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Review

Modeling and Formulation of Optimization Problems for Optimal Scheduling of Multi-Generation and Hybrid Energy Systems: Review and Recommendations

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Abstract: Increasing power demands require multiple generating units interconnected with each other to maintain the power balance of the system. This results in a highly dense power system consisting of multiple generating units which coordinate with each other to maintain the balanced performance of the system. Among different energy sources, the thermal source, the hydro energy source, the photovoltaic system, and the wind energy source are the most popular ones. Researchers have developed several optimization problems in the literature known as dispatch problems to model the system consisting of these different types of energy sources. The constraints for each system depend upon the generation type and the nature of the objective functions involved. This paper provides a state-of-the-art review of different dispatch problems and the nature of the objective functions involved in them and highlights the major constraints associated with each optimization function.

Keywords: economic dispatch; hydrothermal scheduling; photovoltaic energy system; wind energy system; combined economic emission dispatch; forecasting

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1. Introduction

With the increase in energy demand and its impact on economic advancement, several generating sources are currently included in the conventional grid to maintain the power balance of the system [1–3]. In such a dense power system, the major challenge is to optimally control different energy sources while preserving the different energy constraints of the system [4–6]. This constitutes a highly non-linear and multi-dimensional optimization problem in the literature which aims to find the optimal operating point for the system while taking into account the various system constraints [7,8]. The nature of the objective function and the different types of generation constraints depend upon the nature of the dispatch problem. Figure 1 shows the breakdown of different optimization problems which can be formulated from the dispatch of different generation sources. To summarize Figure 1, the three major categories of dispatch problems primarily followed by researchers in the literature to describe the optimum conditions for hybrid power systems are as follows:

- The economic dispatch (ED) problem for multiple thermal units having different quadratic cost characteristics. The ED problem is further classified as: (a) the inclusion of the valve point effect loading for thermal units, also known as the ED problem with valve point loading, and (b) the inclusion of the emission values for the thermal units known as the combined economic emission dispatch problem (CEEDP).
- The optimization problem dealing with two major conventional sources, the hydroelectric source and the thermal energy source. Such a problem is termed the hydrothermal scheduling (HTS) problem. The problem is then modified to STHTS and LTHTS depending upon the duration of the scheduling problem.

- The dispatch problem concerned with the hybrid energy systems consisting of conventional and renewable energy sources. The sources used in addition to the hydro and thermal units are PV source, WES, and BESS.

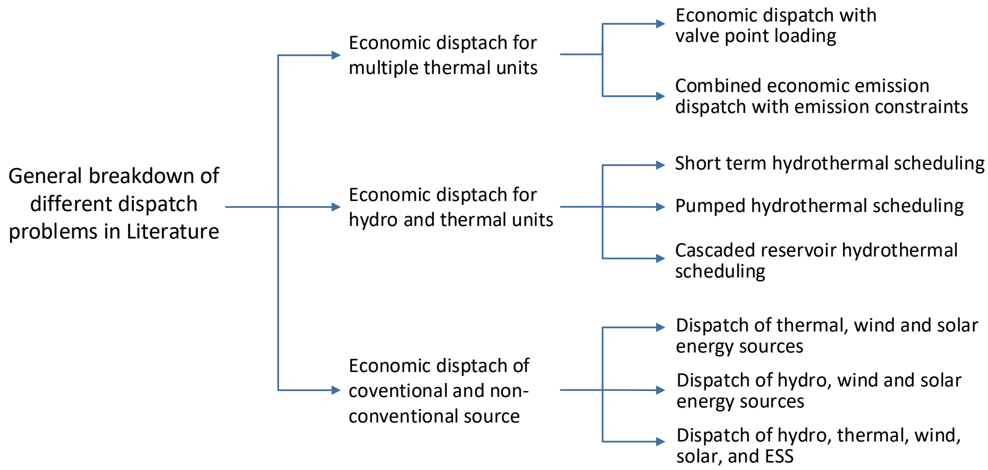

Figure 1. Brief overview of the breakdown of different types of optimization problems based on the economic dispatch of multiple generation sources.

The next part of the Introduction provides a brief outline of each type of dispatch problem given in Figure 1.

1.1. Overview of Economic Dispatch Problem for Multi-Thermal System

The most simple case involves the optimum dispatch of several thermal units having different cost characteristics. Such a problem, which purely deals with the dispatch of the thermal units, is described as the economic dispatch (ED) problem for the thermal units in the literature [9,10]. The possible constraints involved in such a problem are power balance, power limits, ramp limits constraints, and spinning reserve constraints [11,12]. The different types of problems are then derived based on the modifications in the conventional objective function of the ED problem. One such modification is the inclusion of the valve point effect in the quadratic cost equation of the thermal units to practically model the cost characteristics of each thermal unit [13,14]. The valve point effect results in an additional sinusoidal term in the quadratic cost equation of thermal units which makes the objective function highly non-linear and non-convex. The constraints defined for the ED problem having valve point loading are the same in most of the literature as defined for the simple quadratic-based dispatch problem. Another modification suggested while including the valve point effect is to consider the emission constraints of the thermal units. For such a problem, the two objective functions are defined which simultaneously reduce the thermal and emission cost for the system. This constitutes a multi-objective optimization problem and is termed the combined economic emission dispatch problem (CEEDP) in the literature [15,16]. The two constraints defined for the conventional CEEDP are the power balance constraint and the power limits constraint.

