

# Optimized Hybrid Energy Design for Load Management in Solar-Based Electric Vehicle Charging Stations in Rural Area

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**ABSTRACT-** Among various energy-consuming sectors, transportation accounts for a significant contribution to global consumption, most of which is powered by conventional fossil-based sources. The growing urgency to address climate change, along with favorable international policies and technological advancements, has accelerated the transition to electric vehicles (EVs). However, this shift introduces new challenges, including the sustainable generation of electricity, managing increased loads on existing grids, and developing efficient EV charging infrastructure. In this paper, the design and optimization of a grid-integrated solar-lithium battery hybrid EV charging station tailored for rural areas. HOMER Grid and Pro software are used to design the proposed hybrid system, which comprises a 600 kW solar array, 5 lithium-ion batteries, a 25 kW inverter, and a 76.2 kW bidirectional converter. The renewable fraction of the proposed system reached 100%, with an annual generation of 105319 kWh. This leads to a levelized cost of energy of \$0.353/kWh, a net present cost of \$462,686, and zero reliance on fossil fuels, which is suitable for both economic and environmental reasons.

**Keywords:** EV charging station, Solar PV, battery storage, hybrid system, HOMER Grid, techno-economic analysis.

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## 1. INTRODUCTION

Agricultural land-use and farming practices significantly alter the landscape carbon stocks. Grassland and cropland have lower carbon levels than forest land. Therefore, farmers are encouraged to create more forest patches with diverse tree species to enhance ecological functions and improve livelihoods across the landscape [1]. There was a conflict between renewable energy source and society that offshore wind farms and the sociotechnical impact in three ways: fisheries damage, sufficient information, and the siting process [2]. To mitigate load and renewable uncertainties in the US market, a ramping product using a k-nearest-neighbor-based method to predict weather conditions was introduced [3]. To meet the energy demand of German households on the rooftop using solar photovoltaic and a storage battery. The study investigates the impact of battery diffusion on the electricity market, which is used for residential storage [4]. A 4-kW hybrid grid-connected system to charge the electric vehicle supply without any interruption. This paper focuses on encouraging the use of electric vehicles and independence from the IC engine [5]. The integration of solar PV at electric

vehicle charging stations and on electric vehicles is examined to assess the benefits, challenges, and environmental impacts. It also highlights the potential for solar PV integration into electric vehicle charging stations [6]. A theory of planned behavior and a structural equation model were reported for the analysis of customers' electricity price use. The pattern includes the distribution tariff, questionnaire data, and the customer's meter energy usage [7]. Hence, to implement the system using an algorithm to meet energy demand, a backward/forward sweep approach is used to estimate long-term load demand. A modified unbalanced load-flow algorithm is reported to reduce real power losses in the IEEE 25-bus RDS. The incorporation of weather conditions is also reported to reduce losses and enhance the voltage profile at each node on the IEEE 25 and 19 RDS buses. An advanced load flow for the unbalanced RDS is reported to estimate the line flows [8, 9]. As the load demand is uncertain, it also increases over time. Therefore, the researchers focused on integrating renewable energy sources either at the load centers or by connecting them to the existing system. The integration of renewable energy sources to address economic and environmental issues in the reported hybrid system. The hybrid system comprises a wind turbine, storage, solar PV, and biomass [10]. The electrification of Khadva village in Gujarat, India's Kutch District, is simulated using HOMER Pro. The following parameters were utilized: total net present cost, levelized cost of energy, capital and operating expenditures, renewable fraction, and grid dependency [11]. A modified filter-generalized integrator-based control approach is used to reduce harmonics generated by the charging station. The system reported the combination of solar and wind-powered self-excited induction generator with battery storage to meet the small consumer load [12]. To meet demand in

