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RESEARCH ARTICLE

Application of Dynamic Programming for Optimal Hybrid Energy Management System: Hydro-Photovoltaic-Diesel-BESS

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ABSTRACT The rapid advancement of new resources of energy has been increasing in the world day by day with traditional resources of power generation. The goals of such developments are to increase both economic and environmental benefits. In the literature, there have been a lot of hybrid systems that have come into existence as a combination of different energy resources with different configurations. In this scenario, the combination of different energy resources like photovoltaic (PV), water turbine (hydro), diesel generator (D), and battery energy storage system (BESS), each with a different configuration, is taken into account, leading to a hybrid energy management system. Furthermore, the proposed system leads to a real-world optimization problem that is solved by the use of dynamic programming. For this purpose, we have taken into account the existing day-ahead data of load, electricity, and other sources for the optimal output of the proposed hybrid system. Moreover, the objective function is the minimization of cost by organizing distributed energy resources as well as the emission reduction of toxic gases. The objective function is constrained by balancing the power between the supply and load requirements and the restrictions of each distributed energy resource. A multistage decision procedure known as Dynamic programming is used in regard to state of charge (SOC), which yields the optimal cost of the system. For this purpose, we tried to make use of conventional as well as local turbines, which lead to small hydropower plants that contribute to the proposed system as a case study in the northern areas of Pakistan in order to produce low-cost electricity. The purpose of the proposed study is to develop an optimal hybrid energy management system that generates more power at a minimum cost. Moreover, the maintenance cost is reduced to a high extent as compared to the previous hybrid system in the literature. Due to the minimum use of diesel generator, the proposed hybrid system produces optimal results in terms of clean energy provision as compared to the existent techniques in the literature.

INDEX TERMS Dynamic programming, photo-voltaic, hydropower, diesel generators, energy management, optimization.

I. INTRODUCTION

In recent years, the demand for energy has been increasing significantly due to the rapid increase in the world's population as well as new innovations in modern technology. Conventional energy resources usually result in a harmful environment due to the emission of toxic gases. The clean resources of energy have already been used to produce energy due to the rapid advancement in energy technology. There are some resources of energy like hydropower, solar energy, and wind energy, with each of them having its own features that mainly depend on their location and potential area.Generally, these resources of energy are unstable and have a discontinuous nature throughout the year. Therefore, they are considered

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to be integrated into a hybrid system as a power supply system. Such systems include photovoltaic panels, diesel generators, water turbines, converters, and batteries, which are related to amount, changing cost, functioning, and preservation costs [1], [2].

As the name suggests, a hybrid system is a combination of two or more than two types of power producers using adaptive technologies such as photovoltaic and hydropower. There are different optimized methods, algorithms, and strategies that can better integrate hybrid systems into the grid and with island load [3]. Hybrid systems produce a high level of energy security through the combination of different production methods and typically incorporate storage systems (boilers, fuel chambers) or tight fuel generators to ensure reliability and safety. Petroleum prices have been increasing day by day in the world, which leads to the improvement of renewable energy technologies, and hybrid renewable energy systems are increasingly becoming popular as separate power systems for the provision of electricity to remote areas. A hybrid power system or hybrid energy system usually consists of two or more renewable energy sources that are used together in order to increase the system's efficiency and provide a balanced energy supply. There have been a number of publications based on hybrid energy systems; for instance [5], a microgrid (MG) operation problem was proposed on an economical, technological, and environmental topic with a large number of uncertainties in wind, load, speed, and solar radiation. Moreover, mixed-integer nonlinear programming (MINLP) was used for the problem formulation and was tested in Iran. In their work, the outcomes show that load, cost, and pollutant gas emissions have a high effect on the performance of MGs. In this scenario, a recent approach for problem formulation and effective outcome is given in [6]. Furthermore, a hybrid system is presented in Algeria [7], and they find the feasibility of such a system through optimization methods by considering economic and technical factors. The outcomes from both factors result in an optimal solution.

There have been many approaches used in the literature for the optimization of energy management schemes. An Islanded Hybrid Microgrid System (IHMS) for Tioman Motel located at Tioman Island, Malaysia, in which the major challenge was the excretion of efficient energy, which was handled by an electric heater with energy tanks, and the access load was overcome with proper management [8]. Two locations in Bangladesh, Kushighat and Rajendro Bazar, have been selected as test sites for the optimized design of an off-grid hybrid microgrid for alternative load dispatch algorithms. This includes determining the best size for each piece of equipment, examining the voltage and frequency outputs, and comparing the costs of the various proposed microgrids [9]. An AC-linked hybrid wind/photovoltaic (PV)/fuel cell (FC) hybrid system is used that has the capability to work independently [10]. Moreover, PV and wind are the main sources of this system, while for backup storage, FC-electrolyzers exist.

The modelling of the expenditure characteristics and demand response of an energy management system design for residential microgrids is given in [11]. A hybrid microgrid wind-diesel alternative energy system with results for meeting the given load demands is practically feasible and applicable [12]. A clever lattice combination energy system has been designed and imitated for a small group with a typical load demand of 72 kWh/d and a maximum heap of 7 kW to assist those on the planet who live in dispersed, rural, and isolated areas that are topographically disconnected from lattice association [13]. The Penang Hill Resort, which is on Penang Island in Malaysia, has undergone research that focuses on a multi-optimal combination of IHMS with efficient redundant energy consumption [14]. An artificial multi-period bee colony optimization algorithm has been used for the economic dispatch problem in which storage, generation, and responsive load offers are considered. Furthermore, an artificial neural network is combined with a Markov chain approach in order to predict non-dispatchable power generation and load demand according to the given ambiguities. Moreover, the best solution strategy is obtained by mixed integer linear programming (MILP) [15], [16].

A well-known multiobjective algorithm, PSO, has been used for optimal energy systems [17], [18]. Furthermore, an updated PSO has been presented for the solution of the total cost minimization sub-problem. The quadratic programming (QP) technique is presented to control an optimal energy system containing a network of batteries, PV, and electrical vehicles, with the observation that the objective function needs to be convex for optimal results. Game theory and multiobjective optimization techniques have been used to solve optimal energy management problems for a micro grid with two objectives, namely operating cost and emission level [19], [20]. A novel approach has been used for energy management problems with continuous time and rolling horizon methodologies [21]. Furthermore, two methods, known as direct and dynamic programming principles (DDP), have been used for the optimal solution. Their numerical outcomes concluded that the dynamic programming principle is much more effective in terms of CPU time. This further guarantees that the global optimal solution is obtained in less than one second. A solar tower model has been conducted, and a large amount of electrical energy production has been obtained [23]. Furthermore, the amount of energy output from different cities varies with varying weather conditions, which is discussed in detail. In the vehicular electric power system [23], the reduction of fuel is 2% only while the use of fuel in diesel generator which is a factor in the proposed hybrid energy system is almost negligible. The hybrid system presented in [27], the maintenance cost is too much as compared to the hybrid system presented in this study. Differently, here we follow the above literature review and presented a hybrid energy system as a case study in the northern hilly areas of Pakistan in order to provide cheap and clean energy to the locality. Furthermore, these areas are full of snow throughout the year, and there are streams and canals of water that have the potential to construct hydropower plants. For this purpose, we tried to make use of conventional as well as local turbines that lead to small hydropower plants that contribute to the proposed hybrid energy system in order to produce low-cost electricity. In the following, the hydropower potential in Pakistan is given in detail.

A. HYDROPOWER POTENTIAL IN THE NORTHERN AREAS OF PAKISTAN

Pakistan is a country with a lot of water resources [28], but unfortunately, not much investment has been made yet to make this natural gift useful for Pakistan. On the other hand, the provision of electricity to most parts of the country is not sufficient. For this reason, hydropower is an important source of energy in Pakistan. The energy potential from water resources in Pakistan is approximately 41722 MW, most of which lies in the Khyber Pakhtunkhwa, Northern Areas, Azad Jammu and Kashmir, and Punjab. Mountains in the northern areas of Pakistan remain full of glaciers through the year, as shown in Figure 1. The main rivers and boundaries in the northern areas are divided into three regions, which are given below.