1.2. Overview of Hydrothermal Scheduling Problem

To reduce the emission constraints and the dependence on the thermal units, researchers have developed another optimization problem which deals with the combined optimum dispatch of two major conventional sources, the hydroelectric source and the thermal energy source. The main objective of such a problem is to reduce the thermal cost of the system while preserving the reservoir and generation constraints for the hydro and thermal units. Such a problem is termed the short term hydrothermal scheduling (STHTS) problem in the literature [17,18]. The conventional STHTS problem has been extended to include multiple reservoirs connected in a cascaded connection. Such a configuration constitutes an optimization problem termed the cascaded short term hydrothermal scheduling (CSTHTS) problem [19,20]. Another modification suggested in the hydrothermal scheduling problem is to increase the duration of the scheduling time over which different conventional sources are optimally coordinated with each other to meet the demand value. This constitutes an optimization problem termed the long term hydrothermal scheduling (LTHTS) problem [21,22].

1.3. Overview of ED Problem for Hybrid Energy Systems

In recent decades, with the increase in penetration of distributed generation sources to the conventional grid, a large set of optimization problems has been derived based on the economic dispatch of conventional and non-conventional energy sources. Such problems usually deal with the dispatch of hybrid energy systems which include photovoltaic (PV) energy sources, wind energy systems, and battery energy storage systems (BESS), in addition to thermal and hydroelectric sources [23–25]. The majority of these suggested problems deal with the intermittent and variable nature of the renewable energy sources coupled with the addition of certain constraints related to each distributed energy source. The novelties introduced by the researchers related to the combined dispatch of conventional and non-conventional sources were based on the different forecasting techniques and uncertainty analysis of the renewable energy sources [26–29].

1.4. Literature Survey of Review Papers

After highlighting the major types of optimization problems dealing with different energy sources, the next major part of the literature constitutes the set of optimization algorithms used to solve these functions. A large number of research papers have been published over the years on these different types of algorithms and their variants to find the optimum solution of each objective function. These algorithms are either based on a set of well-defined deterministic rules [30–33] or include some random movement criteria to reduce the computational effort for finding the global solution of large scale practical problems [17,18,34,35]. Among these different algorithms, a promising category of algorithms which depend upon the nature-inspired phenomenon is that of the meta-heuristic optimization algorithm. The major advantages of such algorithms are their reduced computational efficiency and complexity in reaching towards the optimum solution for large scale power optimization problems [36–39]. This constitutes a vast literature which covers different aspects related to either the novelties in the dispatch problem or the implementation of novel optimization algorithms for solving such problems. To summarize all these research directions, researchers have recently published some review papers on the individual aspects of each optimization problem. The authors in [40] have discussed the earlier forms of the economic dispatch problem. Their focus was primarily centered around the optimal power flow (OPF) and automatic generation control (AGC) for the ED problem. The authors in [41] have discussed the particle swarm optimization (PSO) on the conventional non-linear dispatch problem. The authors in [42,43] have discussed the economic dispatch with the WES and electric vehicles. The authors in [44,45] have discussed different types of optimization algorithms for CEEDP. Table 1 summarizes different review papers related to this particular problem. These papers mostly address thermal units while considering renewable energy sources and emission constraints. In most of the mentioned review papers, the main objective of the authors was to compare different sets of optimization algorithms for a particular optimization problem. A comprehensive review addressing different types of dispatch problems was not considered by researchers to much of an extent in the literature.

Table 1. Brief summary and analysis of different review papers published on various types of economic dispatch problems.

Reference	Test System	Major Contributions	Shortcomings of Review
Chowdhury et al. [40]	Economic dispatch considering non-conventional energy sources	Review of economic dispatch problems while considering the optimal power flow and automatic generation control for thermal units	The constraints for conventional and non-conventional energy sources are not addressed elaborately while defining the objective functions
Amita et al. [41]	Economic emission dispatch for thermal generators	Review of the different variants of particle swarm optimization algorithm for multi-objective economic emission dispatch	Various forms of dispatch problems, including the distributed energy sources, are not elaborated upon while discussing the application of the optimization algorithm
Ren et al. [42]	Economic dispatch under the penetration of the wind energy source	Review of dispatch problems including the wind source while developing the optimization algorithms to handle the intermittent nature of WES and performing risk management	The forecasting algorithms to handle the variable nature of the wind energy system are not discussed extensively. Moreover, sources like hydro and PV systems are not discussed while modeling the objective function
Peng et al. [43]	Economic dispatch of plug-in electric vehicles	Review of the optimization algorithms for combined dispatch of plug-in electric vehicles and distributed energy sources	The mathematical models and the constraints associated with the renewable energy systems are not elaborated upon in an extensive manner while defining the objective function
Fahad et al. [44]	Multi-objective economic emission dispatch for thermal units	Review of different conventional, heuristic, and hybrid optimization algorithms for combined economic emission dispatch	The dispatch problems for the non-conventional energy sources are not discussed while analyzing different optimization algorithms for combined economic emission dispatch
Tapas et al. [45]	Multi-objective economic emission dispatch for thermal units	Review of different heuristic optimization algorithms and their variants for combined economic emission dispatch	The dispatch problems for the non-conventional energy sources are not discussed while analyzing different optimization algorithms for combined economic emission dispatch
Nazari-Heris et al. [46]	Economic dispatch of power system consisting of hydro and thermal units	Review of the different heuristic optimization algorithms for system consisting of multiple thermal and hydro units	The renewable energy sources such as wind and photovoltaic energy sources are not discussed while defining the optimization problem
Nazari-Heris et al. [47]	Multi-carrier energy systems consisting of gas-, electricity-, and water-based energy sources	Study of hydrothermal scheduling problem along with the planning of pumped hydro units. The integration of different electric-, water-, and gas-based energy sources is also discussed extensively	The renewable energy sources are generally not considered while defining the optimization problem
Nazari-Heris et al. [48]	Combined heat and power economic dispatch (CHPED) for 5 different test systems	Review of different heuristic and meta-heuristic optimization algorithms for CHPED problem while considering valve point loading and transmission losses of the system	Statistical analysis of different algorithms can be discussed to better compare the performance of heuristic techniques for CHPED problem