remote areas, the reported hybrid system comprises wind, solar, battery storage, and a grid-connected mode. Due to this, significant savings in energy costs as well as a reduction in environmental pollutants [13]. A single-phase 5 kW grid-connected PV system was reported to operate effectively with the nonlinear loading. To provide dynamic load control and power quality, a second-order generalized integrator with a frequency-logged loop method is used [14]. Several investigations were conducted to address the potential challenges and assess the effects of integrating renewable sources into the distribution system. The investigations were examined for the on-grid power system that faces the challenges as well as the general performance matrix with compatibility issues [15]. An adaptive transfer-delay-based phase-locked loop algorithm for the PV panel to meet the nonlinear load is reported using MATLAB [16] to determine the nonlinear load's current component. An electric vehicle (EV) charging station combined with a single-phase grid-linked photovoltaic (PV) system is controlled by a unique modified complex coefficient filter-based phase-locked loop (MCCF-PLL) control method. This system was designed for residential use to promote grid stability, facilitate effective bidirectional power transfer, and boost the use of renewable energy. Bidirectional inverters function as both grid-interfacing converters and EV chargers [17]. By incorporating renewable energy sources—such as a 100-kW wind turbine, a 55-kW solar PV system, a 500-kW bidirectional converter, and a 100-kg hydrogen tank—into the current grid, the objective is to reduce costs and emissions [18]. Recently, the integration of renewable sources into the grid has been concentrated primarily in the country's metropolitan areas. In this paper, an optimized hybrid system model is proposed to minimize the demand-supply mismatch and enhance reliability. The proposed EV charging station system is implemented in the Indian rural context.

## 2. HOMER SOFTWARE FOR HYBRID SYSTEM DESIGN

The Hybrid Optimization of Multiple Energy Resources (HOMER) software was developed by the National Renewable Energy Laboratory (NREL), a branch of the United States Department of Energy, to assist in the optimization and design of hybrid energy systems [19]. Total land area or roof space is also available for infrastructure installation. One of the factors in designing the system is the number of electric vehicles to be charged per hour, which determines the energy requirement and system capacity. Charging requirements vary depending on the vehicle type and its battery size. Moreover, the proposed system would provide an ample open space for installation with minimal shading, as shown in *fig. 1*. This would ensure the feasibility and efficiency of a solar-powered EV charging system.

### 2.1. Energy Management System

The steps for the management of the energy approach are as follows:

- Select the input data for the solar radiation, battery capacity, and load profile.

- Estimate the solar PV power output and check whether the demand is met by the solar PV or not. If yes, meet it out; otherwise, check the battery's surplus power. If available, meet with both solar PV and battery. Even though the power demand is insufficient, it will be met by the Grid.
- The power generated by the solar PV is more than the load demand. The power is stored in the battery if storage capacity is available, otherwise it is sold back to the Grid.
- Check the equality and inequality constraints. If not, satisfy this by providing the necessary requirements for an alternative source of equality and replacing the minimum and maximum values that violate the condition.
- Check the convergence criterion against the maximum number of iterations. If not achieved, return to *step 2*, otherwise, end the process.



**Figure 1.** Location of the proposed EV charging site in Rohtak, Haryana, India (28°54.2'N, 76°37.1'E)

### 2.2. System Components

For detailed simulation and optimization, suitable system components were chosen based on design assumptions and the selected installation site. A solar-based hybrid configuration is adopted in the proposed setup, comprising photovoltaic (PV) modules, battery energy storage, and grid interconnection. Several commercially available PV panel options were evaluated to improve system efficiency and performance. The selection process considered parameters such as rated power output, efficiency, and economic viability under the site's local solar conditions.

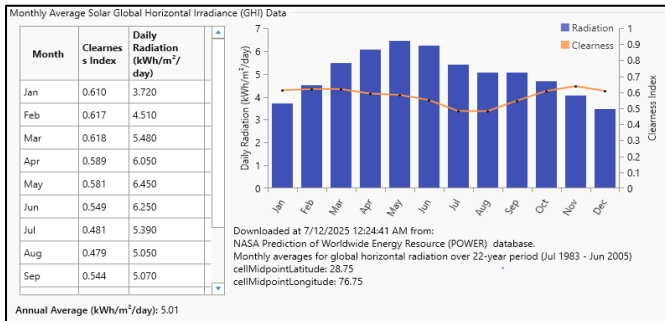
#### 2.2.1. Solar PV

The technical characteristics of the selected PV modules are presented in *table 1* and are used as inputs for the analysis.

