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RESEARCH ARTICLE

An Approach for Attaining Economic Profit by Optimal Operation of Hybrid Thermal-Wind-PHS-EV System in a Deregulated System

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ABSTRACT The suggested hybrid power plant combines conventional and renewable energy sources along with energy storage devices such as wind, pumped hydro storage (PHS), thermal, and solar-powered electric vehicles (EVs). Its major goal is to improve the electricity network's revenue and profitability while maintaining grid frequency stability (f_G). To achieve this purpose, the approach considers the projected wind velocity (WV_{Proj}) in a deregulated market and commits wind farms to meet energy demand appropriately. The functioning of PHS and solar-connected EV power components is closely monitored to reduce the detrimental impact of power system imbalances caused by discrepancies in true (WP_{True}) and projected (WP_{Proj}) wind production. This operational strategy aims to reduce the unpredictability associated with renewable energy sources cost-effectively. Highlighting the resilience of this technique, the approach incorporates four energy stages of the PHS upper basin ($E_{PHS,max}$, $E_{PHS,opt}$, $E_{PHS,low}$, and $E_{PHS,min}$) and four energy stages of the EV battery ($E_{EVB,max}$, $E_{EVB,opt}$, $E_{EVB,low}$, and $E_{EVB,min}$). By considering these energy levels, the approach illustrates the strategy's long-term effectiveness. Several optimization methods are used for implementation and comparison, including Sequential Quadratic Programming (SQP), BAT algorithm, Particle Swarm Optimization (PSO) Algorithm, Genetic Algorithm (GA), and Cuckoo Search Algorithm (CSA). The efficacy of the suggested approach is assessed by analyzing and evaluating the IEEE 14-bus power network. The proposed technique deviates from conventional methods by employing the PHS plant to overcome uncertainties related to wind power, guaranteeing that committed generation patterns are reached with the support of solar power and EV-battery storage. Hourly simulations demonstrate that the proposed approach significantly enhances the use of maximum reservoir constraints, which improves system stability and security. The study demonstrates that the proposed two-phase operating technique is successful at improving revenue and profit while stressing stability and security inside the hybrid system. It also provides a feasible option for effective energy management.

INDEX TERMS Competitive power market, energy level, electric vehicles, grid frequency, pumped hydro storage, wind power.

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NOMENCLATURE

f_G	Grid Frequency.
WV_{Proj}	Projected Wind Velocity.
WV_{True}	True Wind Velocity.

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PHS	Pumped Hydro Storage.
SQP	Sequential Quadratic Programming.
Exp_{Ine}	Inequality Expenses.
WP_{Proj}	Projected Wind Power.
WP_{True}	True Wind Power.
EV	Electric Vehicles.
DG	Distributed Generation.
$E_{PHS,max}$, $E_{PHS,opt}$, $E_{PHS,low}$, $E_{PHS,min}$	Energy Stages of PHS Upper Basin in Maximum, Optimum, Low and Minimum Conditions.
GA	Genetic Algorithm.
ISO	Independent System Operator.
DISCOs	Distribution Companies.
TCSC	Thyristor Controlled Series Compensator.
CAES	Compressed Air Energy Storage.
$PR_{WT,max}$	Wind Farm's Maximum Generated Power Limit.
WV(s)	Wind Velocity at Time 's'.
E_{pum}	Energy Input Necessary for PHS Plant's Pumping Operation.
g	Gravity-Generated Acceleration.
$VFR_{water,gen}$	Flow Rate of Water in Generating Mode of PHS.
ϑ_{gen}	Generating Mode Power Conversion Co-Efficient.
Prof(m)	Profit of the Hybrid Plant.
$Rev_{PHS}(m)$	Revenue Collected from PHS Hybrid Plant.
$Rev_{PSP}(m)$	Revenue Collected from PHS Plant.
$Rev_{SPV-EV-Bat}(m)$	Revenue Collected from Solar-Connected EV Battery System.
$GP_{Ther}(m)$	Thermal Generation Price.
$GP_{SPV-EV-Bat}(m)$	Solar-Connected EV Battery Investment Price.
NG	Total Number of Generators.
α_i, β_i, γ_i	Price Coefficient of Thermal Plant.
$Rev_{gen}(m)$	Revenue Collected at Generation Mode.
$P_{g,pump}(m)$	Power Extracted from Electrical Grid for Pumping Operation of Pumped Storage System.
$P_g(m)$	Generated Power with PHS Operation in Generating Mode.
$P_{g-WF}(m)$	Power Given to Grid from Wind Farm.
$P_d(m)$, $P_g(m)$	Power Requirements and Power Availability in Grid.
P_{cha}^{max}, P_{cha}^{min}, P_{dis}^{max}, P_{dis}^{min}	Maximum and Lowest Charging and Discharging Limits of EV Battery System.
EL_{EV-bat} (s)	Energy Level of EV Battery System.
$V_{m,i}$, $V_{a,i}$	Voltage Magnitude and Angle.
$LL_{T,l}^{max}$	Transmission Line's Thermal Limit.
EL_{EV-bat}^{min}, EL_{EV-bat}^{max}	Lowest and Highest Energy Levels in EV Battery System.
$E_{EVB,max}$, $E_{EVB,opt}$, $E_{EVB,low}$, $E_{EVB,min}$	Energy Stages of the EV Battery in Maximum, Optimum, Low and Minimum Conditions.
CSA	Cuckoo Search Algorithm.
GENCOs	Generation Companies.
EGT	Evolutionary Game Theory.
PSO	Particle Swarm Optimization Algorithm.
$P_{Wind}(s)$	Power Generated by Wind Farm.
WV_{cut-in}, WV_{rated}, $WV_{cut-out}$	Cut-In, Rated and Cut-Out Wind Velocity.
ρ_{water}	Water Density.
E_{gen}	Quantity of Power Generated by PHS Plant.
H_{diff}	PHS Basin's Elevation Difference.
$VFR_{water,pump}$	Flow Rate of Water in Pumping Mode of PHS.
ϑ_{pump}	Pumping Mode Power Conversion Co-Efficient.
$Rev_{PL}(m)$	Revenue Due to Transmission Loss.
$Rev_{Ther}(m)$	Revenue Collected from Thermal Plant.
$Rev_{WF}(m)$	Revenue Collected from Wind Farm.
TGP(m)	Generation Price of Extracted Power from Hybrid Plant.
$GP_{WF}(m)$	Wind Investment Price.
P_t(i,m)	Generated power quantity considering the true wind velocity.
$LBMP_{mrkt}$(i,m)	Location-based Marginal Price.
$Rev_{PSP}(m)$	Revenue of Pumped Storage Plant.
$Price_{pump}(m)$	Price of Power at Pumping Mode.
$P_{w,pump}(m)$	Power Extracted from Wind Farm for Pumping Operation of Pumped Storage System.
$LBMP_{WF}$	Wind Power Investment Price.
ζ	Consequence Factor.
P_{cha} (s)	Overall Charging Load of EV Battery System.

η_{cha}, η_{dis}	EV Battery System's Efficiency at Charging And Discharging.
$P_{\mathrm{real,i}}$, $P_{\mathrm{react,i}}$	Active and Reactive Power Generation.
$V_{\mathrm{m,i}}^{\mathrm{min}}$, $V_{\mathrm{m,i}}^{\mathrm{max}}$, $V_{\mathrm{a,i}}^{\mathrm{min}}$, $V_{\mathrm{a,i}}^{\mathrm{max}}$	Lowest and Highest Limitations of Voltage.
NL_{sys}	Number of Transmission Lines.
$P_{\mathrm{real,i}}^{\mathrm{min}}$, $P_{\mathrm{real,i}}^{\mathrm{max}}$, $P_{\mathrm{react,i}}^{\mathrm{min}}$, $P_{\mathrm{react,i}}^{\mathrm{max}}$	Lowest and Maximum Limits of Active and Reactive Power Generation.

I. INTRODUCTION

In a fully deregulated power system, energy prices are determined by an independent system operator (ISO) who evaluates bids from generation companies (GENCOs) and distribution companies (DISCOs) [1]. However, integrating renewable sources into the grid introduces complexity due to the unpredictable nature of wind speed and solar radiation [2], [3]. These factors significantly impact the grid's stability and reliability [4], [5]. In this scenario, discrepancies between true (WV_{True}) and projected wind speeds, especially post-signing of power distribution deals between GENCOs and DISCOs, can lead to penalties or rewards imposed by the ISO on GENCOs. These penalties or rewards, denoted as Inequality Expenses (Exp_{Ine}), depend on whether there's an excess or shortfall in the power supply.

This mechanism aims to promote accountability and incentivize GENCOs to deliver consistent and reliable electricity. To effectively manage potential mismatches and mitigate Inequality Expense-related repercussions, utilizing energy storage such as PHS and EV battery storage devices proves to be a beneficial alternative strategy [6], [7]. Energy storage devices assist in controlling power shortages by storing extra energy and releasing it when needed, bridging the supply and demand gap for grid stability. They lessen the reliance on expensive and destructive thermal power plants, encouraging a more sustainable and efficient energy-producing approach [8]. The integration of renewables into deregulated electrical systems presents obstacles, however, solutions such as power contracts and energy storage technology can provide a stable and economically profitable power grid [9]. Several initiatives seek to address difficulties connected to hybrid renewable energy and storage systems in the electrical market, providing optimization methodologies for regulating renewable energy allocation alongside storage technology [10], [11], [12].

The study [13] presents a detailed assessment of the wind power spilling problem, including its causes, mitigation approaches, real-world applications, problems, and future developments. Paper [14] makes policy recommendations for maximizing the potential of battery energy storage units in Ireland while considering the European policy perspectives as well as national regulatory and electrical market directives. Paper [15] assesses how the new European regulations of 2019 foresee the future electrical network, as well as reconsiders the role of aggregators based on realized principles. Reference [16] presents an overview of the research that has used evolutionary game theory (EGT) in several energy domains. According to the investigation, EGT has been widely used to study various aspects of energy utilization. The research [17] aims to provide a global state-of-the-art evaluation of the technological, economic, and regulatory status of distribution-level energy storage and power quality services. The study [18] intends to give a complete analysis of Reinforcement Learning applications in a power network with a focus on bidding and dispatching strategy optimization. Research [19] proposes choosing industrial users with substantial shiftable loads in the city as the load adjustment component and providing them with independent pricing. Paper [20] proposes a geographic payback model for Battery Energy Storage Systems operation to correctly handle battery system operating flexibility. The research [21] focuses on tackling the problem of limited flexibility in conventional power grids, which hinders stakeholder adaptability and the integration of renewable sources. To overcome this challenge, the study suggests transitioning towards a decentralized system.

To optimize the net income of the local serving entities through optimum demand response bidding and energy storage scheduling while accounting for demand response uncertainty, a bi-level power arrangement is proposed in the research [22]. The study [23] assumes that merchant actions have no impact on market pricing and concentrates on the function of energy storage in optimizing profitability. The best economic dispatch for merchants is examined using dynamic programming theory. Three forms of electricity generation—wind, photovoltaic, and hydro—are taken into consideration in this research [24], which centers on an actual situation in Southwest China. A polyhedral uncertainty set is used to describe the uncertainty in PV power generation. The research [25] describes a two-step optimization technique for solving congestion problems and maximizing system profit in a deregulated power market, which employs a Thyristor Controlled Series Compensator (TCSC) and wind turbines. A two-stage model for the positioning and sizing of a battery storage system in a distributed power network is developed in the study [26]. The battery energy storage system is intended to give the distribution system operator local flexibility services and the transmission system operator frequency containment reserve for regular operation. Reference [27] analyzes the acceptable distribution of energy storage in a system with significant renewable power curtailment from the standpoint of third-party investors. The study [28] provides an expansion planning model for an Independent Power Producer in the absence of a Power Purchase Agreement. Research [29] offers the notion of BESS as a realistic alternative for power dispatching renewable energy sources. However, it states that BSSs lack both high power and energy capacity, which are essential for renewable energy sources. The proposed technique in [30] is centered on hourly congestion control. Congestion is handled by identifying the best positioning and scale of Distributed Generation (DG) throughout 24 hours. The transmission congestion rent is used to determine the best site for DG deployment.

The study [31] presents a mechanism for strategic bidding in the power market that optimizes profit while mitigating investment risk associated with renewable energy integration. The suggested method employs a Discrete-Time Markov Process algorithm to learn from previous instances and make judgments about energy storage and dispatch. To decrease the unpredictability and imbalance costs associated with renewable energy sources, the article [32] investigates the integration of fuel cells and wind farms into the existing electrical grid. The system's total fuel cost function for producing units and the power balance restrictions in a power system are covered in the work [33]. The non-dominated sorting genetic algorithm-II presented in the paper [34] offers a solution to the multi-objective generation scheduling problem for a hydro-thermal system. This algorithm considers PHS and renewable sources, with seeing outages, and uncertainty in the presence of demand-side management programs.