2. Motivation and Major Contributions of Review

Although the literature has discussed some aspects of the dispatch problem in different places, a comprehensive overview of all the major types of dispatch problems along with the nature of the objective functions has not been presented comprehensively in a single place. Based on these shortcomings of the literature, the major contributions of this review paper are as follows:

1. It presents major types of dispatch problems in the literature and discusses the different objective functions involved in each problem. It also discusses their various forms and presents the updated constraints and the objective functions.
2. It discusses the nature of the objective functions involved in each dispatch problem. It highlights major decision variables and gives suggestions for updating the problem.
3. It proposes improvements for the current forms of typical ED problems and suggests modifications to better formulate the objective function.

The remainder of the paper is organized as follows. Section 3 gives the overview of different dispatch problems for systems having multiple thermal units. Section 4 gives the overview of dispatch problems for hydro and thermal units. Section 5 gives the overview of the dispatch problems of the system including both conventional and distributed generation sources. Section 6 gives a brief overview of different methods used in the literature to solve dispatch problems. Section 7 gives remarks and future directions for different dispatch problems along with the conclusions.

3. Economic Dispatch Problem for Thermal Units

The simplest type of dispatch problem involves the optimum solution of generators consisting of multiple thermal units. The main objective function used in the ED problem aims to minimize the total thermal generation cost [49–52] and is given as follows:

$$C_t = \sum_{i=1}^{N_g} F_i(P_{T,i}) \quad (\$/hr) \tag{1}$$

where C_t represents the total thermal cost of the system, N_g represents the total number of thermal generators, and $F_i(P_{T,i})$ represents the cost function of a particular generator i. The cost characteristics are usually given by the quadratic function as follows:

$$F_i(P_{T,i}) = \alpha_i + \beta_i P_{T,i} + \gamma_i P_{T,i}^2 \tag{2}$$

where α_i, β_i, and γ_i are the cost coefficients of a particular generator i. The constraints involved in the classical ED problem for thermal units are given as follows:

$$\begin{cases} \sum_{i=1}^{N_g} P_{T,i} = P_D + P_L \\ P_{T,i,min} \leq P_{T,i} \leq P_{T,i,max} \\ \max(P_{T,i,min}, P_{T,i}^o - DR_i) \leq P_{T,i} \leq min(P_{T,i,max}, P_{T,i}^o + UR_i) \\ \sum_{i=1}^{N_g} P_{T,i,max} \geq P_D + R_s \\ P_{T,i} \in \begin{cases} P_{T,i,min} \leq P_{T,i} \leq P_{T,i,1}^L \\ P_{T,i,m-1}^U \leq P_{T,i} \leq P_{T,i,m}^L \quad (m = 2, 3, \ldots., N_{zi}) \\ P_{T,i,N_{zi}}^U \leq P_{T,i} \leq P_{i,max} \quad (m = N_{zi}) \end{cases} \end{cases} \tag{3}$$

The first constraint describes the power balance of the system which states that the total output generation must be equal to the load demand P_D and the transmission losses P_L. The second constraint defines that the output of the i generator must be within the maximum $P_{T,i,max}$ and minimum $P_{T,i,min}$ thermal limits. The third constraint defines the ramp up UR_i and ramp down DR_i limits for the i generator. This particular constraint defines a threshold by which the previous output of the i generator $P_{T,i}^o$ can be increased or decreased. The fourth constraint describes the spinning reserve R_s factor for the thermal generators. The fifth constraint describes the prohibited operating zones (POZ) constraint for the generators. $P^U_{T,i,m}$ and $P^L_{T,i,m}$ describe the upper and lower limits for POZ. N_{zi} shows the total number of POZ. The POZ constraint introduces non-linearity and discontinuities in the original quadratic cost equation due to different practical constraints such as the failure of the machine or shaft tremor [53–55].