**Table 1. Technical specifications of selected photovoltaic panel models [19]**

| PV Module Model           | Efficiency (%) | Panel Area (m <sup>2</sup> ) |
|---------------------------|----------------|------------------------------|
| Sunlife Solar SLS210M     | 19.6           | 1.277                        |
| Changzhou GS235 (235 W)   | 14.6           | 1.613                        |
| Galaxy Energy GC240P-60   | 14.78          | 1.624                        |
| Luxor Solar LX-250P       | 15.38          | 1.627                        |
| Triple Z S260 P60 (260 W) | 15.8           | 1.643                        |
| Resun Solar RS6C 270P     | 16.6           | 1.627                        |
| Einnova ESM280 (280 W)    | 17.1           | 1.627                        |
| BY Solar FSP 290 (290 W)  | 14.6           | 1.940                        |
| Shanghai JST300M(300 W)   | 15.46          | 1.940                        |
| AXITEC Energy AC310       | 15.98          | 1.940                        |
| AE Solar M6-72 (320 W)    | 16.49          | 1.940                        |

The findings from this solar resource assessment provide a critical input for the modeling and optimization of the hybrid energy system, helping to ensure a reliable energy supply while reducing reliance on the grid and overall operating costs.



**Figure 2.** Monthly average GHI and clearness index at the selected site (28°54.2'N, 76°37.1'E)

To estimate the energy output of the hybrid system, the analysis begins with calculating the overall efficiency of the solar energy conversion process. The value is obtained from the rated efficiency of the selected photovoltaic (PV) modules as given in *equation (1)*. After determining the system efficiency, the monthly energy generated by each PV module is calculated using *equation (3)* and site-specific irradiance data. The total annual energy production at the site is then determined by aggregating the monthly energy outputs, as represented in *equation (4)*. The efficiency values of auxiliary system components are presented in *table 2*, and the results of the solar power generation calculations are given in *table 3*.

$$\eta_{sys} = \eta_{pv} \cdot \eta_{inv} \cdot \eta_{cable} \cdot \eta_{aux} \cdot \eta_{batt} \quad (1)$$

$$G_{opt,m} = G_{opt,d} \cdot N_{days} \quad (2)$$

$$E_m = G_{opt,m} \cdot \eta_{sys} \cdot A_{pv} \quad (3)$$

$$E_{annual} = \sum_{m=1}^{12} E_m \quad (4)$$

**Table 2.** Efficiency (%) of system components

| Component         | Efficiency (%) |
|-------------------|----------------|
| Battery Storage   | 90             |
| Inverter          | 97             |
| Electrical Cables | 90             |
| Auxiliary Devices | 90             |

**Table 3.** Annual energy output of selected photovoltaic panels

| PV Module Model          | System Efficiency | Annual Energy Output (Wh/year) |
|--------------------------|-------------------|--------------------------------|
| Sunlife Solar SLS 210M   | 0.15              | 405750                         |
| Changzhou GS 235         | 0.11              | 381690                         |
| Galaxy Energy GC 240P-60 | 0.11              | 388910                         |

|                           |      |        |
|---------------------------|------|--------|
| Luxor Solar LX-250P       | 0.11 | 405520 |
| Triple Z S260 P60         | 0.12 | 420820 |
| Resun Solar RS6C 270P     | 0.12 | 437680 |
| Einnova ESM 280 (280 W)   | 0.13 | 450870 |
| BY Solar FSP 290 (290 W)  | 0.11 | 459120 |
| Shanghai JST 300M (300 W) | 0.11 | 486170 |
| AXITEC Energy AC 310      | 0.12 | 502520 |
| AE Solar M6-72 (320 W)    | 0.12 | 518560 |

Since photovoltaic (PV) modules vary in physical dimensions, it is important to estimate the maximum number of panels that can be installed on the available rooftop area. The spacing required between panels to minimize shading losses for efficient operation is also considered in this estimation. The detailed calculation procedure is presented along with the illustration through *equations (5) to eq. (14)*. These calculations help ensure the effective use of the available installation area and accurate panel placement.

$$\sin h = \cos \delta \cdot \cos \phi \cdot \cos \omega + \sin \delta \cdot \sin \phi \quad (5)$$

$$W_z = 90^\circ - h \quad (6)$$

$$\cos \omega_{ew} = \frac{\tan \delta}{\tan \phi} \quad (7)$$

$$C_1 = \begin{cases} 1, & \text{if } |\omega| < \omega_{ew} \\ x, & \text{if } \omega > \omega_{ew} \end{cases} \quad (8)$$

$$C_2 = \begin{cases} 1, & \text{if } (\phi - \delta) \geq 0 \\ 0, & \text{if } (\phi - \delta) < 0 \end{cases} \quad (9)$$

$$C_3 = \begin{cases} 1, & \text{if } \omega \geq 0 \\ 0, & \text{if } \omega < 0 \end{cases} \quad (10)$$