Research [35] describes a stochastic mixed-integer linear programming model for reducing operating costs in transmission networks with large-scale storage systems and substantial renewable energy integration. To optimize the overall revenue from the sale of energy for a single day, the study [36] examines the viability of combining a PHS with solar photovoltaic power plants and wind power plants in a hybrid power system. The study [37] investigates ways to operate island networks that depend on pumped-hydro storage and wind power at 100% renewable energy penetration. The study [38] explores the best bidding and offering techniques for integrated renewable power plants and compressed air energy storage (CAES) in the electricity market, taking into account the volatility of renewable output and electricity pricing. The research [39] uses the analytic hierarchy process to assess several storage options for grid-connected photovoltaic systems.

The presented work digs into a thorough examination of aspects that have previously not been addressed together in other research.

- This study's primary goal is to examine how generator scheduling and hybrid renewable energy affect the power system's economic parameters.
- In addition, another issue that is addressed is the financial influence of introducing energy storage technologies in a deregulated setting, like PHS and EV battery storage.
- Moreover, this paper also tackles the third issue, which focuses on the influence of different energy stages in PSH and EV battery storage on the frequency of the electrical grid.
- This research suggests a multi-functional solution for a thermal-wind-PHS-EV hybrid plant in a deregulated power system to address the challenges outlined above. The major purpose of this technique is to maximize the system's financial profit and income while avoiding the negative impact of Inequality Expenses ($\mathrm{Exp_{Ine}}$), which arise when the true and projected wind outputs diverge.
- The study provides four energy stages of the PHS system's upper basin ($E_{\mathrm{PHS,max}}$, $E_{\mathrm{PHS,opt}}$, $E_{\mathrm{PHS,low}}$, and $E_{\mathrm{PHS,min}}$), and EV battery storage ($E_{\mathrm{EVB,max}}$, $E_{\mathrm{EVB,opt}}$, $E_{\mathrm{EVB,low}}$, and $E_{\mathrm{EVB,min}}$). These energy levels are used to guarantee that the hybrid system operates in optimized mode, utilizing the maximum capacity of the storage systems while still saving some energy for essential power demand scenarios. This is the novelty of this work.
- Furthermore, the suggested solution includes 11 separate operational modes, each with distinctive strategies adapted to the hybrid system. It should be noted that the operational ranges of the PHS and EV battery storage varied by state.

The suggested technique efficiently addressed wind power uncertainties in the hybrid thermal-wind-PHS-EV system. By assessing projected wind velocity in a deregulated market, the technique commits wind farms to satisfy energy demands accordingly, decreasing unpredictability in wind power production. The operational approach tackles the discrepancies in true and projected wind output, reducing the detrimental impact of power system imbalances produced by these fluctuations.

The technique integrates PHS and solar-connected EV power components to reduce uncertainties associated with renewable energy sources while improving system stability and security. The study emphasizes the need for regulating uncertainty in wind power output by using the PHS plant to guarantee that contracted generating patterns are met with the help of solar power and EV-battery storage. Overall, the technique efficiently handles risks associated with wind power by optimizing the operation of varied power-generating sources and increasing revenue and profit within the hybrid system.

Section II depicts the details of the system structure, while Section III presents the development of the objective function. Section IV gives the details of the functions of the projected plant. Section V presents application details on an IEEE 14-bus system with real-time data as well as simulation results. Section VI presents the conclusions and future work.

II. SYSTEM STRUCTURE

System structuring is essential in the process of gaining a thorough knowledge of a particular system. It is a necessary prelude to the succeeding phases in system analysis and assessment, which include objectives, simulations, operations, and obtaining outcomes.

A. WIND ENERGY PRODUCTION

The fluctuating, and indeterminate character of wind creates difficulties at the time of integration with thermal power plants. To solve this issue, the study focuses on estimating wind speeds in a deregulated market. Accurate estimations enable to regulation of the power generated for these specific wind speeds. The wind power production calculations rely on the wind characteristic graph illustrated in Fig. 1. The power generated by a wind farm is designated as $P_{Wind}(s)$ that can be measured using the following formula [40]:

$$\begin{aligned} P_{Wind}(s) &= PR_{WT,max} * \left(\frac{WV(s) - WV_{cut-in}}{WV_{rated} - WV_{cut-in}} \right) \text{ for Case 1} \\ &= PR_{WT,max} \text{ for Case 2} \\ &= 0 \text{ for Case 3} \end{aligned} \tag{1}$$

Case 1: $WV_{cut-in} \leq WV(s) \leq WV_{rated}$
Case 2: $WV_{rated} \leq WV(s) \leq WV_{cut-out}$
Case 3: $WV(s) < WV_{cut-in} \cup WV(s) > WV_{cut-out}$

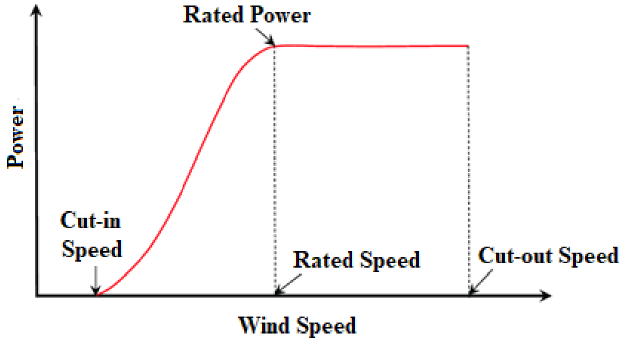


FIGURE 1. Wind power production characteristics.

Here, $PR_{WT,max}$ is the maximum limit of generated power from a wind farm. WV_{cut-in}, $WV_{rated,}$ and $WV_{cut-out}$ are cut-in wind velocity, rated wind velocity, and cut-out wind velocity whereas WV(s) is the wind velocity at time 's'. In this work, WV_{cut-in}, $WV_{rated,}$ and $WV_{cut-out}$ are considered as 3, 15, and 26 m/s.

B. PUMPED HYDRO STORAGE PLANT (PHS)

A PHS plant's functioning is strongly dependent on two variables: the upper basin's capacity and the height difference between the upper and lower basins. These factors are decisive in ensuring that the PHS plant runs smoothly. A PHS power plant can run in a variety of modes depending on the electricity demand. These modes are generating mode and pumping mode, which correspond to peak and off-peak demand hours. The PHS plant's producing mode is also known as the discharging mode. When the plant is in a pumping zone, it saves energy for later use. The following equations depict the quantity of power generated (E_{gen}) and the energy input (E_{pum}) necessary for the PHS plant's pumping operation [41]:

$$E_{gen} = \rho_{water} \cdot g \cdot H_{diff} \cdot VFR_{water,gen} \cdot \vartheta_{gen} \tag{2}$$

$$E_{pump} = \frac{\rho_{water} \cdot g \cdot H_{diff} \cdot VFR_{water,pump}}{\vartheta_{pump}} \tag{3}$$

Here, ρ_{water}, g, H_{diff} are water density, gravity-generated acceleration, and PHS basin's elevation difference. $VFR_{water,gen}$ and $VFR_{water,pump}$ are the flow rate of water in the generating and pumping mode of PHS. ϑ_{gen} and ϑ_{pump} are generating mode and pumping mode power conversion co-efficient.

C. LOCATION-BASED-MARGINAL PRICE (LBMP)

LBMP is a methodology used to determine the energy cost at a definite location within an electric system. The computation of LBMP takes a variety of factors, including energy pricing, transmission congestion, the marginal cost of generation, and losses. LBMP is used to establish the MCP (market clearing price) for various points within the electric system, known as nodes. It is worth noting that LBMP is sometimes referred to as 'nodal pricing' since it estimates the energy price at specific nodes in the system. The MCP is extremely important in calculating LBMP since it represents the equilibrium between supply and demand for electricity in the market. This critical component is determined by balancing the aforementioned supply and demand at various places within an electrical system, which is known as nodal pricing.

D. SQP (SEQUENTIAL QUADRATIC PROGRAMMING)

The SQP approach generates a problem formulation and solution in a step-by-step way by successfully employing the quadratic sub-problems. This strategy requires the integration of two critical methods: the line search route and the trust-region framework route. The line search method plays an important role in determining the ideal step size, which eventually minimizes the objective function along the search direction. In contrast, the trust-area framework procedure is in charge of ensuring that each action executed during each iteration remains inside a defined trust region. This approach excels at tackling nonlinear optimization problems with complex nonlinear objective functions and constraints. The SQP methodology can be viewed as a parallel process that functions similarly to Newton's method. This strategic research enables a more efficient and successful optimization approach. SQP is closely related to two types of algorithms that are useful for addressing nonlinear problems: the active set approach and Newton's method. These algorithms are critical to the iterative SQP process, which is separated into several discrete phases, each of which contributes to the overall optimization process.

- The first phase comprises variable initialization, which prepares the groundwork for subsequent computations and assures the precision of the optimization process.
- Step 2 is dedicated to determining the search direction for the variables related to the objectives. This phase guarantees that the next processes are consistent with the planned outcomes, resulting in a more efficient and successful optimization process.
- Step 3 focuses on defining and solving quadratic programming sub-problems. These sub-problems are important to the entire optimization process because

they give vital insights and answers that help to attain the intended optimum outcome.

- Step 4 entails determining the best outcome. If the intended optimal outcome is obtained, the procedure moves on to the next stage, indicating that the optimization process has been completed successfully. If the optimal result is not yet achieved, the search size is modified, and the procedure returns to Step 2.
- In Step 5, the optimal solution is achieved, which combines all of the iterative phases into a strong and efficient solution.

III. OBJECTIVE FUNCTION

In this study, two objectives have been deliberated that are simultaneously and jointly solved. The first objective, which is given utmost importance, is maximizing the profit of the hybrid plant, represented by the variable Prof(m) at time 'm'. The second objective involves maximizing the revenue generated by the PHS hybrid plant. This objective is achieved through an optimal scheduling operation that efficiently manages renewable energy sources like wind power and solar power. Additionally, it also involves utilizing the energy storage system effectively. To accurately calculate the revenue of the PHS hybrid plant, the authors have devised a comprehensive computation method. This method includes summing up the revenue generated from the PHS plant, wind farm, and solar-connected EV battery storage system, and accounting for any revenue reduction due to losses. Both the profit objective and the revenue objective play a crucial role in ensuring the economic viability and smooth operation of the hybrid plant in a competitive power market.