3.1. Economic Dispatch for Thermal Units including Valve Point Loading

The quadratic cost equation defined in the previous dispatch problem does not consider the valve point loading on the characteristics curve. To model the cost curve of the thermal generation while considering the effect of the opening and closing of steam valves, researchers have suggested an additional sinusoidal term in the conventional cost equation of the thermal generators [56–61]. The cost characteristics for thermal generation having valve point loading are given as follows:

$$F_i(P_{T,i}) = \alpha_i + \beta_i P_{T,i} + \gamma_i P^2_{T,i} + |e_i sin(f_i(P_{T,i,min} - P_{T,i}))| \quad (4)$$

where $\alpha_i, \beta_i, \gamma_i, e_i$ and f_i represent the cost coefficients for the thermal generator while considering the valve point loading effect. For a system having multiple fuels, the cost characteristics for each generator while considering the valve point effect can be written as follows:

$$= \begin{cases} \alpha_1 + \beta_1 P_{T,1} + \gamma_1 P^2_{T,1} + |e_1 sin(f_1(P_{T,1,min} - P_{T,1}))| \\ \alpha_2 + \beta_2 P_{T,2} + \gamma_2 P^2_{T,2} + |e_2 sin(f_2(P_{T,2,min} - P_{T,2}))| \\ \alpha_3 + \beta_3 P_{T,3} + \gamma_3 P^2_{T,3} + |e_3 sin(f_3(P_{T,3,min} - P_{T,3}))| \\ . \\ . \\ \alpha_{N_g} + \beta_{N_g} P_{T,N_g} + \gamma_{N_g} P^2_{T,N_g} + |e_{N_g} sin(f_{N_g}(P_{T,N_g,min} - P_{T,N_g}))| \end{cases} \quad (5)$$

Figure 2 shows the effect of the valve point loading on the cost characteristics of the thermal generation. It is evident that the characteristics become highly non-linear and non-smooth in nature by including an additional term in the cost characteristics of the thermal generators.

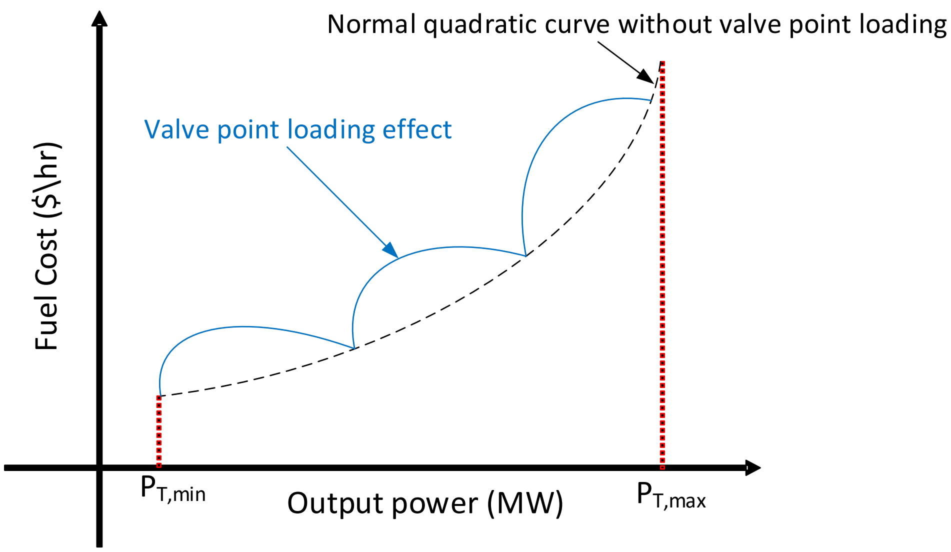

Figure 2. Comparison of the cost characteristics of thermal generators with and without valve point loading effect. The characteristics become non-smooth and contain bumps when the valve point loading is considered for thermal generators.

The constraints defined for the ED problem while considering the valve point loading are same as defined for the quadratic cost characteristics. However, the only up gradation is in the objective function of the ED problem, which makes the optimization problem non-linear and non-convex in nature.

3.2. Economic Dispatch Problem for Thermal Units including Emission Constraints

The thermal generator has certain environmental constraints and can result in emission values which can have adverse effects on the atmosphere. To consider the emission values of the thermal generation, researchers have suggested a multi-objective optimization problem to simultaneously optimize both cost and emission values of thermal generation, which formulates a combined economic-emission dispatch problem [62–66]. The two main objectives involved in the CEEDP are the total thermal cost of the system and the emission values of the thermal generation. The thermal cost is given in accordance with the previously defined cost characteristics and is given as follows:

$$F(P_{T,i}) = \begin{cases} \sum_{i=1}^{N_g} \alpha_i + \beta_i P_{T,i} + \gamma_i P_{T,i}^2 + |e_i sin(f_i(P_{T,i,min} - P_{T,i}))| & \text{Valve Point Loading} \\ \sum_{i=1}^{N_g} \alpha_i + \beta_i P_{T,i} + \gamma_i P_{T,i}^2 & \text{Without Valve Point Loading} \end{cases} \tag{6}$$

The second main objective of the CEEDP deals with the emission values computed as the function of the thermal power. The cost function for the emission of thermal units is given as follows:

$$E(P_{T,i}) = \sum_{i=1}^{N_g} [a_i + b_i P_{T,i} + c_i P_{T,i}^2 + \mu_i exp(\lambda_i P_{T,i})] \tag{7}$$

where a_i, b_i, c_i, μ_i and λ_i represent the emission coefficients of the i thermal generator. The overall objective function deals with the minimization of both thermal cost and the emission values of the generators [67,68] and is mathematically given as follows:

$$FF(P_{T,i}) = \min[F(P_{T,i}), E(P_{T,i})] \tag{8}$$

There are two constraints involved in a typical CEEDP, the power balance constraint and the power limits constraint [69,70]. These constraints are in accordance with the previously defined constraints for the simple ED problem and are given as follows:

$$= \begin{cases} \sum_{i=1}^{N_g} P_{T,i} = P_D + P_L \\ P_{T,i,min} \leq P_{T,i} \leq P_{T,i,max} \end{cases} \tag{9}$$