$$\sin'_s = \frac{\sin \omega \cdot \cos \delta}{\sin \theta_z} \quad (11)$$

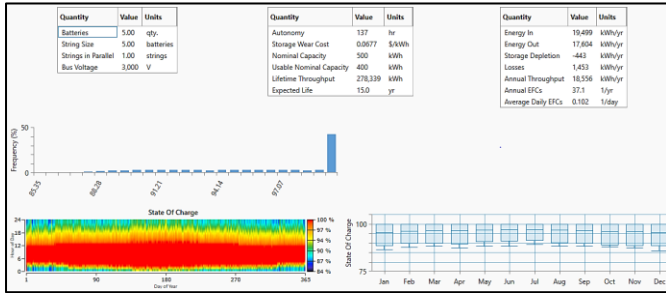
$$\sin'_s \gamma_s = C_1 C_2 \cdot \gamma'_s + C_3 \cdot \left( \frac{1 - C_1 C_2}{2} \right) \cdot 180^\circ \quad (12)$$

$$\tan c_{min} = \frac{\tan h}{\cos \gamma_s} \quad (13)$$

$$\beta \geq \frac{a \cdot \sin (C_{min} + \beta)}{\sin c_{min}} \quad (14)$$

### 2.2.2. Lithium-Ion Battery Model for Solar-Based EV Charging Stations

Due to the high energy density, fast charge/discharge capability, long cycle life and high round trip efficiency, lithium ion (Li-ion) batteries are commonly used as energy storage systems in solar-integrated electric vehicle (EV) charging system as given in *fig. 3*. These factors make them ideal for hybrid energy systems, where a steady and responsive balance is required between the fluctuating EV charging load demand and variable solar generation.



**Figure 3.** Annual Operational Analysis of Lithium-Ion Battery System

The lithium-ion batteries are designed to calculate the energy storage behavior under the condition of excess power generation as well as during energy deficit conditions. The system is designed to reduce reliance on the grid while improving the overall system efficiency.

#### State of Charge (SOC) Dynamics

The battery's state of charge at any time step is influenced by the net energy charged and discharged, and is computed as:

$$SOC_t = SOC_{t-1} + \frac{\eta_{ch} \cdot E_{ch} - \frac{E_{dis}}{\eta_{dis}}}{E_{bat,max}} \quad (15)$$

#### Charging Energy

The energy charged into the battery is limited by PV surplus and available storage capacity:

$$E_{ch} = \min(P_{pv,excess} \cdot \Delta t \cdot \eta_{ch}, (1 - SOC_{t-1}) \cdot E_{bat,max}) \quad (16)$$

#### Discharging Energy

The discharge energy is constrained by the deficit and remaining SOC:

$$E_{dis} = \min\left(\frac{P_{deficit} \cdot \Delta t}{\eta_{dis}}, SOC_{t-1} \cdot E_{bat,max}\right) \quad (17)$$

#### Battery Power Flow

The instantaneous battery power output is determined as:

$$P_{bat}(t) = \begin{cases} \frac{E_{dis}}{\Delta t}, & \text{if discharging} \\ -\frac{E_{ch}}{\Delta t}, & \text{if charging} \end{cases} \quad (18)$$

#### SOC Operational Boundaries

To ensure safe and efficient operation, the battery SOC is maintained within a recommended range:

$$SOC_{min} \leq SOC_t \leq SOC_{max} \quad (19)$$

#### Depth of Discharge (DOD)

$$DOD = 1 - SOC_{min} \quad (20)$$

This model enables simulation of dynamic battery performance in HOMER Grid, supporting system optimization based on life cycle cost, energy balance, and autonomy ratio. Lithium-ion storage ensures that the charging station can reliably operate under varying solar conditions and load demand, with minimal reliance on the grid.

### 3. GRID UTILITY INTEGRATION IN HOMER GRID

HOMER Grid is a simulation and optimization platform developed by the National Renewable Energy Laboratory (NREL) for analyzing grid-connected distributed energy systems. The aim is to techno-economically evaluate hybrid configurations inclusive of renewable energy generation, energy storage and grid interaction under variable load patterns, tariffs and policies. The grid serves both as backup energy source and a potential source to export excess power in the case of solar-powered electric vehicle (EV) charging stations. These interactions are analyzed by simulating multiple dispatch strategies, grid sellback policies, demand charges, time-of-use (TOU) pricing, and outage scenarios using HOMER Grid.

