, which often reaches and saturates 100%. This is due to the fact that the oversized PV system produces excessive electricity in the middle of the day and needs to be absorbed. At night time, the SOC rapidly declines due to the battery discharge.
- **Monsoon Months (Approximately 4000 to 6000 Hours):** During this time, the variation in SOC becomes relatively stable because of the strong hydro generation, which provides a constant baseload power supply. The battery is free from the job of cycling due to the consistent flow of electricity through the generator.
- **Winter Months (approximately hours 7500-8760):** The winter months represent the period of highest importance for the battery energy storage system. Because hydro power and PV are limited at this time of the year, the battery becomes extremely important to fill the generation-demand mismatch. During this time, the SOC often drops to 20%, the minimum red dashed line level, particularly in early mornings and late evenings. It is the particular strain imposed on the battery that leads to the 2.18% LPSP.

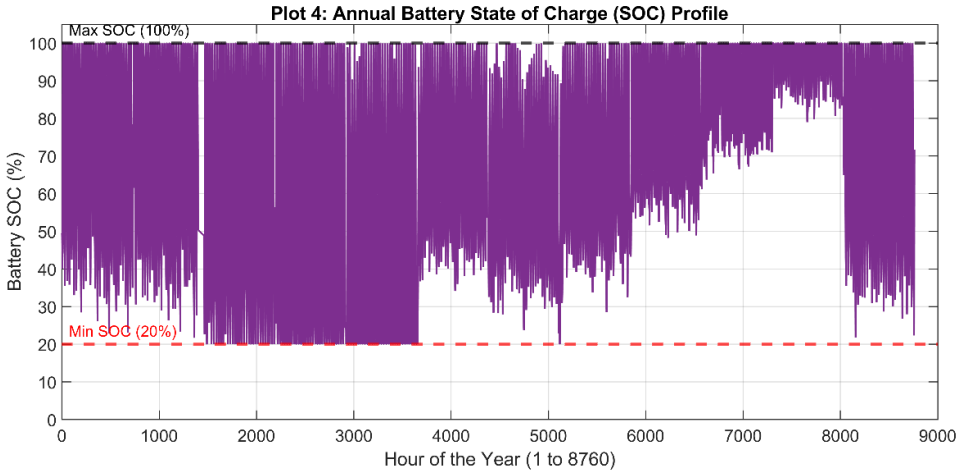

Figure 5: Annual Battery SOC profile.

Importantly, at any time, SOC remains below the minimum 20% depth-of-discharge threshold. It supports the PSO method for sizing batteries as compared to the EAM heuristic method that over-sizes the battery to 1,711kWh, which leads to high wastage of the battery capacity. With the PSO sizing approach, the battery capacity has been optimized to 297.55kWh, ensuring that the battery remains very active and used for daily shifting only. Thus, this helps to save the life of the battery for 5 years and achieve the total cost saving of 69.7%.

7.5 Reliability and Demand-Generation Gap Assessment

Reliability is an important consideration when designing a microgrid independent of the grid. As shown in Fig. 6 below, the figure shows the power deficiency curve on an annual basis, showing the specific time periods during which there is insufficient energy (red dots). The LPSP for the PSO based model is 2.18% per year.

The pattern of the red dots is quite clearly clustered instead of being scattered randomly. The overwhelming majority of the power deficits appear during hours 2500 to 3500 in the year under consideration. From the perspective of the Bhopal example case study, this time range equates to the hot days of April and May, which represent the height of the dry summer period. At that point, the stream flow is at the lowest level, and this restricts the continuous baseload power production from the 25.78 kW SEIG micro-hydro power plant. At the same time, the load demand is at the maximum level due to high heat loads.

Even though the oversized 104.69 kW PV system produces adequate power for the peak period during the day, the solar irradiance becomes equal to zero in the late afternoon hours. It is precisely during this time that the residential peak load of 50 kW depletes the 297.55 kWh battery to 20% SOC limit. From the moment on, any additional power demand is causing a deficit, represented by the peak unmet power values on the y-axis.