Power losses in the CEEDP play an important role in formulating a realistic approach towards modeling a power system. There are several methods proposed by researchers to model transmission line losses of the system. The simplest involves the weighted sum of the quadratic contribution of each thermal power given as follows:

$$P_L = \sum_{i=1}^{N_g} \delta_i P_{T,i}^2 \tag{10}$$

where δ_i represents the loss coefficients. Equation (10) is generally used for small scale power systems having a lesser number of thermal generating units (three-generating-unit system). Another quadratic relation used to evaluate the transmission line losses for large scale power systems is given as follows:

$$P_L = \sum_{i=1}^{N_g} \sum_{j=1}^{N_g} P_{T,i} B_{ij} P_{T,j} \tag{11}$$

To better model transmission line losses of large scale power systems, Kron's loss formula including a quadratic, linear, and constant term [71,72] is given as follows:

$$P_L = \sum_{i=1}^{N_g} \sum_{j=1}^{N_g} P_{T,i} B_{ij} P_{T,j} + \sum_{i=1}^{N_g} B_{i0} P_{T,i} + B_{00} \quad (12)$$

where B_{ij}, B_{i0} and B_{00} are the loss coefficients for modeling the transmission line losses. The coefficients B_{ij}, B_{i0}, and B_{00} are important for modeling the line losses of the system. These constants primarily depend upon the configuration of the power system and number of generating units. Table 2 summarizes the loss coefficients for power systems having a different number of generating units.

Table 2. Summary of loss coefficients for power systems having different number of thermal generating units [71,72].

Test System	Loss Coefficients										
Power system with 3 thermal units	δ_{1x3}	1	2	3	-	-	-	-	-	-	-
		2.18×10^{-4}	2.28×10^{-4}	1.79×10^{-4}	-	-	-	-	-	-	-
	B_{6x6}	1	2	3	4	5	6	-	-	-	-
Power system with 6 thermal units	1	1.4×10^{-4}	1.7×10^{-5}	1.5×10^{-5}	1.9×10^{-5}	2.6×10^{-5}	2.2×10^{-5}	-	-	-	-
	2	1.7×10^{-5}	6.0×10^{-5}	1.3×10^{-5}	1.6×10^{-5}	1.5×10^{-5}	2.0×10^{-5}	-	-	-	-
	3	1.5×10^{-5}	1.3×10^{-5}	6.5×10^{-5}	1.7×10^{-5}	2.4×10^{-5}	1.9×10^{-5}	-	-	-	-
	4	1.9×10^{-5}	1.6×10^{-5}	1.7×10^{-5}	7.1×10^{-5}	3.0×10^{-5}	2.5×10^{-5}	-	-	-	-
	5	2.6×10^{-5}	1.5×10^{-5}	2.4×10^{-5}	3.0×10^{-5}	6.9×10^{-5}	3.2×10^{-5}	-	-	-	-
	6	2.2×10^{-5}	2.0×10^{-5}	1.9×10^{-5}	2.5×10^{-5}	3.2×10^{-5}	8.5×10^{-5}	-	-	-	-
	B_0	0	0	0	0	0	0	-	-	-	-
	B_{00}	0	-	-	-	-	-	-	-	-	-
	B_{10x10}	1	2	3	4	5	6	7	8	9	10
Power system with 10 thermal units	1	4.9×10^{-5}	1.4×10^{-5}	1.5×10^{-5}	1.5×10^{-5}	1.6×10^{-5}	1.7×10^{-5}	1.7×10^{-5}	1.8×10^{-5}	1.9×10^{-5}	2.0×10^{-5}
	2	1.4×10^{-5}	4.5×10^{-5}	1.6×10^{-5}	1.6×10^{-5}	1.7×10^{-5}	1.5×10^{-5}	1.5×10^{-5}	1.6×10^{-5}	1.8×10^{-5}	1.8×10^{-5}
	3	1.5×10^{-5}	1.6×10^{-5}	3.9×10^{-5}	1.0×10^{-5}	1.2×10^{-5}	1.2×10^{-5}	1.4×10^{-5}	1.4×10^{-5}	1.6×10^{-5}	1.6×10^{-5}
	4	1.5×10^{-5}	1.6×10^{-5}	1.0×10^{-5}	4.0×10^{-5}	1.4×10^{-5}	1.0×10^{-5}	1.1×10^{-5}	1.2×10^{-5}	1.4×10^{-5}	1.5×10^{-5}
	5	1.6×10^{-5}	1.7×10^{-5}	1.2×10^{-5}	1.4×10^{-5}	3.5×10^{-5}	1.1×10^{-5}	1.3×10^{-5}	1.3×10^{-5}	1.5×10^{-5}	1.6×10^{-5}
	6	1.7×10^{-5}	1.5×10^{-5}	1.2×10^{-5}	1.0×10^{-5}	1.1×10^{-5}	3.6×10^{-5}	1.2×10^{-5}	1.2×10^{-5}	1.4×10^{-5}	1.5×10^{-5}
	7	1.7×10^{-5}	1.5×10^{-5}	1.4×10^{-5}	1.1×10^{-5}	1.3×10^{-5}	1.2×10^{-5}	3.8×10^{-5}	1.6×10^{-5}	1.6×10^{-5}	1.8×10^{-5}
	8	1.8×10^{-5}	1.6×10^{-5}	1.4×10^{-5}	1.2×10^{-5}	1.3×10^{-5}	1.2×10^{-5}	1.6×10^{-5}	4.0×10^{-5}	1.5×10^{-5}	1.6×10^{-5}
	9	1.9×10^{-5}	1.8×10^{-5}	1.6×10^{-5}	1.4×10^{-5}	1.5×10^{-5}	1.4×10^{-5}	1.6×10^{-5}	1.5×10^{-5}	4.2×10^{-5}	1.9×10^{-5}
	10	2.0×10^{-5}	1.8×10^{-5}	1.6×10^{-5}	1.5×10^{-5}	1.6×10^{-5}	1.5×10^{-5}	1.8×10^{-5}	1.6×10^{-5}	1.9×10^{-5}	4.4×10^{-5}
	B_0	0	0	0	0	0	0	0	0	0	0
	B_{00}	0	-	-	-	-	-	-	-	-	-