Obj. Func. 1:

$$\mathrm{Prof(m)} = \mathrm{Rev_{Ther}(m)} + \mathrm{Rev_{PHS}(m)} - \mathrm{TGP(m)} \tag{4}$$

Obj. Func. 2:

$$\begin{aligned}\mathrm{Rev_{PHS}(m)} = [&\mathrm{Rev_{PSP}(m)} + \mathrm{Rev_{WF}(m)}\\ &+ \mathrm{Rev_{SPV-EV-Bat}(m)} - \mathrm{Rev_{PL}(m)}]\end{aligned} \tag{5}$$

Here,

$$\mathrm{Rev_{Ther}(m)} = \sum_{i=1}^{NG} \mathrm{P_t(i,m)} \cdot \mathrm{LBMP_{mrkt}(i,m)} \tag{6}$$

$$\mathrm{TGP(m)} = \mathrm{GP_{Ther}(m)} + \mathrm{GP_{WF}(m)} + \mathrm{GP_{SPV-EV-Bat}(m)} \tag{7}$$

$$\mathrm{GP_{Ther}(m)} = \sum_{i=1}^{NG} \left(\alpha_i + \beta_i \mathrm{P_a(i,m)} + \gamma_i \mathrm{P_a^2(i,m)}\right) \tag{8}$$

Here, '$\mathrm{Rev_{Ther}(m)}$' and '$\mathrm{Rev_{PHS}(m)}$' are revenue collected from the thermal and PHS hybrid plant (including pumped storage ($\mathrm{Rev_{PSP}(m)}$), wind farm ($\mathrm{Rev_{WF}(m)}$), and solar-connected EV battery ($\mathrm{Rev_{SPV-EV-Bat}(m)}$)) plant respectively. $\mathrm{Rev_{PL}(m)}$ is the revenue due to the transmission loss. 'TGP(m)' is the total generation price of extracted power from the hybrid plant whereas, this price consists of thermal generation price ($\mathrm{GP_{Ther}(m)}$), wind investment price ($\mathrm{GP_{WF}(m)}$), and solar-connected EV battery investment price ($\mathrm{GP_{SPV-EV-Bat}(m)}$). The total number of generators present in the system is denoted as 'NG'. $\mathrm{P_t(i,m)}$ is the generated power quantity considering the true wind velocity at generator-i. $\mathrm{LBMP_{mrkt}(i,m)}$ is the location-based marginal price at time m. α_i, β_i, γ_i are the price coefficient of thermal plant. The revenue of the pumped storage plant ($\mathrm{Rev_{PSP}(m)}$) highly depends on two constraints: Revenue collected at generation mode i.e. $\mathrm{Rev_{gen}(m)}$ and price of power at pumping mode i.e. $\mathrm{Price_{pump}(m)}$.

$$\mathrm{Rev_{PSP}(m)} = \mathrm{Rev_{gen}(m)} - \mathrm{Price_{pump}(m)} \tag{9}$$

$$\mathrm{Rev_{gen}(m)} = \mathrm{P_g(m)} \cdot \mathrm{LBMP_{mrkt}(m)} \tag{10}$$

where '$\mathrm{P_g(m)}$' is generated power with PHS operation in generating mode. The price of power at the pumping mode of the PSP plant is as:

$$\begin{aligned}\mathrm{Price_{pump}(m)} = &\mathrm{P_{w,pump}(m)} \cdot \mathrm{LBMP_{WF}}\\ &+ \mathrm{P_{g,pump}(m)} \cdot \mathrm{LBMP_{mrkt}(m)}\end{aligned} \tag{11}$$

$\mathrm{P_{w,pump}(m)}$ and $\mathrm{P_{g,pump}(m)}$ are the power extracted from the wind farm and electrical grid for the pumping operation of the pumped storage system respectively. $\mathrm{LBMP_{WF}}$ is the wind power investment price.

$$\mathrm{Rev_{WF}(m)} = \mathrm{P_{g-WF}(m)} \cdot \mathrm{LBMP_{mrkt}(m)} \tag{12}$$

$$\begin{aligned}\mathrm{Rev_{PL}(m)} = \zeta \cdot &\mathrm{LBMP_{mrkt}(m)} \cdot [\mathrm{P_d(m)}\\ &- \mathrm{P_{g-WF}(m)} - \mathrm{P_g(m)}]\end{aligned} \tag{13}$$

$\mathrm{P_{g-WF}(m)}$ is the power given to the grid from the wind farm. ζ is the consequence factor. $\mathrm{P_d(m)}$ and $\mathrm{P_g(m)}$ are the power requirements and power availability in the grid at time 'm'. The prime objective of this work mentioned in equations (4) and (5) is solved using the following constraints:

A. CONSTRAINTS FOR SOLAR-CONNECTED EV BATTERY SYSTEM

$$\mathrm{P_{cha}(m)} = \mathrm{P_{Req-cha-WF}(m)} + \mathrm{P_{Req-cha-EG}(m)} \tag{14}$$

$$\mathrm{P_{cha}^{min}} \le \mathrm{P_{cha}(s)} \le \mathrm{P_{cha}^{max}} \tag{15}$$

$$\mathrm{P_{dis}^{min}} \le \mathrm{P_{dis}(s)} \le \mathrm{P_{dis}^{max}} \tag{16}$$

$$\begin{aligned}\mathrm{EL_{EV-bat}(s+1)} = \mathrm{EL_{EV-bat}(s)} + [&(\mathrm{P_{cha}(s)}.\eta_{cha})\\ &- (\mathrm{P_{dis}(s)}/\eta_{dis})]\end{aligned} \tag{17}$$

$$\mathrm{EL_{EV-bat}^{min}} \le \mathrm{EL_{EV-bat}(s)} \le \mathrm{EL_{EV-bat}^{max}} \tag{18}$$

$\mathrm{P_{cha}(s)}$ indicates the overall charging load of the EV battery system. $\mathrm{P_{cha}^{max}}$, $\mathrm{P_{cha}^{min}}$, $\mathrm{P_{dis}^{max}}$ and $\mathrm{P_{dis}^{min}}$ indicate the maximum and lowest charging and discharging limitations of the EV battery system. $\mathrm{EL_{EV-bat}(s)}$ denotes the energy level of the EV battery system. The EV battery system's efficiency when charging and discharging is represented by η_{cha} and η_{dis}. $\mathrm{EL_{EV-bat}^{min}}$ and $\mathrm{EL_{EV-bat}^{max}}$ represent the lowest and highest energy levels in the EV battery system. The variables and parameters given are utilized to determine the EV battery system's operation strategy. These variables are critical for improving the hybrid plant's functioning and maximizing its profit and income. The charging and discharging mode's lowest and most severe limitations guarantee that the EV battery system runs within its capacity. The EV battery system's energy level is monitored and adjusted to ensure that energy supply and demand are balanced.

B. CONSTRAINTS FOR OPF SOLVING

$$V_{m,i}^{min} \leq V_{m,i} \leq V_{m,i}^{max} \quad i = 1, 2, 3 \ldots NB_{sys} \tag{19}$$

$$V_{a,i}^{min} \leq V_{a,i} \leq V_{a,i}^{max} \quad i = 1, 2, 3 \ldots NB_{sys} \tag{20}$$

$$LL_{T,l} \leq LL_{T,l}^{max} \; l = 1, 2, 3 \ldots NL_{sys} \tag{21}$$

$$P_{real,i}^{min} \leq P_{real,i} \leq P_{real,i}^{max} \quad i = 1, 2, 3 \ldots NB_{sys} \tag{22}$$

$$P_{react,i}^{min} \leq P_{react,i} \leq P_{react,i}^{max} \quad i = 1, 2, 3 \ldots NB_{sys} \tag{23}$$

The power flow in the system is modeled and examined using the equations. A variety of characteristics, including power generation at a particular unit, transmission loss, voltage magnitude, voltage angle, and real and reactive power injection, are represented by the variables in the equations. The voltage's magnitude and angle are represented by the variables $V_{m,i}$ and $V_{a,i}$, while its lowest and highest limitations are denoted by the variables $V_{m,i}^{min}$, $V_{m,i}^{max}$, $V_{a,i}^{min}$, and $V_{a,i}^{max}$. $LL_{T,l}^{max}$ represents the transmission line's thermal limit. NL_{sys} is the number of transmission lines in the electrical network. The active and reactive power generation is represented by $P_{real,i}$ and $P_{react,i}$, while the lowest and maximum limits are represented by $P_{real,i}^{min}$, $P_{real,i}^{max}$, $P_{react,i}^{min}$ and $P_{react,i}^{max}$.

C. CONSTRAINTS FOR THE PSH HYBRID PLANT

$$P_p(m) = P_{w,pump}(m) + Pg_{,pump}(m) \tag{24}$$

$$P_p^{min} \leq P_p(m) \leq P_p^{max} \tag{25}$$

$$P_g^{min} \leq P_g(m) \leq P_g^{max} \tag{26}$$

IV. FUNCTIONING PHASES OF PROJECTED PLANT

A highly effective and well-organized strategy, consisting of two stages has been presented here to achieve the extreme possible revenue and financial profit for the system, while simultaneously ensuring that the grid frequency remains stable. This is accomplished through the optimal scheduling of a hybrid power plant that combines wind, pumped hydro storage, EV, and thermal technologies.

The proposed system comprises a range of power sources, such as thermal plants and wind farms. Additionally, storage systems like PHS and solar-connected EV batteries are also incorporated into this power plant. The energy demand is measured in terms of electricity consumption, and there is a transmission system in place known as the electricity grid. There is a controlling station that oversees the entire operation of the power network. The process of this hybrid plant is primarily working based on the true and projected wind velocity scenarios. To ensure a smooth action, a power distribution agreement is established between GENCOs and DISCOs. This agreement considers the electricity produced by wind power facilities and also takes into account the projected wind speed.

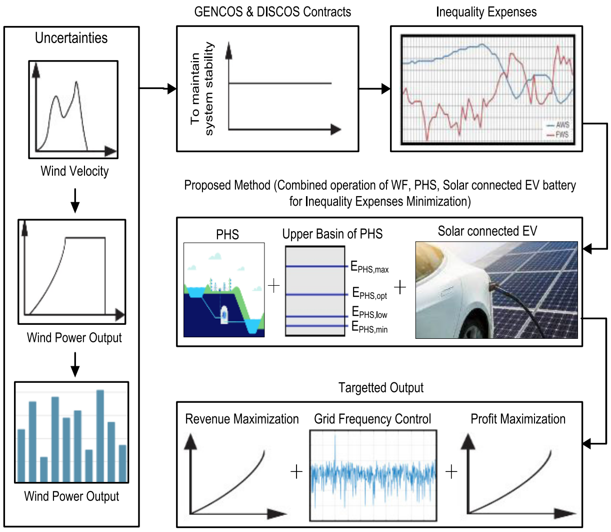


FIGURE 2. **Proposed hybrid system operating flow diagram.**

In instances where the projected wind velocity (WV_{Proj}) is superior to the true wind velocity (WV_{True}), then the PHS plant and solar-connected EV system are utilized to meet the electricity requirement and maintain the frequency of the electricity grid. When true wind velocity (WV_{True}) exceeds projected wind velocity (WV_{Proj}), the PHS plant functions in the pumping zone, and the solar-connected EV battery works in the charging zone. This allows for energy storage for future use. In this particular scenario, the solar-connected EV battery is also utilized. To ensure a wide range of variations and to determine the most suitable results, four different energy stages are considered for both the upper basin of the PHS plants and the solar-connected EV battery systems. The prime aim of the proposed operation scheme is to optimize the functioning of the hybrid plant to exploit financial welfare. This optimization is attained by making use of the available renewable energy sources and aligning them with the electricity demand. Throughout this process, it is crucial to maintain the system stability and frequency of the electricity grid.

The overall operation model of the hybrid plant is illustrated in Fig. 2, which showcases the intricate and meticulously designed system that combines various sources of power generation to achieve maximum efficiency and effectiveness. This approach ensures that every aspect of the power plant is streamlined and synchronized to work effectively towards a common goal of meeting the ever-growing electricity demand. During the peak-demand period, when the need for electricity is at its highest, the power generated from the wind farm is directly channeled and supplied to the grid. This direct supply ensures that the electricity reaches the consumers in a timely and efficient manner, without any unnecessary delays or interruptions.