1) Northern Region: The northern areas of Pakistan are to be made up of Gilgit (River Gilgit, Naltar, and its side streams), Hunza (River Boladas, Hunza, and other side streams), Ishkuma (River Ishkuman, Ghizar, and their side streams), Khunjerab (River Khunjarab, River Kilik, and its side streams), and Yasin (River Yasin, River Gilgit, and their side streams).
2) Eastern Region: The eastern areas of Pakistan are to be made up of the Kharmang (River Kharmang and its side streams), Shyok (River Shyok and its side streams), Skardu (River Braldu, River Bashu, River Shigar, and River Indus), and Rondu/Haramosh (River Indus and its side streams).
3) Southern Region: The southern areas of Pakistan are to be made up of the Chilas (the River Indus and its side streams) and the Astore (the River Astore and its side streams).

A large number of hydroelectric potential sites have been identified in the northern areas, but, due to the difficult mountainous region and the non-availability of high-power transmission lines, not much development has been made so far on these sites. Currently, electricity has not reached approximately 60% of the local population. Approximately 241 [22] potential sites have been identified, with an electricity capacity of about 12314 MW. The overall energy potential in Pakistan from different resources is given in Table 1.

Differently, in this study, we intend to introduce a novel hybrid energy system and validate its reliability and punctuality. This system includes a hydroelectric, photovoltaic, diesel generator, and battery energy storage system, which is abbreviated as the Hy-PV-D-BESS system. Furthermore, this problem is considered an optimization problem for an optimal solution. The main contributions of this study are its optimal cost results as well as its environmental benefits at constant charge. Moreover, the proposed hybrid system is well applicable in the northern areas of Pakistan for optimal outcomes, where plenty of hydropower turbines exist. Furthermore, these hydropower turbines could be combined with photovoltaic, diesel generators, and battery energy storage in order to propose a low-cost hybrid system. The proposed system is well applicable in the northern areas of Pakistan, so it was applied over there as a case study. In these areas, mountains remain full of snow throughout the year, which leads to the existence of a lot of small streams and rivers that could be used to establish small projects and, consequently, to provide clean and cheap energy to the locality. These hydropower projects are very fruitful due to their natural structures. Although there are some hydropower projects in these areas that already provide electricity to the locality. In this study, hydropower is combined with photovoltaic, diesel generators, and BESS to yield the proposed hybrid energy system (Hy-PV-D-BESS) in order to get much more optimal results as compared to the existing hybrid energy systems in the literature. For instance, a hybrid energy system has been presented in the literature that consists of a wind-PV-diesel-battery system [27], which is more expensive than the proposed hybrid system.

TABLE 1. Energy potential through different sources in Pakistan.

Energy	Potential
Wind Energy	35 Tera watt/h
Solar Energy	300 $Watt/m^2$
Hydro Power	19547 Mega watt
Oil	27 Billion barrels
Gas	1.6 TCF/year
Nuclear	8800 Mega watt
Coal	100000 Mega watt

This paper is further categorized as follows: Section II presents the proposed hybrid energy system. This section is followed by Section III, which outlines the proposed hybrid system under consideration with a mathematical model. Section IV presents the regulatory energy management strategy. Section V explains the proposed hybrid system for dynamic programming in energy management. This section further describes how the target function calculates the maximum charge from the initial to the last step using the Bellman-Ford algorithm.

II. THE PROPOSED HYBRID ENERGY SYSTEM CONFIGURATION

The system under consideration, which consists of hydroelectric, photovoltaic, diesel generator, and a battery energy storage system (BESS), is given in Figure 2. In the proposed system, 136 solar panels are used, which cover up to 4000 square feet of area and produce around 50 kW of energy. Moreover, a 50 kW diesel generator is used, and a battery energy storage system is used that can support up to 40 kW of load. The battery energy storage system (BESS)

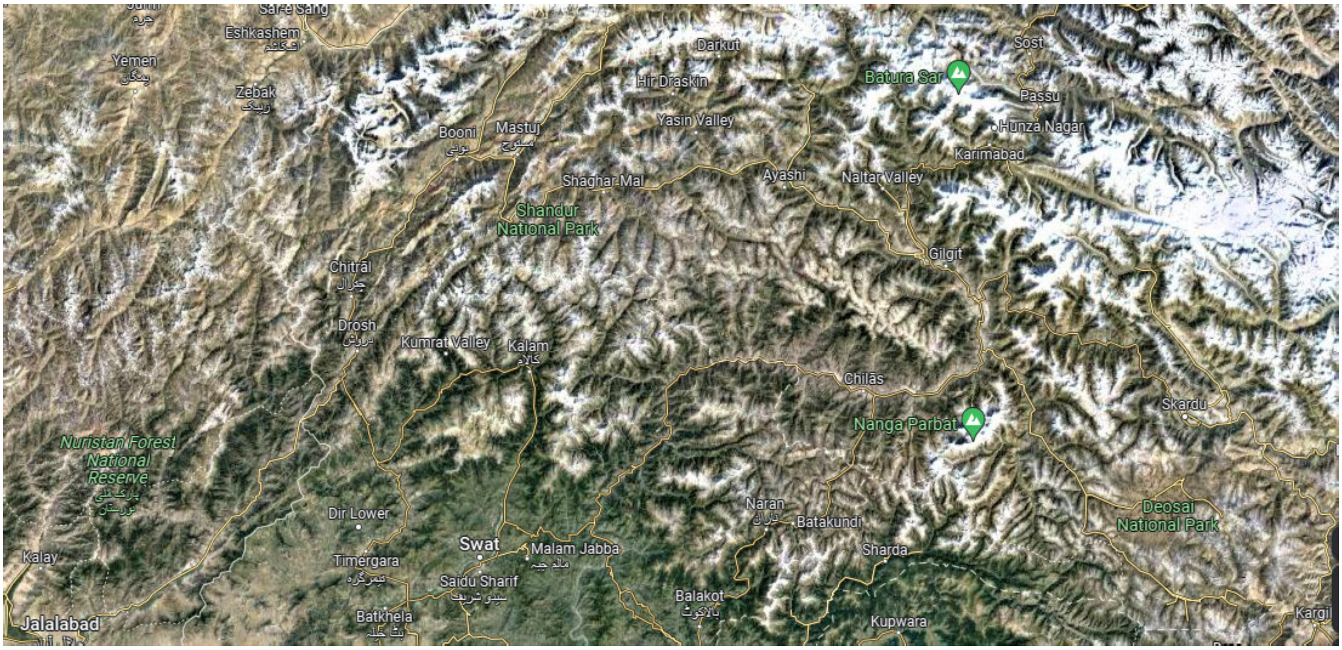

FIGURE 1. Northern areas of Pakistan.

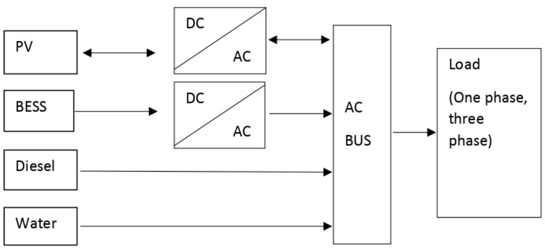

FIGURE 2. Proposed hybrid energy system configuration.

operations mainly rely on the working principles of this system. In case of overload, BESS is charged automatically from the hybrid system, and if consumption exceeds energy production, then BESS unloads the rest of the energy to meet demand. The state of the charge (SOC) equations is given by:

$$SOC(t) = \frac{C(t)}{C_{ref}} \tag{1}$$

In the above equation, $C(t)$ represents the capacity of the battery at time t, and C_{ref} represents the reference battery capacity. SOC(t) is evaluated first from SOC(t-1). In other words, the obtained power and the required load demand for the time duration from (t-1) to t. During the charging period, one can express the state of the charge for the time period given by:

$$SOC(t) = SOC(t-1) + \frac{P_PV(t) + P_w(t) + P_D(t) - P_L(t)}{C_{ref}} \Delta t \tag{2}$$

In the above equation, at time t, we have:
1. $P_L(t)$ represent load;
2. $P_{PV}(t)$ represent PV power;
3. $P_water(t)$ represent mini hydro plant power;
4. $P_D(t)$ represent the diesel power;

Where $\Delta t = 1$ represents the unit time interval and C_{ref} is the battery energy storage system (BESS) capacity (in KWh). If a power shortage happens due to PV, hydropower, or BESS, then a 50 KW generator will need to be installed in order to accomplish the load requirements. On the other hand, the diesel generator will be tripped if output from other production units fulfils the required demand.