To solve the multi-objective economic emission dispatch problem dealing with both objective functions, the authors have discussed two main methods to compute the optimal solution. The first method combines two objective functions and takes the weighted sum by assigning a scaling factor for the emission values. In this case, the overall objective function can be written as follows:

$$FF(P_{T,i}) = \delta F + w(1-\delta)E \quad (13)$$

In the above equation, F and E represent the cost and emission objective functions, respectively. δ represents the priority weight for each objective function. The value of δ is in the range [0,1]. w represents the scaling factor. The value of δ is important for controlling the contribution of each objective function. For $\delta = 1$, the problem is reduced to the simple ED problem, having only thermal cost as the objective function. For $\delta = 0$, the problem only deals with the emission objective function. If we increase the value of δ in the above equation, the objective function will give more priority to the thermal cost, and hence the optimum solution found will give a lower thermal cost at the expense of more emission values. The selection of δ largely depends upon the nature of the problem and the desired values for each of the individual objective functions [73].

Another technique adopted by the authors in the literature to visualize the multi-objective CEEDP is to compute the Pareto front for the problem. The graph between the emission values and the total cost is computed over the range of the decision variables, and the best compromise solution is obtained. The Pareto optimal point in this case would describe a situation where any attempt to improve an individual objective function would degrade the performance of the second objective function. This is an efficient method suggested by researchers to visualize the CEEDP and understand the nature of two objective functions [74–76]. Table 3 shows the summary of the ED problems for multiple thermal units.

Table 3. Summary of different types of ED problems involving only thermal units as generating source. The nature of the optimization problem and the decision variables are highlighted for each type.

Optimization Problem	Objective Function	Constraints	Decision Variables	Nature of Objective Function
Economic dispatch problem for multiple thermal units having different cost characteristics [49–55]	$C_t = \sum_{i=1}^{N_g} F_i(P_{T,i}) \quad (\$/hr)$	Power balance constraint, power limits constraint, prohibited operating zones constraint, reserve constraint, and ramp limits constraint	P_T	The objective function is non-linear and multi-dimensional in nature. The cost curve is smooth over the range of decision variables. However, the addition of prohibited operating zones introduces discontinuity in the curve
Economic dispatch problem for multiple thermal considering valve point loading [56–61]	$C_t = \sum_{i=1}^{N_g}[\alpha_i + \beta_i P_{T,i} + \gamma_i P_{T,i}^2 + \lvert e_i sin(f_i(P_{T,i,min} - P_{T,i}))\rvert] \quad (\$/hr)$	Power balance constraint, power limits constraint, prohibited operating zones constraint, reserve constraint, and ramp limits constraint	P_T	The objective function is non-linear and multi-dimensional in nature. The addition of the valve point loading introduces bumps on the smooth cost equation for the thermal generation
Economic dispatch problem for multiple thermal considering emission constraints [62–76]	$\min[F(P_{T,i}), E(P_{T,i})]$	Power balance constraint and power limits constraint	P_T	The optimization problem is a multi-objective problem. Both objective functions are non-linear and multi-dimensional in nature. Weighting factors and Pareto fronts are used to solve the combined problem

4. Economic Dispatch Problem for Thermal and Hydro Units

Another abundantly used conventional energy source to fulfill the load demand over the scheduling period is the hydroelectric energy source. The power system consisting of both thermal and hydro units gives rise to another interesting optimization problem which aims to reduce the thermal cost of the system while maintaining certain levels of the reservoir [77–79]. The cost of the generation of hydro power is usually not included in the objective function due to the negligible running cost of hydro units as compared to thermal generators [80–82]. In this section, we will highlight some major forms of the dispatch problem including hydro and thermal units.