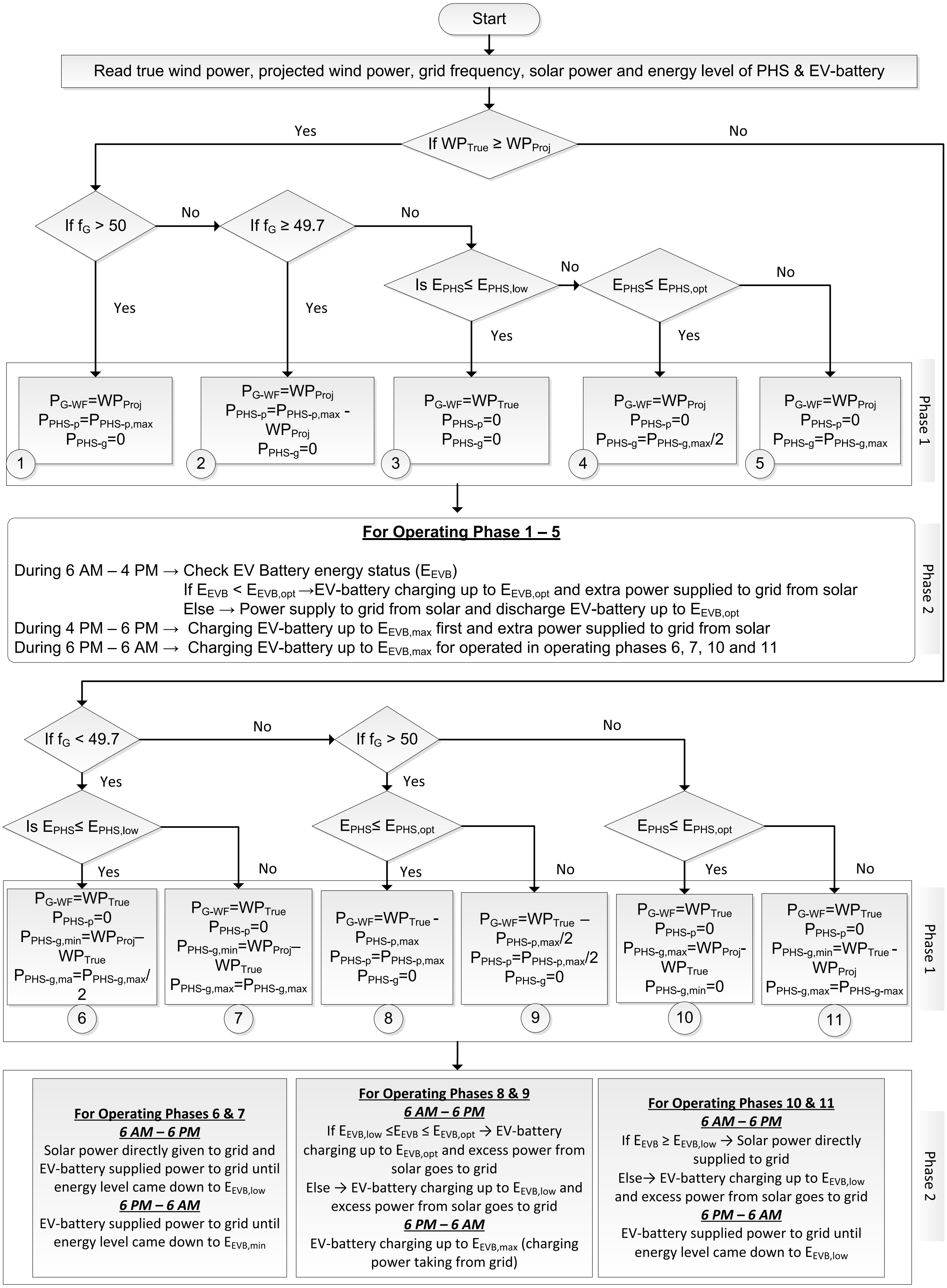
This is imperative in ensuring that the demands of the consumers are met without any compromise. However, during the off-peak period, a different approach is adopted. The surplus power generated by the wind farm during this period is not wasted or left unused. Instead, it is intelligently utilized for the pumping operation of the PHS plant. It means that the excess power is efficiently stored in the PHS plant, serving as a valuable reserve for future use when the demand for electricity surges once again. By adopting such a strategic approach and effectively utilizing wind power in this manner, the hybrid power plant can meet the electricity demand in a highly efficient and economical manner. This, in turn, reduces the reliance on other conventional power sources, such as thermal power plants.

The optimal operation scheduling of a solar-connected EV hybrid system is divided into three distinct periods, namely 6 AM-4 PM, 4-6 PM, and 6 PM-6 AM. Each of these periods has its objectives and strategies to ensure the uninterrupted supply of electricity. During the 6 AM-4 PM period, the primary focus of the solar-connected EV hybrid plant is to maximize the system's profit by supplying solar power directly to the grid. This not only ensures a steady and reliable supply of electricity but also capitalizes on the abundant solar energy available during this period. To further enhance the efficiency of the system, the EV battery is charged using solar power if its energy level reaches a certain predefined point known as the $E_{EVB,low}$. As the day progresses and enters the 4 PM-6 PM period, solar power shifts its attention towards maintaining the energy level of EV batteries. After full charging of EV batteries, surplus power is seamlessly directed and supplied to the grid. This ensures that the battery remains adequately charged and serves as a reliable backup option during times when solar power is not readily available. Finally, during the third time interval, which spans from 6 PM to 6 AM, the availability of solar power significantly diminishes. This makes the energy level of the EV battery critically important, as it serves as a lifeline during the nighttime to maintain the grid frequency. The EV battery then acts as a power backup option, ensuring that the flow of electricity remains uninterrupted and the grid operates smoothly.

To gauge the effectiveness and efficiency of the proposed strategy, it is essential to compare it with various other algorithms and approaches. The Mi-Power, GA, PSO, BAT, and CS algorithms are some of the algorithms that have been considered for this purpose. Furthermore, it is important to note that the calculations and predictions involved in the operation of the hybrid plant are based on extensive data and analysis. The output power is initially calculated using a power output characteristics graph, which considers the various factors and variables associated with the wind velocity data. This meticulous approach ensures that the calculations are accurate and reliable, serving as a solid foundation for the subsequent decision-making process.

Additionally, the mode of operation of the PHS plant is determined based on several crucial factors. These factors include the true and projected wind power, grid frequency, and the energy level of both the PHS and the EV battery system. These factors collectively influence and dictate whether the PHS should operate in generating, pumping, or remain in idle mode. This dynamic and adaptive approach ensures that the PHS plant operates optimally, aligning itself with the specific needs and demands of the system. All operating conditions and parameters are set within the designated operating limits of the PHS units. This ensures that the system operates within safe and sustainable parameters, mitigating any potential risks or issues. Once these operating conditions are established, an optimal power flow (OPF) algorithm is executed to achieve the objectives set by the hybrid plant. This algorithm optimizes the distribution and flow of power, ensuring that the electricity is efficiently allocated and utilized. The integration of wind, PHS, and solar-connected EV battery power generation with the least cost of generation is a pivotal aspect of the proposed strategy. By maximizing the use of renewable energy sources and minimizing the reliance on thermal plants, the overall cost of power generation is significantly reduced. This, in turn, maximizes the profit margin and ensures that the system operates in an economically sustainable manner. However, it is important to acknowledge the challenges associated with integrating wind power with thermal power plants. The variable and uncertain nature of wind power poses a unique challenge in terms of synchronization and coordination. Therefore, the presented methodology incorporates wind speed prediction for a deregulated market. This prediction is crucial in accurately calculating and estimating the corresponding power output using a wind characteristic graph. This comprehensive approach ensures that the system operates optimally, even in the face of inherent uncertainties and complexities. The flowchart depicted in Fig. 3 provides a visual representation of the presented methodology for achieving the most efficient operation of a hybrid plant. This approach considered various factors and variables to ensure optimal performance. For instance, the power supplied to the grid from the wind source is denoted as P_{G-WF}. Additionally, there are upper and lower limits of power in the pumping mode (P_{PHS-p}) of the PHS system, which are referred to as $P_{PHS-p,max,}$ and $P_{PHS-p,min}$ respectively. Similarly, the generating mode of the PHS system (P_{PHS-g}) has maximum and minimum limits of power generation known as $P_{PHS-g,max,}$ and $P_{PHS-g,min}$. To ensure the most effective operation of the hybrid power plant, an optimal operating strategy has been devised. This strategy considered a total of 11 different operating states, each with its unique characteristics and requirements.

These operating states are extensively operated to provide a comprehensive understanding of the various conditions that may arise. These states are further categorized into six distinct conditions based on wind velocity and grid frequency, allowing for a more organized and systematic approach to operation. The operation of the hybrid power plant is thoroughly explained in Fig. 2, providing a detailed overview of the entire system. This system consists of several key



For Operating Phase 1 – 5

During 6 AM – 4 PM → Check EV Battery energy status (E_{EVB})
If $E_{EVB} < E_{EVB,opt}$ →EV-battery charging up to $E_{EVB,opt}$ and extra power supplied to grid from solar
Else → Power supply to grid from solar and discharge EV-battery up to $E_{EVB,opt}$
During 4 PM – 6 PM → Charging EV-battery up to $E_{EVB,max}$ first and extra power supplied to grid from solar
During 6 PM – 6 AM → Charging EV-battery up to $E_{EVB,max}$ for operated in operating phases 6, 7, 10 and 11

For Operating Phases 6 & 7
6 AM – 6 PM
Solar power directly given to grid and EV-battery supplied power to grid until energy level came down to $E_{EVB,low}$
6 PM – 6 AM
EV-battery supplied power to grid until energy level came down to $E_{EVB,min}$

For Operating Phases 8 & 9
6 AM – 6 PM
If $E_{EVB,low} \leq E_{EVB} \leq E_{EVB,opt}$ → EV-battery charging up to $E_{EVB,opt}$ and excess power from solar goes to grid
Else → EV-battery charging up to $E_{EVB,low}$ and excess power from solar goes to grid
6 PM – 6 AM
EV-battery charging up to $E_{EVB,max}$ (charging power taking from grid)

For Operating Phases 10 & 11
6 AM – 6 PM
If $E_{EVB} \geq E_{EVB,low}$ → Solar power directly supplied to grid
Else→ EV-battery charging up to $E_{EVB,low}$ and excess power from solar goes to grid
6 PM – 6 AM
EV-battery supplied power to grid until energy level came down to $E_{EVB,low}$

FIGURE 3. Flow-chart of the presented method.

components, including main power sources such as a wind farm and a thermal power plant.

Additionally, there are backup energy sources in the form of a solar-connected EV battery system. The energy demand, in terms of electricity consumption, is another crucial factor in the operation of the hybrid plant. Furthermore, a transmission system in the form of an electricity grid ensures the smooth flow of electricity. Lastly, a controlling station is responsible for overseeing and managing the entire operation. These elements play a vital role in maximizing revenue and profit by minimizing the reliance on thermal power. This is achieved through effective scheduling in the first stage of operation, allowing for efficient utilization

Presented Method Phase-1: This stage focuses on the process of efficiently operating the hybrid WF-thermal-PHS power plant, which is visually depicted in Fig. 3 under the designation of Phase-1.

Presented Method Phase-2: In this stage, the incorporation of the optimal operating strategy of the solar-connected EV battery system has been performed, along with the scheduling from the first phase. This incorporation is done to achieve maximum revenue and profit by minimizing the utilization of thermal power, as demonstrated in Fig. 3. To ensure the robustness of the presented methodology, three different types of EV-battery storage, namely Li-ion, Super-capacitor, and Lead-acid have been considered.

These storage systems have varying efficiency levels and working principles, which ultimately result in different profit gains based on their respective operating models. To thoroughly examine the performance of the presented approach, three battery stacks have been chosen, each consisting of 30 batteries, for each of the aforementioned types: Li-ion, Super-capacitor, and Lead-acid. The capacity of each battery is 60 kW. Furthermore, it is worth mentioning that the efficiency of the inverter, which plays a crucial role in the overall system, has also been taken into consideration. The inverter efficiency is considered as 95% for this work.

V. RESULTS AND DISCUSSION

The effectiveness of the method is evaluated by implementing the presented methodology in a modified IEEE 14-bus system. This system consists of 5 generators, 10 loads, and 20 transmission lines. To ensure the accuracy of the results, all the necessary system data and cost coefficients have been extracted from a reliable source, namely [42]. To carry out the necessary calculations and analysis, a wind farm comprising 20 turbines is taken into consideration. Each of these turbines has a maximum capacity of 3.5 MW, resulting in a total net output of 70 MW when operating at its rated speed.

Additionally, a 2 MW solar power plant is also included in the proposed hybrid system. When determining the cost of wind power investment, a value of 3.75 \$/MWh is assigned, as stated in [43]. On the other hand, the cost equation for PHS plants is assumed to be linear and less significant compared to other costs. Therefore, the cost of generating hydropower can be considered negligible in this context. To assess the applicability and effectiveness of the presented methodology, hourly data of various parameters such as true and projected wind velocity (measured at a height of 120 m from the ground level), solar irradiance, solar cell temperature, and grid frequency are collected for a specific location. This data is illustrated in Figure 4.

TABLE 1. Energy stages of PHS & EV's battery storage system.