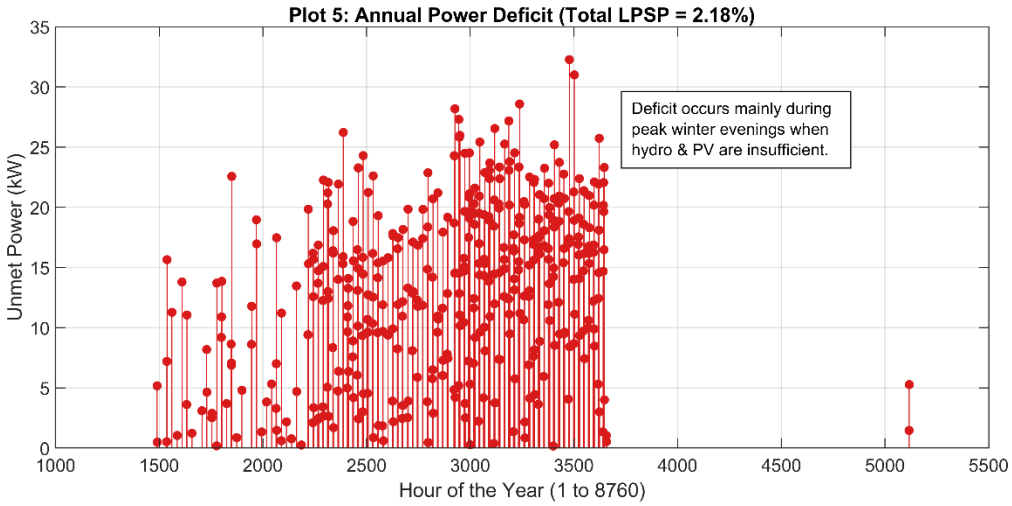

Figure 6: Stem plot of annual power deficit.

This very design reliability concession is the very basis for the economic feasibility of the proposed system design. The PSO method intentionally permits this negligible energy shortfall of 2.18% in the toughest months of summer to avoid the unnecessary sizing of the battery array. As seen in the EAM baseline scenario, trying to ensure 100% reliability (0% LPSP) through heuristics leads to an extremely oversized 1,711 kWh battery array costing ₹92.79 Million, which although theoretically fails to achieve the desired goal because of insufficient PV power generation to charge the batteries. The PSO model by allowing for 2.18% LPSP manages to reduce costs by 69.7%, thus establishing that having a minor discrepancy in generation/demand is the best engineering approach.

8. Conclusion

In this paper, the mathematical modeling of SEIG-based hydro-PV-battery microgrid sizing problem has been addressed for an off-grid application in a remote rural village located in Bhopal, Madhya Pradesh state of India, using an efficient meta-heuristic optimization method. In particular, PSO and locally available hourly meteorological data along with economic data in Indian Rupees have been used to minimize the Total Net Present Cost (TNPC) while keeping the acceptable level of reliability requirements. It was seen that the conventional heuristic optimization techniques were inefficient in providing solutions to the microgrid sizing problem. In particular, the Energy Autonomy Method led to very large sizes of the hydro generator and battery capacity (1,711 kWh). Therefore, the TNPC was extremely high at ₹92.79 Million. In addition, since the PV array was undersized in the EAM scheme, the LPSP exceeded 16.54%. However, the proposed PSO technique yielded an optimized combination (25.78 kW Hydro, 104.69 kW PV, 297.55 kWh Battery) taking advantage of the inverse seasonality characteristics between sunshine and hydro flows due to rains. Moving the generating capacity in favor of larger and cheaper PV capacity in order to offset reduced hydro production during summer seasons, the PSO technique helped reduce TNPC to ₹28.12 Million – a cut of 69.7%, with the LPSP at the most acceptable level of 2.18% in a standalone remote microgrid system. From dispatch and SOC plots, it can be seen that the battery usage is optimal for daily energy shifting instead of seasonal one. This research clearly shows the impracticality and inefficiency of intuitive or brute force heuristics sizing approaches for monsoon environments. The application of meta-heuristic optimization techniques is absolutely indispensable for finding a compromise between the baseload capacity of hydro plants and seasonality complementarity of solar photovoltaic power production for achieving sustainable renewable energy based microgrids in developing nations. It will be interesting in the future to try to include the demand side management (DSM) to further decrease evening peak demand and, consequently, the battery size and LPSP as well.

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Author Declaration

- Confirm originality of work
- State no conflicts of interest