4.1. Scheduling Problem of Single Thermal and Hydro Unit

The simplest form of the hydrothermal scheduling problem involves the optimum dispatch of a single equivalent thermal unit and a hydro energy source [83,84]. Figure 3 shows the equivalent block diagram for a hydrothermal scheduling problem while considering the transmission line losses. The objective function in this case can be written as follows [85,86]:

$$f = \sum_{i=1}^{n_s} N_i F(P_T) \qquad (\$) \tag{14}$$

where N_j represents the total duration of each scheduling interval, and n_s represents the total number of scheduling intervals. $F(P_T)$ represents the cost function for the thermal unit which is equal to the previously defined characteristics for the ED of multiple thermal units. If the length of N_j spans over few days, it can be categorized as the short term scheduling problem. The above objective function sums the total cost of the thermal generation over each scheduling interval. In simple dispatch problems for thermal units, the length of the scheduling interval is not usually considered, and we have static load demand which must be fulfilled by the optimal contribution of different thermal units in the system. However, in the case of hydrothermal scheduling, the length of the scheduling interval plays an important role. The entire scheduling period is divided into different intervals n_s (usually of the same length), and the load demand varies for each interval [87,88]. The optimal contribution of thermal and hydro units changes for each interval depending upon the demand value and the remaining generation constraints. Another important aspect of the objective function defined above is the unit of the function. The function is expressed in \$ instead of $\$/hr$, since we are considering the duration of each scheduling interval N_i while computing the thermal cost [89,90]. The constraints involved in the defined optimization problem are as follows:

$$P_{T,i} + P_{H,i} = P_{D,i} + P_{L,i} \tag{15}$$

$$P_{T,min} \leq P_{T,i} \leq P_{T,max} \tag{16}$$

$$P_{H,min} \leq P_{H,i} \leq P_{H,max} \tag{17}$$

$$V_{min} \leq V_i \leq V_{max} \tag{18}$$

$$V_o = V_i \tag{19}$$

$$V_1 = V_f \tag{20}$$

$$d_{min,i} \leq d_i \leq d_{max,i} \tag{21}$$

$$\sum_{i=1}^{n_s} N_i d_i = d_T \tag{22}$$

$$V_i = V_{i-1} + N_i(inf_i - d_i - sp_i) \tag{23}$$

where V, V_o, V_1, d, inf, and sp represent the volume, initial volume, final volume, discharge rate, inflow, and spillage of the reservoir, respectively. Equation (15) represents the power balance constraint. Equations (16) and (17) represent the power limits constraint for hydro and thermal units. Equations (18)–(20) show the volume constraints for the hydro unit. These constraints indicate that the volume for a particular scheduling interval i must be with in the maximum V_{max} and minimum V_{min} limits. Moreover, the initial and final values of the reservoir must be equal to defined the values of V_i and V_f to ensure the proper storage of water in the reservoir. Equations (21) and (22) show the discharge rate constraints. Equation (23) shows the equation of continuity which indicates the relation between the volume values for two consecutive intervals i [91]. An important thing to note is that the i represents a particular scheduling interval and not the index of a thermal or hydro unit.

The next important step is to define the hydro and thermal equations. The normal flow of the hydrothermal scheduling problem is to compute the discharge rate based on the volume levels of the reservoir using the equation of continuity [92] as defined in Equation (23). The hydro power is then defined as the function of the discharge rate given as follows:

$$P_H = \text{func}(d) \tag{24}$$

The transmission line losses for the conventional hydrothermal scheduling problem are modeled using only the hydro power, given as follows:

$$P_L = \text{func}(P_H) \tag{25}$$

Based on the hydro power and transmission losses, the thermal power can be computed using the power balance equation defined in Equation (15). The objective function can then be computed using the value of thermal power for each scheduling interval.