**Grid Power Balance Equation:** The net power exchange with the grid at any time  $t$  is defined as:

$$P_{grid}(t) = P_{load}(t) - P_{pv}(t) - P_{bat}(t) \quad (21)$$

**Grid Energy Cost Calculation:** The total cost of grid energy purchase over the simulation horizon is calculated as:

$$C_{grid} = \sum_{t=1}^T P_{grid}^+(t) \cdot C_{tariff}(t) \cdot \Delta t \quad (22)$$

**Grid Export Revenue:** If grid export is permitted, revenue earned from selling surplus energy is:

$$R_{export} = \sum_{t=1}^T P_{grid}^-(t) \cdot C_{sell}(t) \cdot \Delta t \quad (23)$$

**Demand Charge:** In addition to energy charges, utilities may apply demand charges based on peak usage:

$$C_{demand} = D_{peak} \cdot C_{demand,rate} \quad (24)$$

By simulating these parameters, HOMER Grid allows optimization of system architecture that minimizes total net present cost (NPC), ensures energy reliability, and reduces carbon emissions. Grid utility plays a crucial role in balancing variability of solar generation and EV charging demand, particularly during evening hours or high usage days.

### 4. METHODOLOGY

HOMER grid software was used to optimize the proposed solar-powered electric vehicle (EV) charging stations. Minimizing the total Net Present Cost (NPC) and reduction on grid dependency while simultaneously maintaining reliable energy supply were the primary objectives. It is well suited to analyze grid-connected hybrid system with integrated storage since it can simulate a huge number of configurations through a wide spectrum of technical and economic conditions [20, 21]. For optimization, the objective function used is defined as:

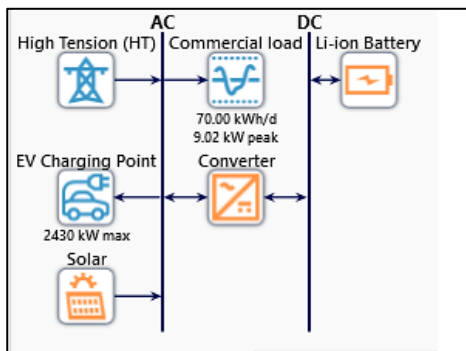
$$\min NPC = \sum_{t=1}^T \left( \frac{C_{rep} + C_{rep}(t) + C_{O\&M}(t) + C_{grid}(t)}{(1+r)^t} \right) \quad (25)$$

The optimization is subject to the following key constraints:

- Energy Balance at every timestep:  
 $P_{pv}(t) + P_{bat}^{dis}(t) + P_{grid}(t) \geq P_{load}(t)$  (26)
- Component capacity limits: PV sizing constrained by rooftop area.
- Battery storage and inverter size are optimized to avoid load curtailment and ensure efficient energy dispatch.
- Tariff sensitivity is examined by evaluating load shifting strategies under Time-of-Use (ToU) pricing schemes.

## 5. SYSTEM CONFIGURATION AND SIMULATION SETUP

This section outlines the system design approach and simulation parameters implemented using HOMER Grid to achieve the stated research objective: to develop an optimized solar-grid-battery configuration that reduces the demand-supply load imbalance for an electric vehicle (EV) charging station. The selected study site is Rohtak, Haryana, India, a semi-urban region with substantial solar potential and emerging electric mobility needs. The system is designed to satisfy a daily energy demand of 2500 kWh/day, representing a mid-scale EV charging station serving either a fleet or public charging infrastructure. The schematic layout of the proposed system is shown in fig. 4.