III. THE PROPOSED METHODOLOGY

This section presents the optimum power management of the proposed hybrid management system. The objective and constraint functions are described below:

A. OBJECTIVE FUNCTION

For an optimal hybrid system, a model is designed in order to minimize the overall cost of the system. The main objective of the system is to reduce fuel costs (FC), battery replacement costs (B_rC) and emissions costs (EC). This objective function is given by:

$$K = \sum_{j=1}^{24} FC(t) + EC(t) + B_rC(t) \tag{3}$$

In which,

1. Determine the FC by

$$FC(t) = C_f \cdot F(t) \tag{4}$$

FIGURE 3. The proposed Hy-PV-D-BESS hybrid system configuration.

Note that:

1. C_f represent fuel price.
2. F(t) represent the diesel generator (DG) consumption cost per hour.

$$F(t) = 0.2460\, P_D(t) + 0.084150\, P_R \tag{5}$$

where P_R denote the rated power of DG.

3. the EC is given below:

$$EC(t) = \frac{E_t E_{cf} P_D(t)}{1000} \tag{6}$$

where:

1. E_f = is a function of emission of noxious gases (kg/KWh)
2. E_{cf} = cost on emission.
3. B_rC = battery replacement cost.

In this study, BrC in time t corresponds to the total consumption of the battery capacity utilized during time t. In this case, the simulation is carried out in a way that depends on the variation of SOH (ΔSOH)at each time step interval t. The difference in state of health (ΔSOH) at any two consecutive states x_i and x_j during a single step is given in eq; (7). Also, ΔSOH is given in equation (8), which is the linear function of the change in charge state ΔSOC and the aging coefficient (Z). Moreover, ΔSOH is evaluated only during the reset process.

$$\Delta SOHx_i, x_j(t) = SOH(x)_i(t - \Delta t) - SOHx_j(t) \tag{7}$$

$$\Delta SOHx_i, x_j(t) = Z \cdot (SOH(x)_i(t - \Delta t) - SOCx_j(t)) \tag{8}$$

B_rC can be represented as follows [22]:

$$B_rC(t) = BiC\frac{\Delta SOH(t)}{1 - SOH_{min}} \tag{9}$$

where,

1. The investment cost of the battery is represented by BiC.
2. The minimum state of health is represented by (SOH_{min})

Note that the value of Z is (3.1^{-4}) [26].

From equation (4) to equation (9), the objective function is represented by K and given by:

$$K = min \sum_{j=1}^{24} c_f \cdot (0.08415 \cdot P_R + 0.246 \cdot P_D(t)) + \frac{E_t \cdot E_f P_D(t)}{1000} + B_i C \frac{Z \cdot (SOCx_i(t-\Delta t) - SOCx_j(t))}{1 - SOH_{min}} \tag{10}$$

This objective function is the minimization of cost by organizing scattered energy resources as well as the emission reduction of toxic gases. Moreover, objective function is constrained by balancing the power betwixt the supply and load requirements and restrictions of each distributed energy resource.

B. PROBLEM CONSTRAINTS

The objective function in equation (10) is restricted by the following constraints:

$$P_L(t) = P_{PV}(t) + P_{water}(t) + P_B(t) + P_D(t) \tag{11}$$

In the above equation, the power of BESS at time t is represented by $P_B(t)$.

2. BESS power output is given in the following equation:

$$P_{bmin} \leq P_b(t) \leq P_{bmax} \tag{12}$$

The power $P_B(t)$ of BESS with respect to a changeover between two restrictions over a single time step; therefore, the restriction to the SOC is given below:

$$\Delta SOC_{min} \leq \Delta SOC(t) \leq \Delta SOC_{max} \tag{13}$$

3. The state-of-charge (SOC) constraint of the battery is restricted by its pre-defined extreme values:

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \tag{14}$$

4. SOH restriction is given by:

$$SOH(t) \geq SOH_{min} \tag{15}$$

5. Restriction of diesel generator:

Diesel generators should not be run when the production power is less than the lowest power suggested by the producer. The power of diesel at time t is restricted by:

$$P_{die-min} \leq P_D(t) \leq P_{die-max} \tag{16}$$

The lower bound of diesel is $P_{die-min}$ and upper bound of diesel is $P_{die-max}$ respectively.

IV. RULE BASED ENERGY MANAGEMENT STRATEGY

The constraint management technique is based on the pre-defined principles as given in Figure 3. A rule-based energy management strategy is applied that relies on PV power and consumption. It should be noted that this methodology is bounded because the battery state is not considered in the pre-defined principles. Rule-based energy management depends on the following factors, which are known to be the foundation of this system:

1. Renewable energy is an initial source to cover loads.
2. Battery energy storage system start emitting emissions when there is insufficient production.
3. Battery energy storage system will be charged if production is greater than consumption.

The rule-based energy management algorithm based on the above principles will fulfil the following constraints:

$$P_L(t) = P_{PV}(t) + P_{water}(t) + P_B(t) + P_D(t) \tag{17}$$

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \tag{18}$$

$$P_{die-min} \leq P_D(t) \leq P_{die-max} \tag{19}$$

The process is explained in the following steps.

1. Renewable energy and load demand are given as a function of diesel power output.
2. The output of BESS is obtained from the power balance principle.
3. BESS and diesel constraints, that is, (12) to (16), must be fulfilled.

V. APPLICATION OF DYNAMIC PROGRAMMING IN THE PROPOSED HYBRID ENERGY MANAGEMENT SYSTEM

We know that dynamic programming is a multistage decision-making problem. Therefore, the system under consideration is classified as a multistage decision-making process. The system state refers to a set of state variables that are determined by the ΔSOC. The initial state of charge (SOC_0) is expressed as a mode of relationship without the previous nodes. Similarly, the state of the last charge is determined. All fields are listed systematically from t to $t + \Delta t$. As a result, the shift of SOC is plotted sequentially from the initial stage (SOC_0) to the final stage (SOC). Thus, the Bellman method is used to find out the state of SOC, which gives rise to the low cost of the system (CS), as given in Figure 5. The conditions for change in charge (ΔSOC) between two steps x_i and x_j in the same state are given in [22] and are as follows:

$$\Delta SOCx_i, x_j(t) = SOC(x)_i(t - \Delta t) - SOCx_j(t) \tag{20}$$

1. Battery energy storage system discharges if $\Delta SOC < 0$.
2. Battery energy storage system charged if $\Delta SOC > 0$.
3. Battery energy storage system stops if $\Delta SOC = 0$.

From now on, the system cost (CS) is discussed as a relationship to the variation of the state of charge in the objective function (10). The Bellman algorithm is used to get the most reasonable cost of the system (CS), as shown in Figure 4, and is used to find a decent amount of state of charge (SOC) order from the first to the last moment step. Figure 6 shows a flowchart of the Bellman process with the entire calculation of the mass of all the edges. In the diagram, we have described the flowchart of the Bellman method on the right side. There is a step in the flowchart to calculate the mass on the left side. To calculate the weight, the process on the left-hand side is used in the given figure.