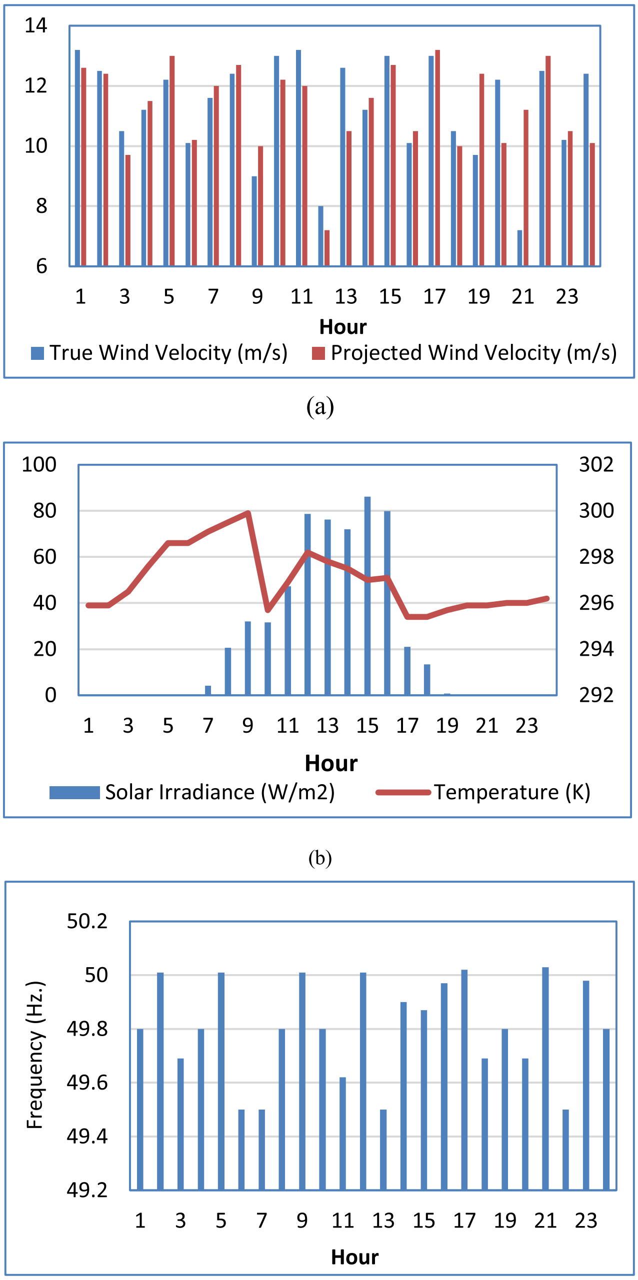
PHS Plant		EV's Battery Storage System	
Energy Stages	Values	Energy Stages	Values
$E_{PHS,max}$	100 MWh	$E_{EVB,max}$	2 MWh
$E_{PHS,opt}$	50 MWh	$E_{EVB,opt}$	1 MWh
$E_{PHS,low}$	25 MWh	$E_{EVB,low}$	0.5 MWh
$E_{PHS,min}$	12.5 MWh	$E_{EVB,min}$	0.25 MWh
Initial Point	51 MWh	InitialPoint	2 MWh

PHS is a form of energy storage system that utilizes two water reservoirs situated at varying elevations to both store and generate electricity. The determination of whether PHS functions as a generator or a pump is reliant upon the logic presented in Figure 3. This particular logic is most likely an outline of the conditions and criteria used to decide when the PHS system should operate as a generator, thus generating electricity, or as a pump, thereby storing energy. At the commencement of operation, the PHS plant possesses an initial energy level of 51 MWh, while the EV battery storage is assumed to have an initial energy level of 2 MWh. These respective energy levels signify the quantity of energy stored within the PHS plant and EV battery storage at the initiation of operation. Table 1 furnishes comprehensive details regarding the energy levels of both the PHS plant and the EV battery storage systems.

The presented methodology outlined within this paper is compared with an existing methodology as elucidated in reference [44]. The cost equation of generators, the utilized input data, and the objective function employed in both the presented methodology and the existing methodology are identical. This comparative analysis is presumably conducted to assess the efficacy and efficiency of the presented methodology concerning the existing methodology.

In a majority of instances, the grid frequency is discovered to be lower than the standard value of 50 Hz, thereby indicating a potential disparity between power generation and demand. The maintenance of grid frequency is fundamentally crucial to avert power system blackouts. The presented methodology offers a viable and cost-effective solution by optimizing the scheduling of power generation from the hybrid system, thereby effectively maintaining the grid frequency.

The profitability of a power system is reliant upon the revenue garnered from customers and the cost associated with power generation. The revenue is influenced by the generated power of each generator and the corresponding Location-Based-Marginal Price at generator buses. The presented methodology considered backup generation units,



(a)

(b)

(c)

FIGURE 4. Real-time control parameters of the system.

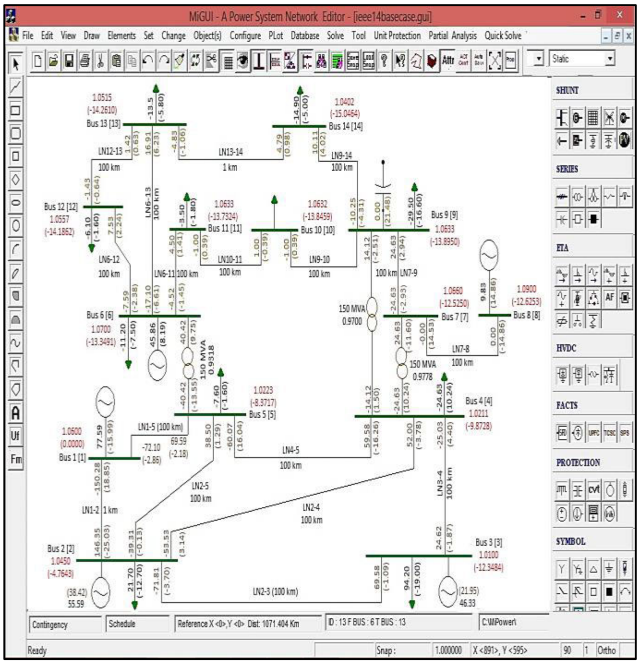


FIGURE 5. Diagram of the connected network using Mi-Power.

such as PHS, solar power, and EV-battery storage, to balance the power system and circumvent scenarios in which demand exceeds supply. The integration of thermal and renewable power generation necessitates the consideration of the uncertain nature of renewable energy sources.

The objective of the paper is to maximize the economic sustainability of the hybrid power system by addressing the Inequality Expenses ($\mathrm{Exp}_{\mathrm{Ine}}$) and incorporating double auctioned bidding. This likely entails the development of strategies and algorithms to optimize the operation and coordination of diverse power generation sources in the presence of uncertainty. The entire work has been performed using Mi-Power software and a comparison has been performed among different optimization techniques. Fig. 5 displays the diagram of the connected network using Mi-Power. The power generated from wind farms considering the true and projected wind velocity are depicted in Table 2.

Application of Presented Methodology Phase-1: The operating modes of the PHS plant and EV battery are subject to change every hour to fulfill the commitment to the system and maintain the frequency of the grid. This dynamic adjustment of operating modes is crucial in ensuring the smooth functioning of the power system.

The presented methodology, which is implemented using Mi-Power, takes into account the technological aspects and scheduling operations of the hybrid plant to supply power most efficiently and economically. The use of Mi-Power allows for a comprehensive analysis of the system and enables optimal decision-making in terms of power generation and storage. Table 3 provides a detailed comparative study of the economic parameters of the system and the levels of new energy after the application of the presented methodology in phase 1 using Mi-Power.

This table serves as a valuable resource for understanding the impact of the presented methodology on the financial aspects of the system. The energy levels of the PHS plant exhibit variability between the optimal energy stage ($E_{\mathrm{PHS,opt}}$) and the lower energy level ($E_{\mathrm{PHS,low}}$) during maximum hours. This variability in energy levels has a direct influence on the profitability and revenue generation of the plant. By operating at higher energy levels during peak hours, the PHS plant can maximize its profit and revenue. The profit of the system is directly influenced by the true wind power generation. This is due to the lower investment cost associated

TABLE 2. Power generated from wind farms considering the true and projected wind velocity (in MW).

Hour	WP_{True}	WP_{Proj}	Hour	WP_{True}	WP_{Proj}	Hour	WP_{True}	WP_{Proj}
1	59.56	56.06	9	35.06	40.8933	17	58.3933	59.56
2	55.4767	54.8933	10	58.3933	53.7267	18	43.81	40.8933
3	43.81	39.1433	11	59.56	52.56	19	39.1433	54.8933
4	47.8933	49.6433	12	29.2267	24.56	20	53.7267	41.4767
5	53.7267	58.3933	13	56.06	43.81	21	29.2267	24.56
6	41.4767	42.06	14	47.8933	50.2267	22	55.4767	58.3933
7	50.2267	52.56	15	58.3933	56.6433	23	42.06	43.81
8	54.8933	56.6433	16	41.4767	43.81	24	54.8933	41.4767

TABLE 3. Economic parameters of PHS hybrid plant (By presented methodology phase-1 using Mi-Power).

Hour	PHS Final Energy level (MWh)	Revenue ($/h)						Gen. Price ($/h)	Profit ($/h)
		From PSP Generation	From Wind Farm	PSP Plant Cost of Pumping Operation	Total Revenue of PHS Plant	From Thermal Plant	Total Revenue of Hybrid Plant		
1	53.94	0	1069.768	138.35	931.418	5056.405	5987.823	2763.09	3224.733
2	62.34	0	1179.621	247.7958	931.8248	5344.887	6276.712	2914.07	3362.642
3	51.23	217.53	765.59	0	983.12	4909.848	5892.968	2686.04	3206.928
4	45.67	109.64	836.8354	0	946.4754	4909.848	5856.323	2686.04	3170.283
5	54.07	0	939.8514	398.35	541.5014	5344.887	5886.388	2914.07	2972.318
6	42.96	217.53	724.8786	0	942.4086	4909.848	5852.257	2686.04	3166.217
7	31.85	217.53	877.5486	0	1095.079	4909.848	6004.927	2686.04	3318.887
8	29.91	39.5115	958.9714	0	998.4829	4909.848	5908.331	2686.04	3222.291
9	38.31	0	539.04	398.35	140.69	5344.887	5485.577	2914.07	2571.507
10	42.23	0	1050.619	185.018	865.601	5106.974	5972.575	2789.52	3183.055
11	36.67	109.64	1040.396	0	1150.036	4909.848	6059.884	2686.04	3373.844
12	45.07	0	528.304	313.0812	215.2228	5344.887	5560.11	2914.07	2646.04
13	39.51	109.64	979.328	0	1088.968	4909.848	5998.816	2686.04	3312.776
14	36.92	52.09795	836.8354	0	888.9334	4909.848	5798.781	2686.04	3112.741
15	38.39	0	1037.828	68.35	969.4776	4982.219	5951.697	2724.19	3227.507
16	35.8	52.09795	724.8786	0	776.9765	4909.848	5686.825	2686.04	3000.785
17	44.2	0	1040.053	398.35	641.7026	5344.887	5986.59	2914.07	3072.52
18	38.64	109.64	765.59	0	875.23	4909.848	5785.078	2686.04	3099.038
19	27.53	217.53	684.1654	0	901.6954	4909.848	5811.543	2686.04	3125.503
20	27.53	0	938.6166	0	938.6166	4909.848	5848.465	2686.04	3162.425
21	35.93	0	313.584	398.35	-84.766	5344.887	5260.121	2914.07	2346.051
22	24.82	217.53	969.1506	0	1186.681	4909.848	6096.529	2686.04	3410.489
23	22.88	39.5115	735.056	0	774.5675	4909.848	5684.416	2686.04	2998.376
24	31.28	0	964.9006	398.35	566.5506	5344.887	5911.438	2914.07	2997.368
Total					**19266.49**	**121297.7**	**140564.2**	**66279.85**	**74284.32**