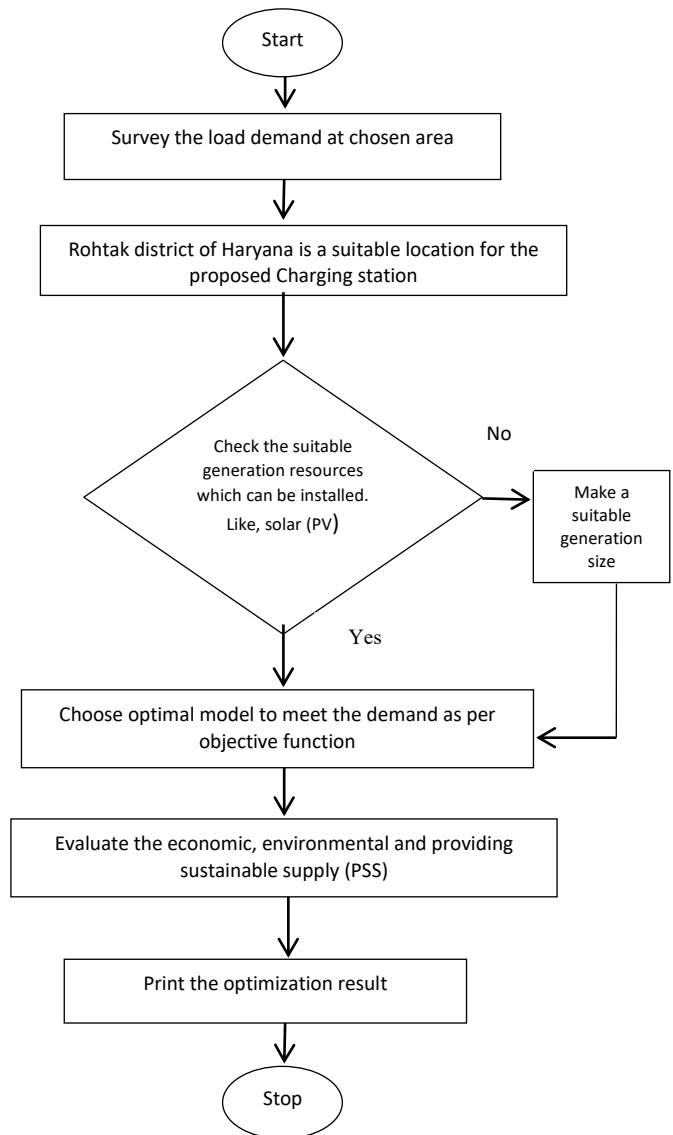


**Figure 4.** Schematic representation of a hybrid system

## 6. RESULT AND DISCUSSION

The optimal hybrid configuration for the proposed solar-powered EV charging station was identified through simulation performed in HOMER Grid software, based on a daily load demand of 2500 kWh at Rohtak, Haryana shown in fig. 7. Several system architectures were evaluated, and the configuration consisting of 600 kW photovoltaic (PV) array, 25 kW inverter, 5 lithium-ion battery units, and a 76.2 kW bidirectional converter connected to the utility grid was found to be most economically and technically viable solution. The optimized system achieves a renewable fraction of 100%, with no fuel consumption, demonstrating its complete reliance on

solar and battery storage. The total annual PV generation was estimated at 105,319 kWh, corresponding to an average daily output of 289 kWh/day, despite a relatively low-capacity factor of 2.00%. A substantial surplus energy generation relative to the direct load demand is reflected as a high PV penetration level was observed. However, around 826,839 kWh/year of energy was reduced due to limitations of inverter capacity, giving the importance of appropriate inverter sizing to better utilize generation of excess solar power. The flowchart for the proposed system is shown in fig. 5.



**Figure 5.** The flowchart for the proposed system

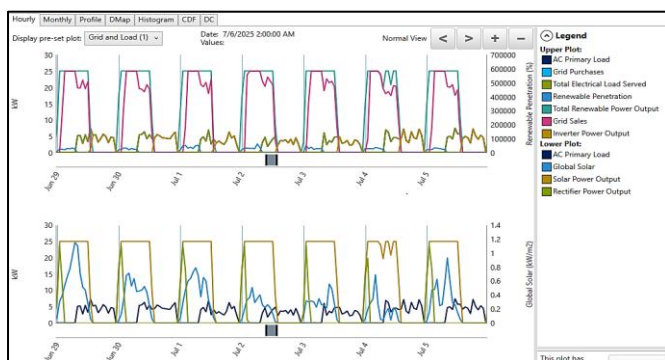
| Architecture | Solar Area (m²) | Solar Array (kWp) | Li-ion Battery (kWh) | High Tension (HT) (kV) | Converter (kW) | NPC (\$)  | LCM (\$/kWh) | Operating cost (\$/yr) | CAPEX (\$) | Ren. Frac. (%) | Total Fuel (\$/yr) | System |
|--------------|-----------------|-------------------|----------------------|------------------------|----------------|-----------|--------------|------------------------|------------|----------------|--------------------|--------|
| 1            | 600             | 25.0              | 1                    | 1                      | 76.2           | \$492,686 | \$0.153      | \$2,389                | \$431,797  | 100            | 0                  | 0      |
| 2            | 600             | 25.0              | 5                    | 1                      | 152            | \$470,328 | \$0.158      | \$2,354                | \$437,311  | 100            | 0                  | 0      |
| 3            | 600             | 25.0              | 15                   | 1                      | 305            | \$632,641 | \$0.163      | \$18,429               | \$699,239  | 100            | 0                  | 0      |
| 4            | 600             | 25.0              | 25                   | 1                      | 410            | \$1,194   | \$0.169      | \$18,415               | \$932,194  | 100            | 0                  | 0      |
| 5            | 600             | 25.0              | 50                   | 1                      | 1,220          | \$2,104   | \$1.40       | \$38,773               | \$1,604    | 100            | 0                  | 0      |
| 6            | 600             | 25.0              | 50                   | 1                      | 2,439          | \$2,224   | \$1.49       | \$41,407               | \$1,694    | 100            | 0                  | 0      |
| 7            | 600             | 25.0              | 50                   | 1                      | 3,659          | \$2,344   | \$1.79       | \$44,040               | \$1,784    | 100            | 0                  | 0      |
| 8            | 600             | 25.0              | 100                  | 1                      | 1,220          | \$1,784   | \$2.89       | \$76,457               | \$2,884    | 100            | 0                  | 0      |