The change in SOC is indicated as a function of (P_B). Therefore, each ΔSOC x_i, x_j (t) is calculated by $P_B(t)$. Then

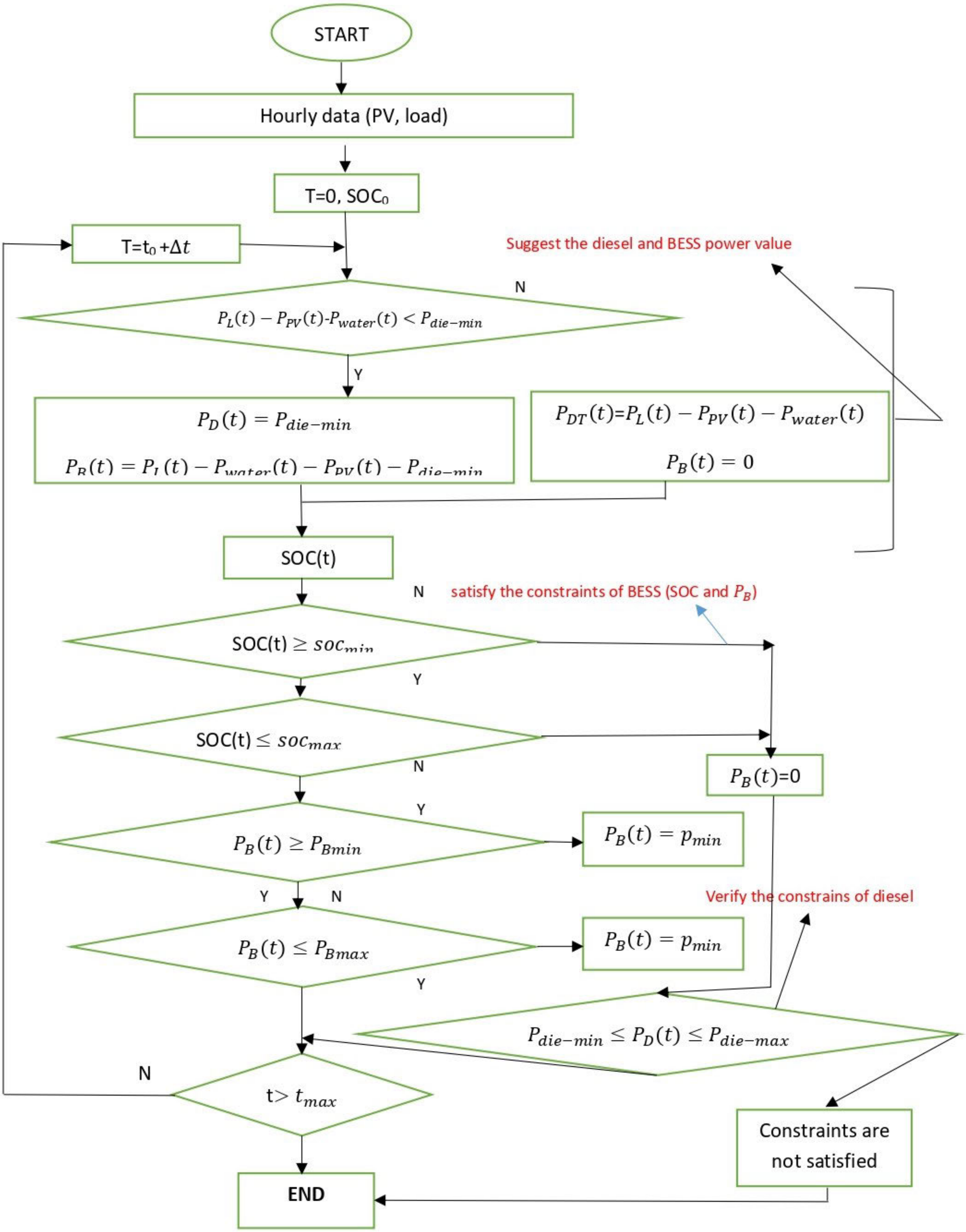

FIGURE 4. The proposed hybrid system flowchart by rule based energy management strategy.

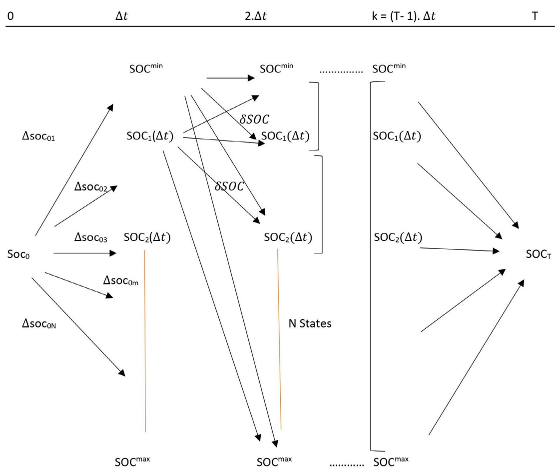

FIGURE 5. Proposed multistage decision process w.r.t SOC.

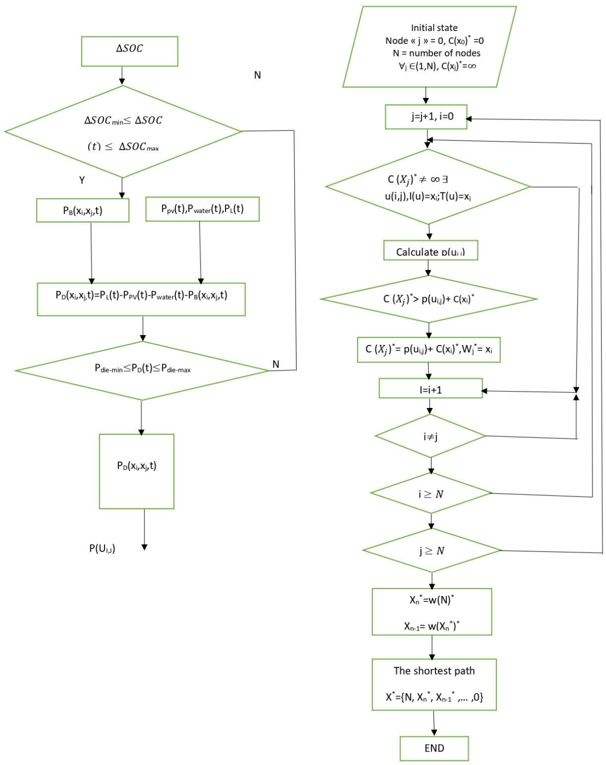

FIGURE 6. Flow-chart of the Bellman process with a full calculation of mass of the sides.

$P_D(t)$ is evaluated subject to $P_B(t)$, the expected value of $P_{pv}(t)$, P_{water}(t) and $P_L(t)$.

VI. SIMULATION

This section demonstrates optimal energy management for hydro, photovoltaic, diesel, and BESS (Hy-PV-D-BESS) systems. The procedure is implemented for optimal results of the optimization problem in order to find the minimum expenditure on the Hy-PV-D-BESS hybrid system. The proposed hybrid system will produce optimal results for both the diesel generator and BESS at the same time. The optimal process is carried out by the following objective function:

TABLE 2. Simulation parameter values.