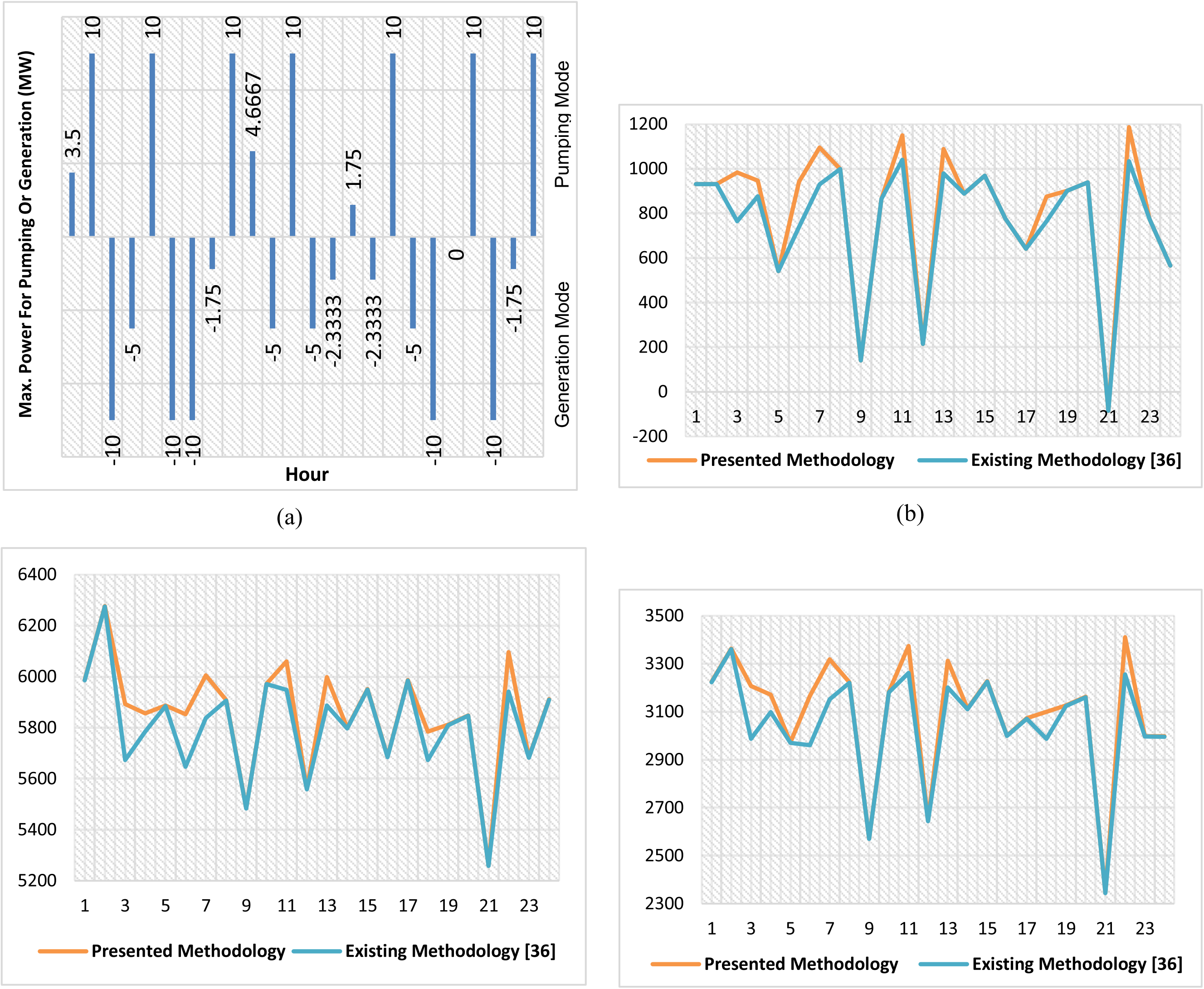
TABLE 4. Economic parameters of PHS hybrid plant (By existing methodology phase-1 using Mi-Power).

Hour	PHS Final Energy level (MWh)	Revenue ($/h)						Gen. Price ($/h)	Profit ($/h)
		From PSP Generation	From Wind Farm	PSP Plant Cost of Pumping Operation	Total Revenue of PHS Plant	From Thermal Plant	Total Revenue of Hybrid Plant		
1	53.94	0	1069.768	138.35	931.418	5054.555	5985.973	2763.36	3222.613
2	62.34	0	1179.621	247.7958	931.8248	5343.037	6274.862	2914.34	3360.522
3	62.34	0	765.59	0	765.59	4907.998	5673.588	2686.31	2987.278
4	60.4	39.5115	836.8354	0	876.3469	4907.998	5784.345	2686.31	3098.035
5	68.8	0	939.8514	398.35	541.5014	5343.037	5884.538	2914.34	2970.198
6	68.15	14.33645	724.8786	0	739.215	4907.998	5647.213	2686.31	2960.903
7	65.56	52.09795	877.5486	0	929.6465	4907.998	5837.645	2686.31	3151.335
8	63.62	39.5115	958.9714	0	998.4829	4907.998	5906.481	2686.31	3220.171
9	72.02	0	539.04	398.35	140.69	5343.037	5483.727	2914.34	2569.387
10	75.94	0	1050.619	185.018	865.601	5105.124	5970.725	2789.79	3180.935
11	75.94	0	1040.396	0	1040.396	4907.998	5948.394	2686.31	3262.084
12	84.34	0	528.304	313.0812	215.2228	5343.037	5558.26	2914.34	2643.92
13	84.34	0	979.328	0	979.328	4907.998	5887.326	2686.31	3201.016
14	81.75	52.09795	836.8354	0	888.9334	4907.998	5796.931	2686.31	3110.621
15	83.22	0	1037.828	68.35	969.4776	4980.369	5949.847	2724.46	3225.387
16	80.63	52.09795	724.8786	0	776.9765	4907.998	5684.975	2686.31	2998.665
17	89.03	0	1040.053	398.35	641.7026	5343.037	5984.74	2914.34	3070.4
18	89.03	0	765.59	0	765.59	4907.998	5673.588	2686.31	2987.278
19	77.92	217.53	684.1654	0	901.6954	4907.998	5809.693	2686.31	3123.383
20	77.92	0	938.6166	0	938.6166	4907.998	5846.615	2686.31	3160.305
21	86.32	0	313.584	398.35	-84.766	5343.037	5258.271	2914.34	2343.931
22	83.08	64.68655	969.1506	0	1033.837	4907.998	5941.835	2686.31	3255.525
23	81.14	39.5115	735.056	0	774.5675	4907.998	5682.566	2686.31	2996.256
24	89.54	0	964.9006	398.35	566.5506	5343.037	5909.588	2914.34	2995.248
Total					**18128.44**	**121253.3**	**139381.7**	**66286.33**	**73095.39**

with wind power compared to thermal power. As the true wind power generation increases, the profit of the system also increases, resulting in a more cost-effective operation. The presented methodology introduces different maximum and minimum power ratings for the generation or pumping modes of the PHS power plant. This flexibility in power ratings allows for greater utilization of wind power and the PHS plant compared to other existing methodologies. By optimizing the power ratings, the presented methodology enables a more efficient and effective utilization of the available resources. Figure 6(a) represents the maximum and minimum power capacities for the pumping and generation mode of the PHS plant after the implementation of the presented methodology. The figure serves as a graphical representation of the power capacities, providing a clear understanding of the operational capabilities of the PHS plant.

At the 20th hour, the PHS plant remains in an idle condition, as the maximum power rating is zero during that specific hour. This idle state of the PHS plant is a result of the specific operational constraints and requirements of the system. In a power system, the generator offers price coefficients that are fixed for all generators. This means that the solution to the optimal power flow problem aims to minimize the generation cost by adjusting the generation schedules of thermal power plants.

The presented methodology has been compared with the existing methodology [44] to confirm the efficacy of the presented methodology. A thorough comparison analysis of the system's economic characteristics and the amount of additional energy following the use of the existing methodology in phase 1 with Mi-Power is given in Table 4. When comparing the presented methodology with the existing one,



(a) (b)

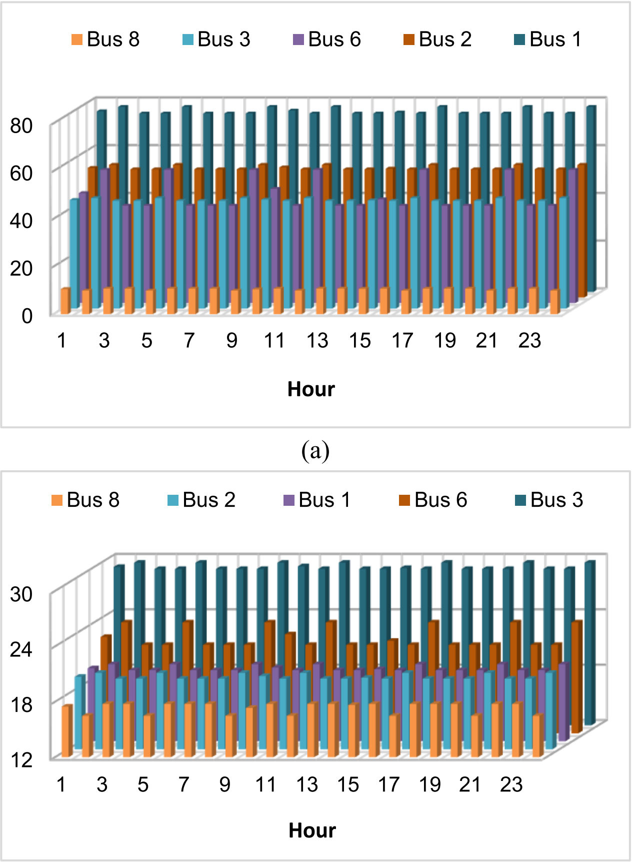
(c) (d)

FIGURE 6. System performance (a) PHS Plant's Operating Power Range (b) Revenue of PHS System (c) Revenue of Hybrid System (d) Profit of Hybrid System.

all limitations and system utilization have been taken into account.

From the comparison that has been made between the presented methodology and the existing methodology, one can observe that all types of revenue have been maximized through the minimization of the system generation cost in the presented methodology. As a result, the system profit is automatically maximized. This occurrence is a direct result of the optimal scheduling of the PHS plant energy level that has been proposed in the presented methodology. Figures 6(b) and 6(c) present a comparative study of the revenue generated from the PSH power plant and hybrid power plant. The figure demonstrates that the presented methodology outperforms the existing methodology [44] in terms of revenue maximization. Throughout the analyzed interval, the presented methodology consistently yields the maximum revenue. By employing the presented methodology, the overall system revenue has reached a remarkable value of 140564.2$ for a particular day. In contrast, the existing methodology only generates revenue of 139381.7$ during the same period. This significant increase in revenue showcases the superiority of the presented methodology in maximizing the financial gains of the system.

In a renewable integrated system, the economic benefit of the system heavily relies on the optimal scheduling of the renewable sources, storage devices, and the corresponding selling prices of the power. The efficient management and coordination of these elements are key factors in ensuring the success of the system for both the operators and customers. One of the primary contributors to the system's performance is the power generation from the thermal power plant, which must be carefully controlled and optimized.



(a)

(b)

FIGURE 7. **(a) Thermal power generation (MW) (b) LBMP ($/MWh) for presented methodology.**

Additionally, location-based marginal pricing (LBMP) also plays a pivotal role in determining the overall effectiveness of the system. It is essential to consider the fluctuating nature of wind power generation, which cannot be easily controlled. Therefore, it becomes imperative to focus on controlling and managing the thermal power and power from storage devices. To illustrate the findings and conclusions, specific cases were considered and analyzed.

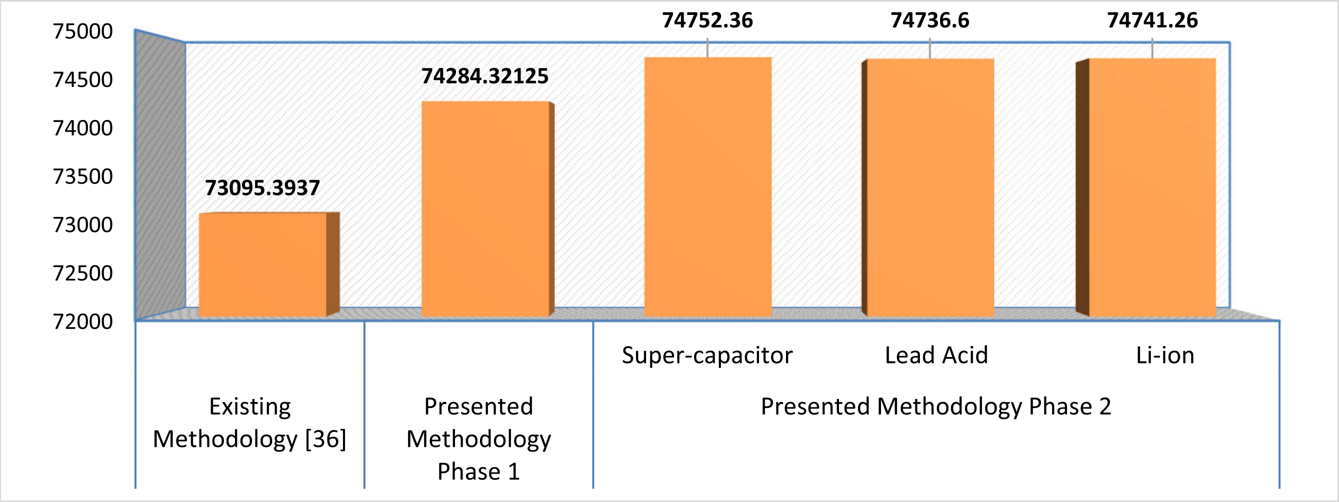
Figures 7(a) and 7(b) visually represent the generated thermal power and the corresponding LBMP for these examined scenarios using the presented methodology. The revenue obtained from the hybrid plant remains consistent for both Phases 1 and 2 of the presented methodology as the power committed to the system remains fixed in both scenarios. Nevertheless, the cost incurred for power generation differs between Phases 1 and 2 due to the distinct scheduling of power generation. The system's profitability is contingent upon both the revenue and generation cost. Profit is attained when the revenue surpasses the generation cost. Upon observing Figure 6(d), it becomes apparent that the presented methodology yields superior outcomes in terms of maximizing profit as compared to the existing methodology.