**Figure 6.** Results showing performance of various solar-battery hybrid configurations based on cost, capacity, and renewable fraction in HOMER Grid. (SIMULATION)

These values are found to be well within the efficient operating range for typical grid-connected systems. The resulting total system autonomy of approximately 137 hours is achieved by the lithium-ion battery bank which played a central role in balancing generation and load, with five units providing a nominal capacity of 500 kWh each and a usable capacity of 400 kWh per unit. The annual battery energy yield was 18,156 kWh, accounting storage losses of 1,453 kWh. The battery State of Charge (SOC) remained above 90% for throughout the year, demonstrating stable operation and low degradation stress. The estimated battery lifespan is approximately 15 years, aligned with deep-cycle lithium-ion performance benchmarks. In a nutshell, the system can handle the daily energy demand with minimal operational costs and nil use of fossil fuels, demonstrating the technical and economic feasibility of solar-powered EV charging stations for similar urban and suburban locations in India. The performance of various solar battery for the proposed system is shown in *fig. 6*.

### 6.1. Grid and Solar Interaction Analysis

Over a week-long period, consistent system behavior is demonstrated by obtaining hourly performance profile from HOMER Grid, shown in *fig. 7*. The generation of solar power is at peak during daylight hours which supplies a significant portion of the AC load and inverter demand. Correspondingly, during these periods, renewable penetration reaches its highest levels, while a sharp decrease in grid electricity purchases is observed. In contrast, when solar generation is unavailable during dark hours, grid dependency increases. The trends of the rectifier output and global solar irradiance further confirm the strong correlation between solar availability and overall system operation. The effective integration of solar PV within the hybrid system shows high renewable utilization and reduction of grid reliance during peak solar hours.



**Figure 7.** Hourly results showing grid purchases, AC load, solar irradiance, solar power output, and inverter/rectifier response for over a week period

## 7. CONCLUSION

A techno-economic assessment of a grid-connected solar photovoltaic (PV) system integrated with lithium-ion battery storage for an electric vehicle (EV) charging station was carried out for Rohtak, Haryana using HOMER Grid. The analysis shows an optimal configuration that consists of a 600 kW PV array, five lithium-ion battery units, a 25-kW inverter,

and a 76.2 kW bidirectional converter, designed to provide a daily electricity demand of 2500 kWh. A Net Present Cost (NPC) of \$462,686 and a Levelized Cost of Energy (LCOE) of \$0.353/kWh with zero dependency on fossil fuels and a 100% renewable fraction was achieved by this hybrid system. Reliable charge/discharge performance with minimal storage losses were illustrated by lithium-ion batteries while maintaining an SOC above 90% for most of the year. The system also achieved efficient PV penetration, with annual generation exceeding 105 MWh. The proposed design provides a renewable energy-based configuration that is both technically viable and economically feasible for medium-scale EV charging infrastructure in the Indian rural context.

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**Data availability:** The data will be provided as per the request.

**Author Contribution:** The contribution of Nikhil Malik is to formulate and implement the proposed hybrid algorithm and write the manuscript. Surender Singh contribution for identifying the research gaps to formulate the objective function under his supervision. Gurdiyali Singh and Sombir Kundu drafted the manuscript in accordance with the journal's requirements.

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