Quantity name	Range	Quantity unit
T	24	h
Δt	1	h
δSOC	0.001	-
SOC_{min}/SOC_{max}	0.2/0.9	-
$\delta SOCmin/\delta SOCmax$	-0.7/0.7	-
SOH_{min}	0.7	-
Min/Max power values of diesel	15/50	-
BESS value	200	-

$$K = min \sum_{j=1}^{24} c_f \cdot (0.08415 \cdot P_R + 0.246 \cdot P_D(t)) + \frac{E_t \cdot E_f P_D(t)}{1000} + B_i C \frac{Z \cdot (SOCx_i(t-\Delta t) - SOCx_j(t))}{1 - SOH_{min}} \tag{21}$$

Subject to:

$$P_L(t) = P_{PV}(t) + P_{water}(t) + P_B(t) + P_D(t) \tag{22}$$

$$P_{Bmin} \leq P_B(t) \leq P_{Bmax} \tag{23}$$

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \tag{24}$$

$$SOH(t) \geq SOH_{min} \tag{25}$$

$$P_{die-min} \leq P_D(t) \leq P_{die-max} \tag{26}$$

To deal with the proposed constrained optimization problem, we use the predicted day-ahead loads, PV, and hydro input data, as shown in Figures 7, 8, and 9, respectively. The outcomes showed that PV systems start supplying power around 6:00, work stops around 18:00, the maximum power available around 15:00 is 55 kW, and the power production by PV changes throughout the year. Furthermore, in Figure 7, the load fluctuates from 30 kW to 46 kW. The heaviest consumption of power in the form of load is noted at 12:00, while On the other hand, water turbines produce constant power throughout the day.

Figure 9 shows hydropower production, while Figure 10 shows the solar irradiance for the whole year in the northern regions of Pakistan, respectively. It should be noted that the results obtained in each case are compared with the existing methods in the literature. The state of charge (SOC) is taken as 0.5 at the start of the day because it gives us the best result in terms of cost. The outcomes are given in the following four simulations:

Simulation 1 results for the month of July $SOC(t_0) = 0.5$,

Simulation 2 results for the month of December $SOC(t_0) = 0.5$,

Simulation 3 results for the month of March $SOC(t_0) = 0.5$,

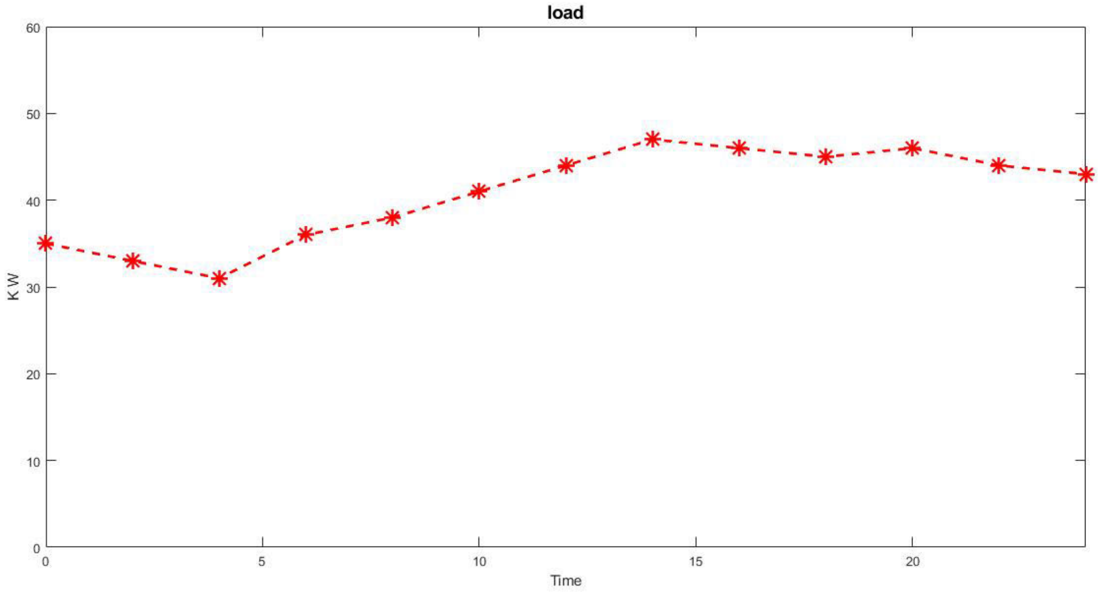

FIGURE 7. Load.

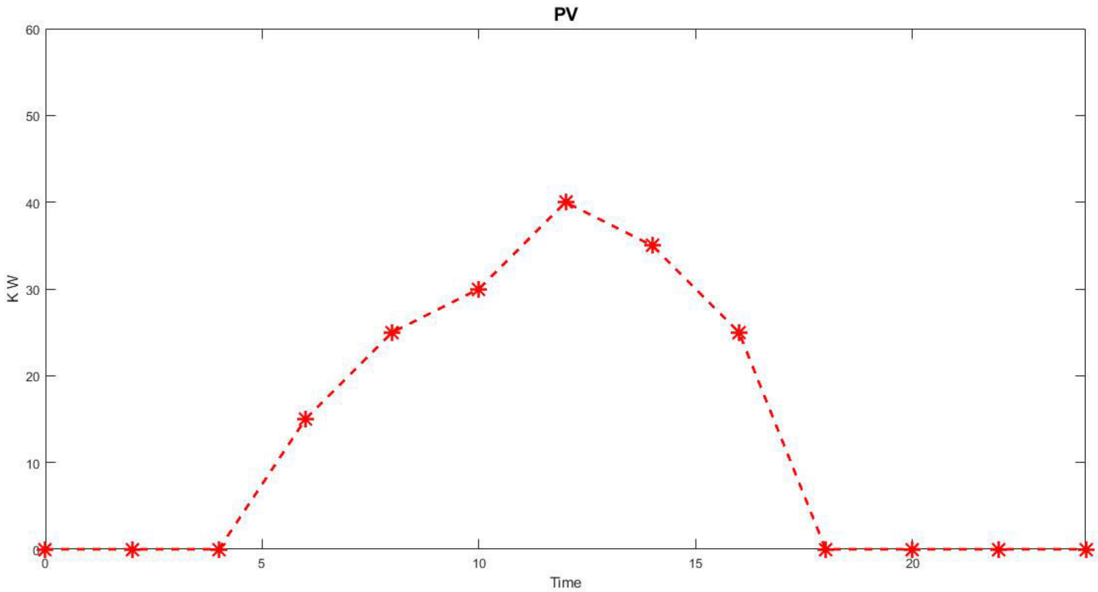

FIGURE 8. PV production.

Simulation 4 results for the month of September $SOC(t_0) = 0.5$,

Simulation 1 results for the month of July $SOC(t_0) = 0.5$,

In this scenario, the main generating power units fulfill the load demands. The main goal of DP and the rule-based method is to determine the relative diesel cut-off time required for the load. In these methods, load demands are met by diesel and hydropower at the start of the day.

Figure 11 shows the graphical visualization of the obtained values for the whole month of July. Furthermore, Figure 10 shows that each individual value is simulated separately to find the minimum cost for each day. From these analyses, we found that monthly minimum cost of the system.On any day in the month of July, we can see that the PV system starts work at around 6:00 while BESS stops the provision of power from the batteries. Therefore, PV systems and hydropower fulfill the required load demand. Furthermore, the excess energy is transferred for BESS charging. At around 18:00, the PV system stops producing energy, so the load demand is fulfilled by the diesel generator and BESS together. At the end of the day, the initial state of charge of BESS again comes to level 0.5.