Application of Presented Methodology Phase-2: In Phase 2 of the study, a total of three distinct types of EV batteries are employed, which are distinguished and classified based on their respective ratings and efficiency levels. According to the presented scheduling strategy, it is stipulated that the EV battery undergoes regular charging and discharging processes throughout the daytime period. Nevertheless, once the solar radiation falls below a specific predetermined threshold level, the EV battery is strictly prohibited from engaging in any discharging activities. The rationale behind this prohibition lies in the fact that the energy that has been stored within the EV battery is crucially required during the nighttime period to effectively balance the overall power demand and supply, thereby ensuring the maintenance of the grid frequency at an optimal level.

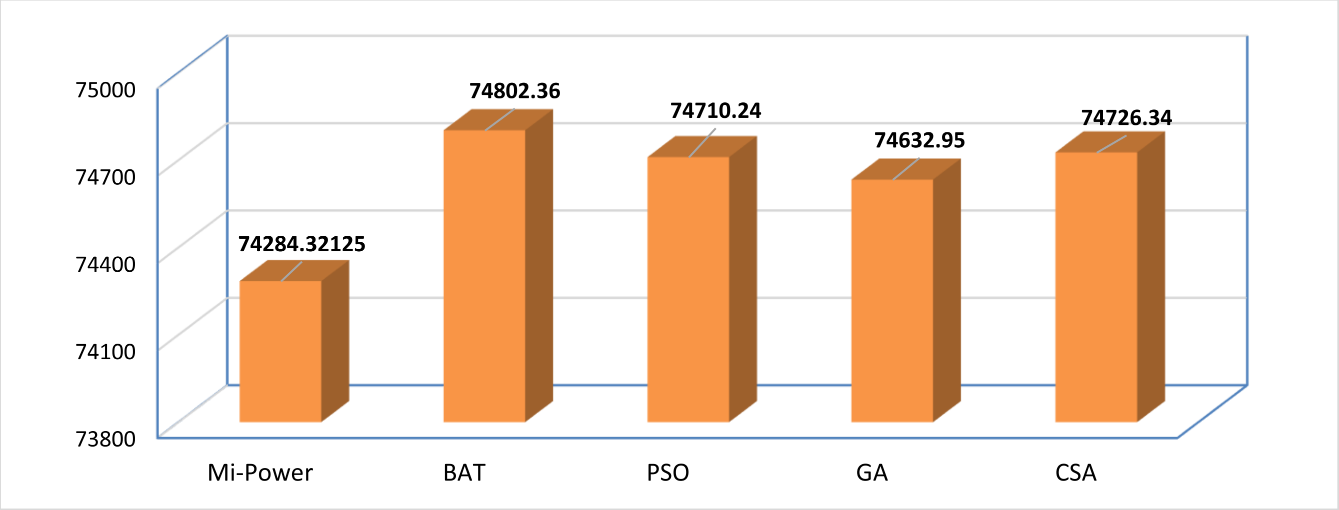
Consequently, it can be deduced that the EV battery functions normally until 4 PM, and subsequently, no discharging activities are permitted to occur until certain predetermined conditions, namely conditions 5 and 6, come into play and are satisfied. Upon careful examination of Fig. 8, one can easily discern and observe the comprehensive and detailed outcomes and results of the revenue and profit that have been successfully attained and achieved for a wide variety of different intervals, all of which were obtained and derived after the diligent and meticulous application of the presented methodology in Phase 2. It is important to note that upon thorough analysis of the aforementioned table, it becomes readily apparent that the overall profit experiences a consistent and notable increase as the contribution and involvement of PV power and wind power gradually amplify and intensify.

Furthermore, it is also crucial to emphasize the fact that for significantly large-scale systems, wherein the contributions made by PV power and wind power are substantial, the resultant profit can indeed be exceptionally and remarkably high, thereby showcasing the immense potential and viability of such systems. Phase 2 is unequivocally and incontrovertibly superior and more advantageous as compared to Phase 1, primarily because the former incorporates and integrates the utilization and deployment of both solar power and EV batteries in addition to the regular wind-PHS plant. The scheduling and arrangement of the wind-PSH-solar-EV battery system is explicitly found to be considerably more beneficial and advantageous in terms of profit maximization when compared to the scheduling and arrangement of solely the wind-PHS plant, thereby providing tangible evidence of the immense and significant value and worth of such a hybrid system.

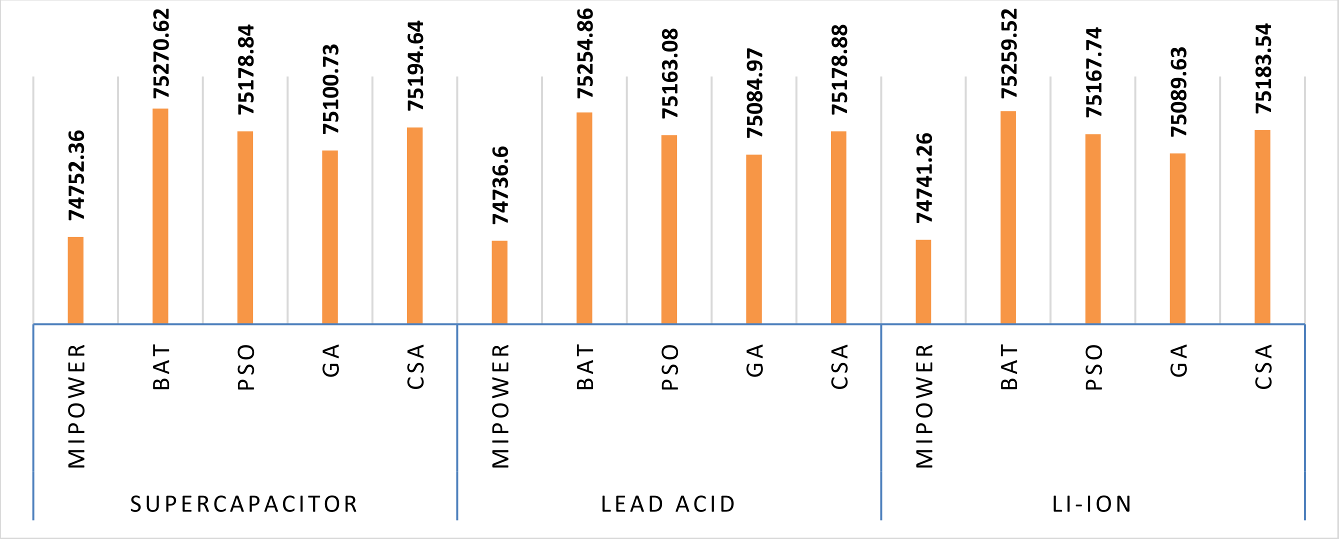
The comprehensive analysis of Fig. 8 effectively and efficiently showcases and depicts the meticulous and diligent study and examination that has been conducted and carried out about the overall profit that has been attained and achieved over a specific day by employing and utilizing various existing methodologies, Phase 1 of the presented methodology, as well as Phase 2 of the presented methodology. It is crucial to note that after extensively and thoroughly analyzing and scrutinizing all of the aforementioned approaches, it becomes readily apparent and evident that the utilization and integration of a supercapacitor in Phase 2 of the presented methodology results in the generation of the maximum profit.



(a)



(b)



(c)

FIGURE 8. System profit (In $/Day) (a) With Existing and Presented Methodology (Using Mi-Power), (b) Using different algorithms with presented methodology Phase-1, (c) Using different algorithms with presented methodology Phase–2.

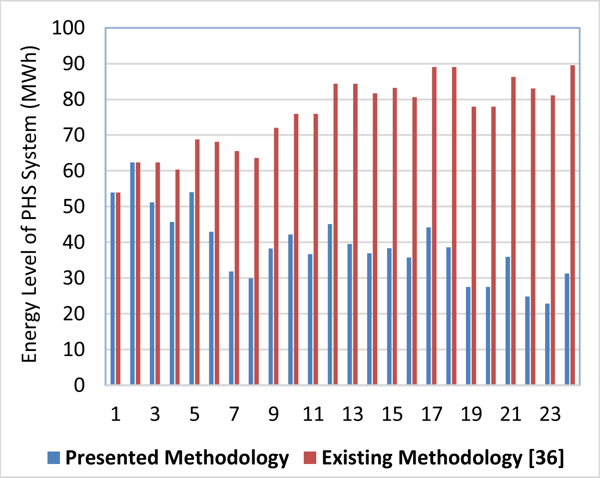


FIGURE 9. Energy level comparison of PHS system.

This notable and significant outcome can be attributed to the higher efficiency levels that are inherently associated and linked with the aforementioned supercapacitor.

The results and findings that have been obtained and derived from the presented methodologies are meticulously and comprehensively compared and contrasted with the outcomes and findings that have been derived from a variety of other well-known and widely utilized algorithms, such as BAT, PSO, GA, and CSA algorithms. Upon thorough examination and analysis, it becomes readily apparent and evident that the BAT algorithm is unequivocally and incontrovertibly the most successful and effective in terms of profit generation, as it successfully generates and yields a maximum profit amounting to an impressive value when utilized and employed in conjunction with Phase 1 of the presented methodology. After conducting and performing an exhaustive study and analysis of the outcomes and results on the system profit that has been obtained and achieved by implementing and utilizing Phase 2 of the presented methodology in combination with various types of EV batteries, it can be definitively concluded and determined that the BAT algorithm, when utilized in conjunction with a supercapacitor, unquestionably generates and yields the maximum profit. Conversely, the utilization and integration of Mi-Power in combination with a lead-acid battery results in the generation of the minimum profit. The underlying and fundamental strategy that has been proposed and put forth in the paper revolves around the optimal scheduling and arrangement of the energy levels of the PHS plant, the solar-connected EV battery storage, as well as the effective and efficient utilization and deployment of solar-battery to effectively and efficiently maximize the overall profit.

The comprehensive and detailed analysis provided by Fig. 9 effectively and efficiently showcases and depicts the meticulous and diligent study and examination that has been conducted and carried out about the energy levels of the PHS plant, both when utilizing the existing methodology and the presented methodology. It is crucial to note that upon thorough analysis and scrutiny, it becomes readily apparent and evident that the energy levels that are associated and linked with the existing methodology consistently and persistently surpass and exceed those that are associated and linked with the presented methodologies, thereby providing tangible evidence of the superior and more advantageous nature of the presented method. This notable disparity can be primarily attributed to the fact that the proposed method not only focuses on the energy levels of the PHS plant itself but also places considerable emphasis and importance on the optimal utilization and deployment of PHS, solar power, as well as EV battery power to effectively and efficiently maximize the overall system revenue and profit.

In the presented methodology, it is always ensured that a specific lower energy level is consistently upheld. This maintenance of a certain lower energy level is an integral aspect of the approach being put forth. By consistently maintaining this lower energy level, the presented methodology aims to achieve the desired outcome. It is crucial to note that this lower energy level is not subject to fluctuations or deviations, but rather is upheld with unwavering consistency. This deliberate emphasis on maintaining a specific lower energy level serves as a foundational principle within the presented methodology and is integral to its overall effectiveness and success. By adhering to this principle, the approach seeks to optimize its outcomes and ensure the desired results are attained. The significance of this lower energy level lies in its ability to contribute to the overall efficiency and effectiveness of the approach, as it serves as a guiding force and parameter for the actions and processes within the presented methodology. Therefore, it is imperative to maintain this lower energy level to maximize the benefits and potential of the presented methodology.

VI. CONCLUSION

The paper introduces a detailed proposal for a two-stage operational strategy aimed at maximizing revenue and profit of a wind-PHS-solar connected EV battery hybrid system in a day-ahead double auctioned electricity market. This strategy considers grid frequency and energy levels of the PHS plant and EV batteries. It differs from traditional PHS and solar power operations, where the PHS plant is mainly used for peak demand shaving. Instead, the proposed method utilizes the PHS plant to offset wind power uncertainties, ensuring generation patterns are met with solar power and EV-battery storage. By optimizing solar power and EV batteries, along with first phase scheduling, the goal is to increase revenue and profit while reducing reliance on thermal power. Results show the proposed method outperforms an existing one in all cases. Additionally, the second phase enhances system reliability and security, ultimately improving performance. Simulations conducted hourly demonstrate enhanced reservoir utilization, contributing to system stability. Proper scheduling of the solar-EV battery combination further reinforces system stability and security, boosting confidence in its performance. The study concludes that the proposed method effectively maximizes revenue and profit while addressing grid frequency maintenance and wind power uncertainties. The BAT algorithm is recommended for optimal power flow, underlining its importance in achieving desired outcomes. Overall, the two-phase operational strategy represents a significant advancement in maximizing revenue and profit in a hybrid system within a day-ahead double auctioned electricity market, ensuring stability and security.