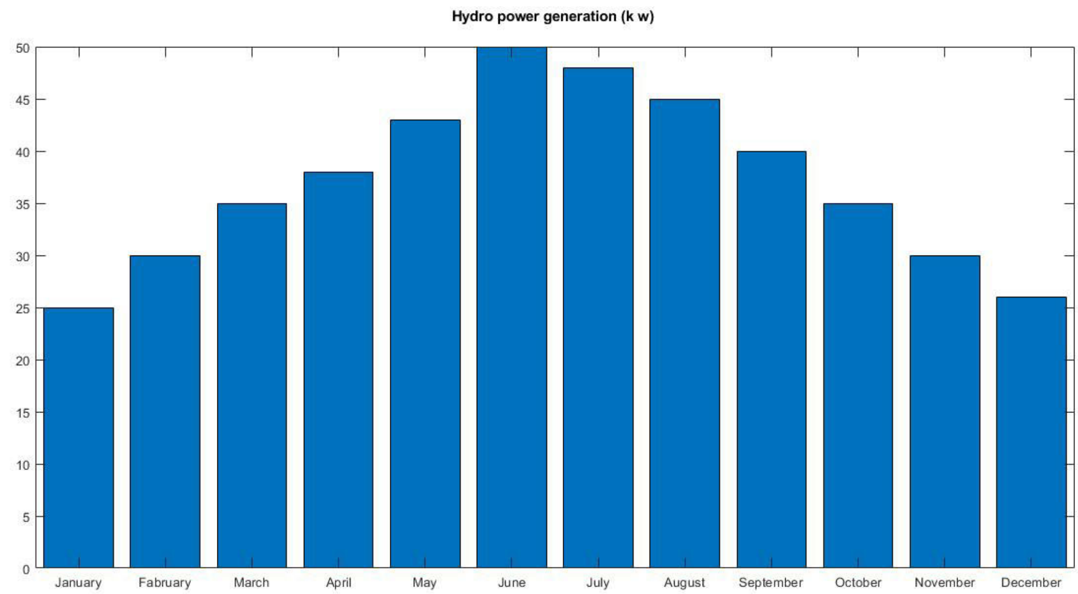

FIGURE 9. Monthly hydro power generation.

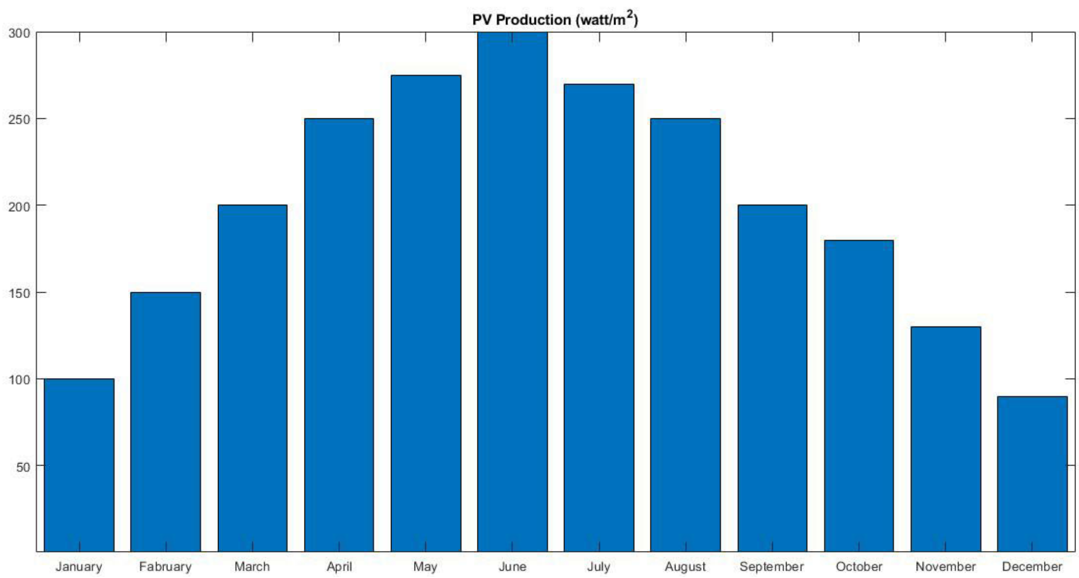

FIGURE 10. Monthly solar irradiance.

The results obtained in Figure 11 show that the diesel generator is not working for 16 hours per day. This led to the creation of an operating pattern that extends the life of diesel generators. Moreover, this operating system reduces fuel use and, as a result, greenhouse gas emissions. In addition, the same value of SOC at the first and last stages makes the charging operation easier at the beginning of the following day. For the rule-based approach, since there is no forecast for the next day, BESS remains at maximum power for routine performance. As a result, the terminal SOC is greater than the initial SOC. Thus, the next day's energy management strategy is limited because this is actually the full charge of BESS. Therefore, as a conclusion, the charging rule will not be made early on the next day. Therefore, it is concluded that rule-based techniques suffer from several disadvantages when applied to day-to-day supervision. Therefore, the proposed approach dominates the rule-based techniques as well as the one presented in [27] in the sense that the hydro factor in the proposed system remains constant throughout the day, and as a result, BESS remains at full charge. Furthermore, the overall cost of the proposed hybrid system is much more optimal as compared to the other two approaches.

The final values of the objective functions are used to optimize dynamic programming and rule-based control

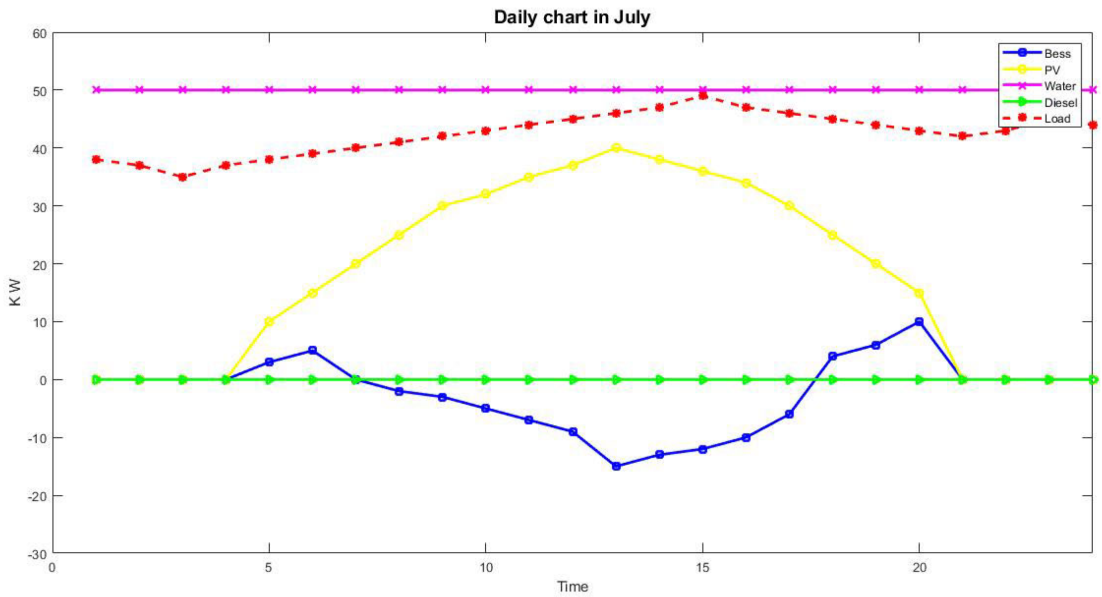

FIGURE 11. One day forecast in July.

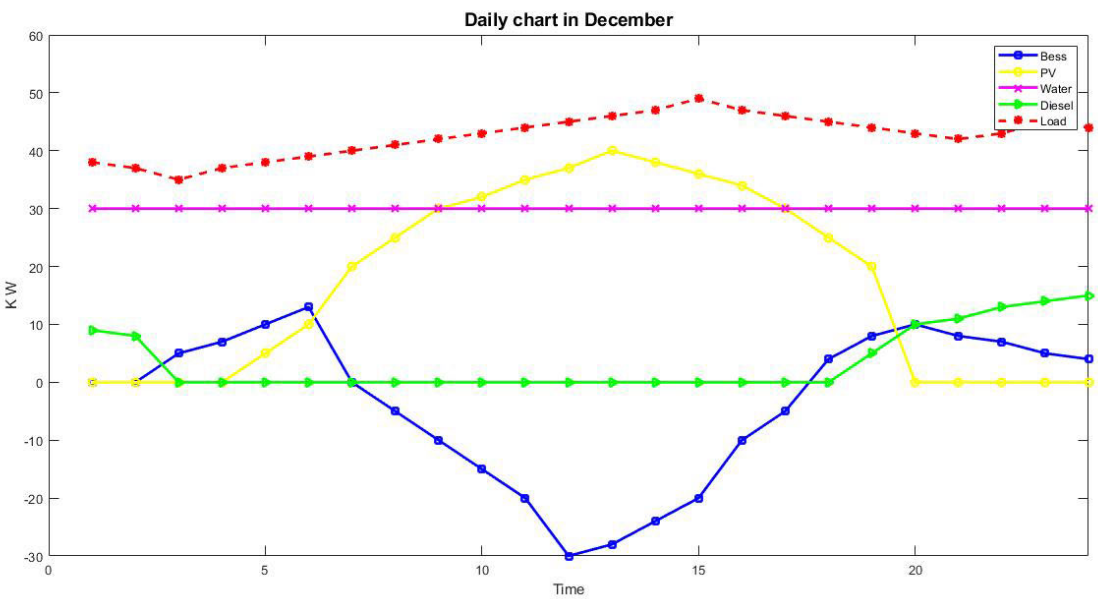

FIGURE 12. One day forecast in December.