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REFERENCES

[1] J. B. Basu, S. Dawn, P. K. Saha, M. R. Chakraborty, and T. S. Ustun, "Economic enhancement of wind–thermal–hydro system considering imbalance cost in deregulated power market," *Sustainability*, vol. 14, no. 23, p. 15604, Nov. 2022.

[2] P. P. Dey, D. C. Das, A. Latif, S. M. S. Hussain, and T. S. Ustun, "Active power management of virtual power plant under penetration of central receiver solar thermal-wind using butterfly optimization technique," *Sustainability*, vol. 12, no. 17, p. 6979, Aug. 2020.

[3] A. Chauhan, S. Upadhyay, M. T. Khan, S. M. S. Hussain, and T. S. Ustun, "Performance investigation of a solar photovoltaic/diesel generator based hybrid system with cycle charging strategy using BBO algorithm," *Sustainability*, vol. 13, no. 14, p. 8048, Jul. 2021.

[4] S. Dawn, P. K. Tiwari, and A. K. Goswami, "An approach for long term economic operations of competitive power market by optimal combined scheduling of wind turbines and FACTS controllers," *Energy*, vol. 181, pp. 709–723, Aug. 2019.

[5] A. K. Barik, D. C. Das, A. Latif, S. M. S. Hussain, and T. S. Ustun, "Optimal voltage–frequency regulation in distributed sustainable energy-based hybrid microgrids with integrated resource planning," *Energies*, vol. 14, no. 10, p. 2735, May 2021.

[6] N. K. Singh, C. Koley, S. Gope, S. Dawn, and T. S. Ustun, "An economic risk analysis in wind and pumped hydro energy storage integrated power system using meta-heuristic algorithm," *Sustainability*, vol. 13, no. 24, p. 13542, Dec. 2021.

[7] S. M. S. Hussain, M. A. Aftab, I. Ali, and T. S. Ustun, "IEC 61850 based energy management system using plug-in electric vehicles and distributed generators during emergencies," *Int. J. Electr. Power Energy Syst.*, vol. 119, Jul. 2020, Art. no. 105873.

[8] I. Hussain, D. C. Das, N. Sinha, A. Latif, S. M. S. Hussain, and T. S. Ustun, "Performance assessment of an islanded hybrid power system with different storage combinations using an FPA-tuned two-degree-of-freedom (2DOF) controller," *Energies*, vol. 13, no. 21, p. 5610, Oct. 2020.

[9] A. Das, S. Dawn, S. Gope, and T. S. Ustun, "A risk curtailment strategy for solar PV-battery integrated competitive power system," *Electronics*, vol. 11, no. 8, p. 1251, Apr. 2022.

[10] M. Shirkhani, J. Tavoosi, S. Danyali, A. K. Sarvenoee, A. Abdali, A. Mohammadzadeh, and C. Zhang, "A review on microgrid decentralized energy/voltage control structures and methods," *Energy Rep.*, vol. 10, pp. 368–380, Nov. 2023.

[11] C. Zhu, M. Wang, M. Guo, J. Deng, Q. Du, W. Wei, Y. Zhang, and S. S. Ashraf Talesh, "Optimizing solar-driven multi-generation systems: A cascade heat recovery approach for power, cooling, and freshwater production," *Appl. Thermal Eng.*, vol. 240, Mar. 2024, Art. no. 122214.

[12] X. Zhou, Y. Cai, and X. Li, "Process arrangement and multi-aspect study of a novel environmentally-friendly multigeneration plant relying on a geothermal-based plant combined with the goswami cycle booted by Kalina and desalination cycles," *Energy*, vol. 299, Jul. 2024, Art. no. 131381.

[13] A. A. Eladl, S. Fawzy, E. E. Abd-Raboh, A. Elmitwally, G. Agundis-Tinajero, J. M. Guerrero, and M. A. Hassan, "A comprehensive review on wind power spillage: Reasons, minimization techniques, real applications, challenges, and future trends," *Electric Power Syst. Res.*, vol. 226, Jan. 2024, Art. no. 109915.

[14] M. Haji Bashi, L. De Tommasi, and P. Lyons, "Electricity market integration of utility-scale battery energy storage units in ireland, the status and future regulatory frameworks," *J. Energy Storage*, vol. 55, Nov. 2022, Art. no. 105442.

[15] S. Kerscher and P. Arboleya, "The key role of aggregators in the energy transition under the latest European regulatory framework," *Int. J. Electr. Power Energy Syst.*, vol. 134, Jan. 2022, Art. no. 107361.

[16] G. Wang, Y. Chao, Y. Cao, T. Jiang, W. Han, and Z. Chen, "A comprehensive review of research works based on evolutionary game theory for sustainable energy development," *Energy Rep.*, vol. 8, pp. 114–136, Nov. 2022.

[17] M. R. Chakraborty, S. Dawn, P. K. Saha, J. B. Basu, and T. S. Ustun, "A comparative review on energy storage systems and their application in deregulated systems," *Batteries*, vol. 8, no. 9, p. 124, Sep. 2022.

[18] Z. Zhu, Z. Hu, K. W. Chan, S. Bu, B. Zhou, and S. Xia, "Reinforcement learning in deregulated energy market: A comprehensive review," *Appl. Energy*, vol. 329, Jan. 2023, Art. no. 120212.

[19] F. Xu, W. Zhu, Y. F. Wang, C. S. Lai, H. Yuan, Y. Zhao, S. Guo, and Z. Fu, "A new deregulated demand response scheme for load over-shifting city in regulated power market," *Appl. Energy*, vol. 311, Apr. 2022, Art. no. 118337.

[20] Y. Hu, M. Armada, and M. J. Sánchez, "Potential utilization of battery energy storage systems (BESS) in the major European electricity markets," *Appl. Energy*, vol. 322, Sep. 2022, Art. no. 119512.

[21] S. Panda, S. Mohanty, P. K. Rout, B. K. Sahu, S. M. Parida, I. S. Samanta, M. Bajaj, M. Piecha, V. Blazek, and L. Prokop, "A comprehensive review on demand side management and market design for renewable energy support and integration," *Energy Rep.*, vol. 10, pp. 2228–2250, Nov. 2023.

[22] R. Han, Q. Hu, H. Cui, T. Chen, X. Quan, and Z. Wu, "An optimal bidding and scheduling method for load service entities considering demand response uncertainty," *Appl. Energy*, vol. 328, Dec. 2022, Art. no. 120167.

[23] J. Liu, R. Bo, S. Wang, and H. Chen, "Optimal scheduling for profit maximization of energy storage merchants considering market impact based on dynamic programming," *Comput. Ind. Eng.*, vol. 155, May 2021, Art. no. 107212.

[24] L. Pan, X. Xu, J. Liu, and W. Hu, "Adaptive robust scheduling of a hydro/photovoltaic/pumped-storage hybrid system in day-ahead electricity and hydrogen markets," *Sustain. Cities Soc.*, vol. 95, Aug. 2023, Art. no. 104571.

[25] P. K. Tiwari, M. K. Mishra, and S. Dawn, "A two step approach for improvement of economic profit and emission with congestion management in hybrid competitive power market," *Int. J. Electr. Power Energy Syst.*, vol. 110, pp. 548–564, Sep. 2019.

[26] H. Khajeh, C. Parthasarathy, E. Doroudchi, and H. Laaksonen, "Optimized siting and sizing of distribution-network-connected battery energy storage system providing flexibility services for system operators," *Energy*, vol. 285, Dec. 2023, Art. no. 129490.

[27] B. Wang, X. Wang, Z. Zhu, and X. Wu, "Siting and sizing of energy storage for renewable generation utilization with multi-stage dispatch under uncertainty: A tri-level model and decomposition approach," *Appl. Energy*, vol. 344, Aug. 2023, Art. no. 121286.

[28] V. Asgharian, A. Hajebrahimi, M. Abdelaziz, and I. Kamwa, "Coordinated generation expansion planning & energy storage planning model of the IPP's participation in the electricity markets," *Electr. Power Syst. Res.*, vol. 205, Apr. 2022, Art. no. 107743.

[29] M. Khosravi, S. Afsharnia, and S. Farhangi, "Optimal sizing and technology selection of hybrid energy storage system with novel dispatching power for wind power integration," *Int. J. Electr. Power Energy Syst.*, vol. 127, May 2021, Art. no. 106660.

[30] D. Asija and P. Choudekar, "Congestion management using multi-objective hybrid DE-PSO optimization with solar-ess based distributed generation in deregulated power Market," *Renew. Energy Focus*, vol. 36, pp. 32–42, Mar. 2021.

[31] A. Sanyal, P. K. Tiwari, and A. K. Goswami, "An efficient bidding strategy for selecting most economic horizon in restructured electricity market with hybrid generation and energy storage," *J. Energy Storage*, vol. 28, Apr. 2020, Art. no. 101289.

[32] J. B. Basu, S. Dawn, P. K. Saha, M. R. Chakraborty, F. Alsaif, S. Alsulamy, and T. S. Ustun, "Risk mitigation & profit improvement of a wind-fuel cell hybrid system with TCSC placement," *IEEE Access*, vol. 11, pp. 39431–39447, 2023.

[33] S. Kumar, B. Dwivedi, and N. A. Shrivastava, "A game theory strategy-based bidding evaluation for power generation market," *IEEE Can. J. Electr. Comput. Eng.*, vol. 44, no. 3, pp. 283–288, Summer. 2021.

[34] C. Jena, J. M. Guerrero, A. Abusorrah, Y. Al-Turki, and B. Khan, "Multi-objective generation scheduling of hydro-thermal system incorporating energy storage with demand side management considering renewable energy uncertainties," *IEEE Access*, vol. 10, pp. 52343–52357, 2022.

[35] S. F. Santos, M. Gough, D. Z. Fitiwi, A. F. P. Silva, M. Shafie-Khah, and J. P. S. Catalão, "Influence of battery energy storage systems on transmission grid operation with a significant share of variable renewable energy sources," *IEEE Syst. J.*, vol. 16, no. 1, pp. 1508–1519, Mar. 2022.

[36] L. C. Kien, N. T. Y. Tuyet, T. M. Phan, and T. T. Nguyen, "The combination of energy storage and renewable energies to reach a maximum profit for power systems," *IEEE Access*, vol. 11, pp. 125929–125950, 2023.

[37] A. G. Papakonstantinou, A. I. Konstanteas, and S. A. Papathanassiou, "Solutions to enhance frequency regulation in an island system with pumped-hydro storage under 100% renewable energy penetration," *IEEE Access*, vol. 11, pp. 76675–76690, 2023.

[38] M. R. Chakraborty, S. Dawn, P. K. Saha, J. B. Basu, and T. S. Ustun, "System profit improvement of a thermal–wind–CAES hybrid system considering imbalance cost in the electricity market," *Energies*, vol. 15, no. 24, p. 9457, Dec. 2022.

[39] M. Liaqat, M. G. Khan, M. R. Fazal, Y. Ghadi, and M. Adnan, "Multi-criteria storage selection model for grid-connected photovoltaics systems," *IEEE Access*, vol. 9, pp. 115506–115522, 2021.

[40] M. H. Athari and M. M. Ardehali, "Operational performance of energy storage as function of electricity prices for on-grid hybrid renewable energy system by optimized fuzzy logic controller," *Renew. Energy*, vol. 85, pp. 890–902, Jan. 2016.

[41] K. Kusakana, "Optimal scheduling for distributed hybrid system with pumped hydro storage," *Energy Convers. Manag.*, vol. 111, pp. 253–260, Mar. 2016.

[42] A. Das, S. Dawn, S. Gope, and T. S. Ustun, "A strategy for system risk mitigation using FACTS devices in a wind incorporated competitive power system," *Sustainability*, vol. 14, no. 13, p. 8069, Jul. 2022.

[43] S. Dawn and P. K. Tiwari, "Improvement of economic profit by optimal allocation of TCSC & UPFC with wind power generators in double auction competitive power market," *Int. J. Elect. Power Energy Syst.*, vol. 80, pp. 190–201, Sep. 2016.

[44] S. Dawn, P. K. Tiwari, and A. K. Goswami, "A joint scheduling optimization strategy for wind and pumped storage systems considering imbalance cost & grid frequency in real-time competitive power market," *Int. J. Renew. Energy Res.*, vol. 6, no. 4, pp. 1248–1259, 2016.

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