TABLE 3. Final values in simulation 1.

S1	DP (Hy-PV-D-BESS)	DP (Wind- PV-D-BESS)	Rule based
F. value	24.5	72.1	146.6

techniques, as shown in Table 3. The outcomes showed that the proposed hybrid system (Hy-PV-D-BESS) using the DP technique produces much smaller value as compared to the other techniques in the literature. Therefore, we conclude that the DP method produces optimal results for the proposed system.

Simulation 2 results for the month of December $SOC(t_0) = 0.5$

In Figure 12, we obtained results for the whole month of December and found the minimum cost for each day. From these analyses, we found the minimum monthly cost of the system. As we can see, the PV system starts working at around 6:00, and the BESS stops the output power from the batteries. This shows that PV system and hydropower now fulfill the load demand. Meanwhile, if extra energy production takes place, it will be transferred to BESS charging. At around 18:00, the PV system stops working, so to

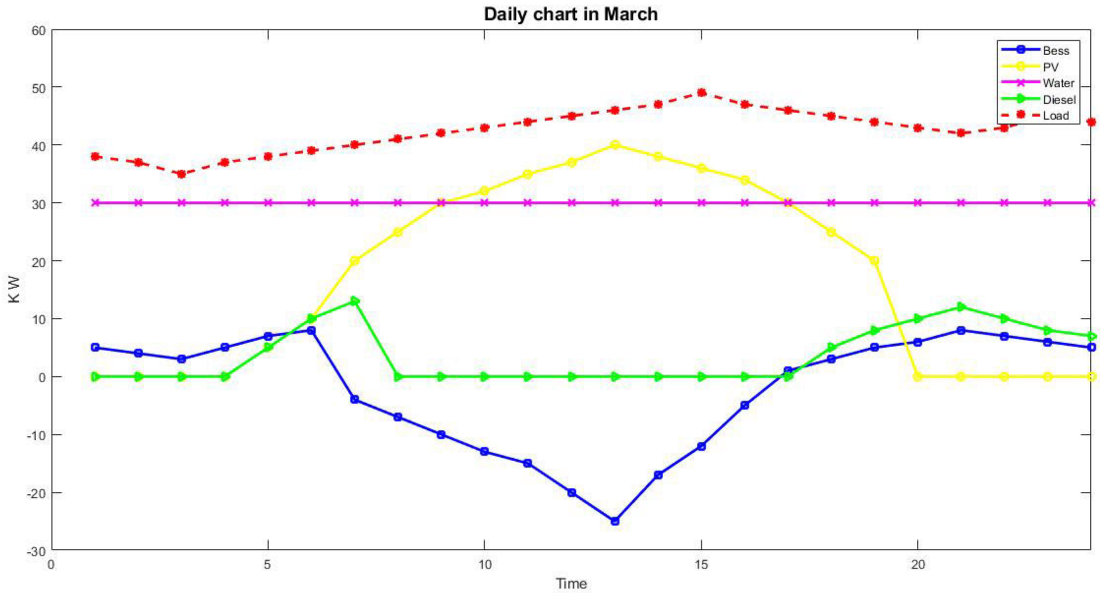

FIGURE 13. One day forecast in March.

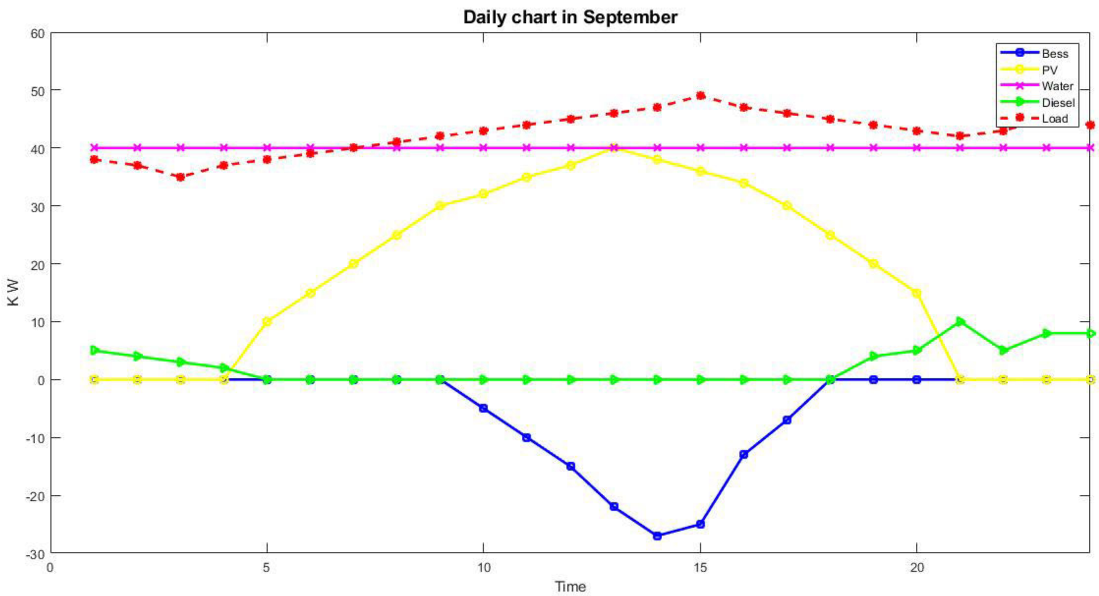

FIGURE 14. One day forecast in Septumber.

fulfill the load demand, a diesel generator and BESS are used together to fulfill the given demand. At the end of the day, the initial state of charge of BESS again comes in at 0.5.

The final objective values are shown in Table 4. The result obtained from the proposed hybrid system (Hy-PV-D-BESS) using DP is optimal as compared to the other methods.

Simulation 3 for the month of March $SOC(t_0) = 0.5$

In Figure 13, the simulation results obtained for the month of March and the minimum cost of each day are determined separately. From these analyses, we found the monthly minimum cost of the system. We can see that the PV system starts working at around 6:00, and BESS stops the output power from the batteries. As a result, PV systems and hydropower fulfill the load demand. Moreover, the excess energy is transferred to charge BESS. At around 18:00, the PV system stops working, so to meet the load demand, a diesel generator and BESS are used together. At the end of the day, the initial state of charge of BESS again comes in at 0.5.

The final objective value obtained from the hybrid system (Hy-PV-D-BESS) using DP gives a better result as compared to the existing methods in the literature, as shown in Table 5.

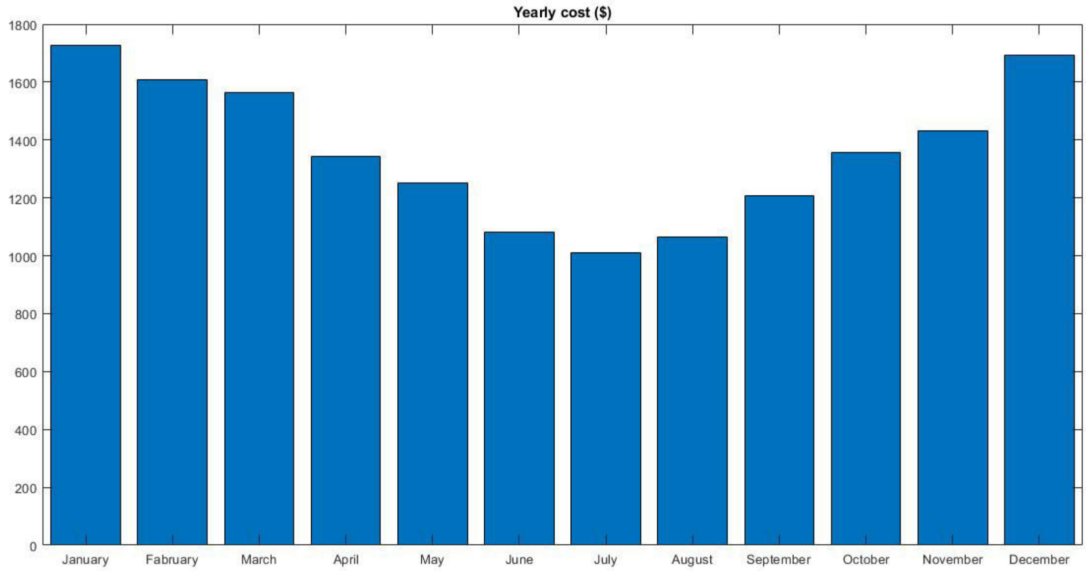

FIGURE 15. Yearly forecast.

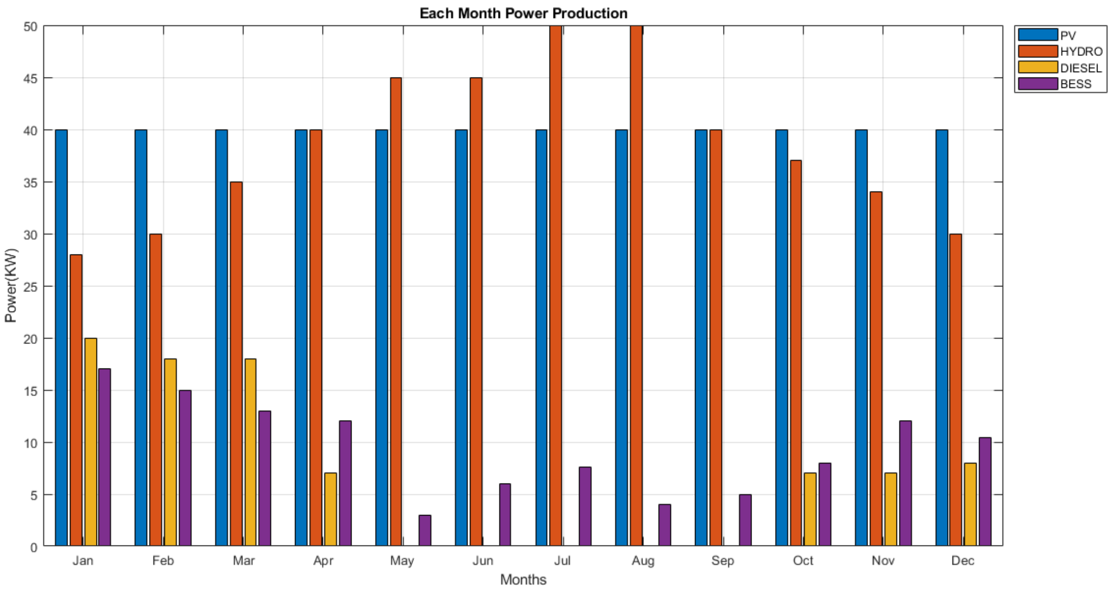

FIGURE 16. Yearly forecast of each factor in the hybrid system.

The simulation results presented in Table 3 and Table 4 validate the best performance of the DP method for the proposed hybrid system (Hy-PV-D-BESS) under the given conditions. This further validated that the proposed hybrid system controls the power consumption of hydro, photovoltaic, diesel, and BESS.

Simulation 4 for the month of September $SOC(t_0) = 0.5$

In Figure 14, we have carried out the outcomes for the whole month of September and found the individual outcomes for each day in order to find the minimum cost of each day. Furthermore, we found the monthly minimum cost of the system. From this analysis, we can see that the PV system starts working at around 6:00 and the diesel generator stops providing power to the system. In this case, PV systems and hydropower fulfill the load demand. The extra energy that is produced in the hybrid system is transferred to charge the BESS. At around 18:00, the PV system stops working, so to meet the load demand, a diesel generator and BESS are used together. At the end of the day, the initial state of charge of BESS again comes in at 0.5. The final value obtained from the proposed hybrid system (Hy-PV-D-BESS) using DP is much smaller than other approaches, as shown in Table 6.

TABLE 4. The final value in simulation 2.

S2	DP (Hy-PV-D-BESS)	DP (wind-PV-D-BESS)	Rule based
F. value	59.32	81.9	146.21

TABLE 5. Final value in simulation 3.

S3	DP(Hy-PV-D-BESS)	DP(wind-PV-D-BESS)	Rule based
F. value	45.71	78.5	146.21

TABLE 6. Final value in simulation 4.

S4	DP (Hy-PV-D-BESS)	DP (Wind- PV-D-BESS)	Rule based
F. value	38.21	65.73	147.32

TABLE 7. Monthly cost of the proposed hybrid system.

Jan Jul	Feb Aug	Mar Sep	Apr Oct	May Nov	Jun Dec	Total cost
1727 786	1609 1064	1564 1207	1342 1356	1251 1430	859 1693	15888

Yearly simulation analysis of the proposed hybrid system: In Figure 15, we have evaluated the yearly cost of the hybrid system (Hy-PV-D-BESS). From the figure, we can see that the cost of the proposed hybrid system is minimal in the summer. This minimum cast value is happening due to the availability of a large amount of water, which leads to fulfilling the load requirements without a diesel generator. On the other hand, the quantity of water decreases in winter, due to which the load demand could be fulfilled by the use of a diesel generator, and consequently, the cost of the hybrid system increases. The monthly cost of the proposed hybrid system is given in Table 7.

The monthly output of each factor of the hybrid system (Hy-PV-D-BESS) is given in Figure 16. This clearly shows that during the summer season, the use of diesel generators is almost negligible, which validates the importance of the proposed hybrid system in terms of minimum cast benefits as well as environmental benefits.

VII. CONCLUSION

In this work, we have proposed an optimal hybrid system known as Hy-PV-D-BESS by using the dynamic programming technique. The proposed hybrid system dominates other hybrid systems in terms of economic benefits as well as environmental benefits. The application of dynamic programming is used to build the optimal chart of power resources, namely hydro, photo-voltaic, diesel generators, and battery energy storage systems. The proposed system minimizes the total operational cost as well as the emission of toxic gases from the system, subject to the given technical conditions and a constant initial state of charge. The experimental results showed that the proposed hybrid energy management system dominates both the rule-based method and the method given in [27]. The proposed system yields optimal objective values as compared to the other methods used in this study. Furthermore, the best optimization environment is carried out for optimal energy management systems at constant charge. The proposed system could be a fruitful project in the northern areas of Pakistan as an application of the proposed Hy-PV-D-BESS hybrid system. These areas are full of snow throughout the year and have the capability to establish small hydropower projects, although there are some hydropower projects in these areas that produce electricity for the locality. The purpose of the proposed work is to establish a low-cost energy system in the northern areas of Pakistan in order to provide clean energy to the locality and to further extend the proposed model to the different areas of Pakistan where the installation of such a hybrid system is possible. We can also use the proposed methodology for other hybrid energy systems while increasing the possible parameters.

AUTHOR'S CONTRIBUTIONS

All authors participated equally in the preparation of this manuscript. All authors verified the final version of this manuscript. All authors contributed equally to this work. All authors read and approved the final manuscript.

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