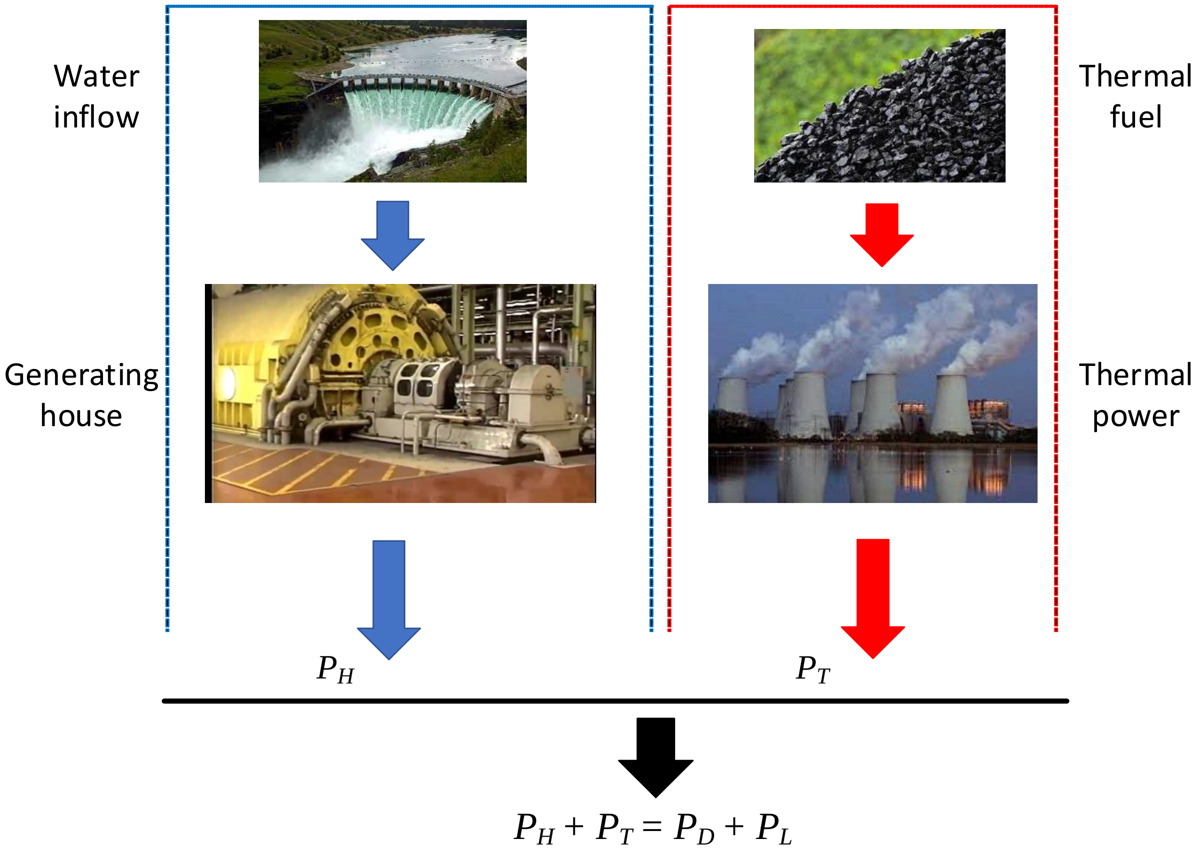

Figure 3. Block diagram representation for hydrothermal scheduling problem including single hydro and thermal unit.

4.2. Scheduling of Single Thermal and Multiple Hydro Units

Another common type of the dispatch problem deals with a power system consisting of single thermal and multiple hydro units [93,94]. In such a problem, the hydro units are connected in a cascade connection. The discharge of the upstream reservoir will be added to the downstream reservoir with a certain time delay in the case of the cascaded connection of the reservoirs [95,96]. Figure 4 shows the basic connection of the multiple hydro units having reservoirs connected in a cascaded connection. It is evident from the figure that the inflow of the downstream reservoir will be in accordance with the discharge rate and the spillage of the upstream reservoir. In this particular case, separate inflow for the downstream reservoirs is not considered.

The objective function in the case of the cascaded hydrothermal scheduling problem can be given as follows [97,98]:

$$f = \sum_{i=1}^{n_s} N_i F(P_T) \qquad (\$) \tag{26}$$

subject to the following constraints:

$$= \begin{cases} P_{T,i} + \sum_{j=1}^{G} P_{H_j,i} = P_{D,i} + P_{L,i} \\ P_{T,min} \le P_{T,i} \le P_{T,max} \\ P_{H_j,min} \le P_{H_j,i} \le P_{H_j,max} \\ V_{jmin} \le V_{j,i} \le V_{jmax} \\ d_{jmin,i} \le d_{j,i} \le d_{jmax,i} \\ \sum_{i=1}^{n_s} N_i d_{j,i} = d_{j,T} \\ V_{j,i} = V_{j,i-1} + inf_{j,i} - d_{j,i} - sp_{j,i} + \sum_{m=1}^{R_{uj}} (d_{m,i-\tau} + sp_{m,i-\tau}) \end{cases} \quad (27)$$

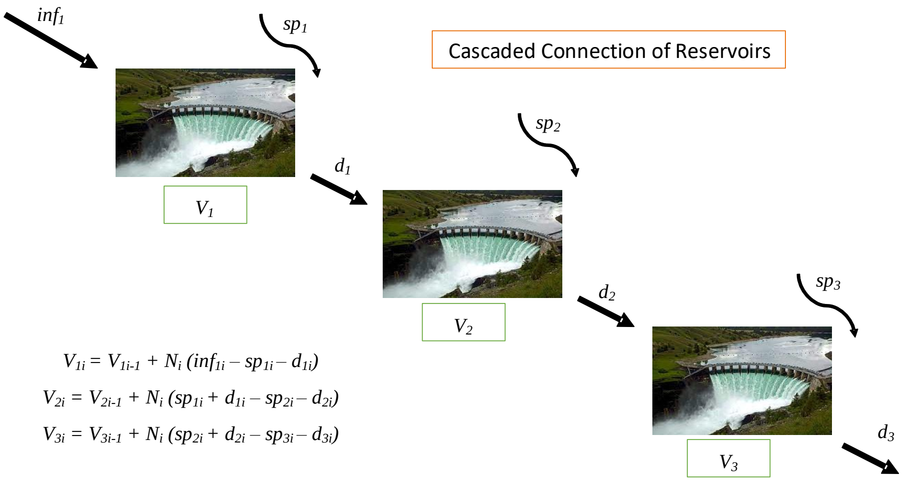

Figure 4. Block diagram representation for cascaded hydrothermal scheduling problem having reservoirs connected in a cascade connection.

The objective function remains same for the cascaded problem and aims to minimize the total generation cost of the equivalent thermal plant. The cost equation for the thermal plant is again modeled using the conventional quadratic equation (and with the addition of a sinusoidal term for valve point loading) with various cost coefficients. The updated power balance equation takes into account the total hydro power contribution of all units in addition to the thermal power while meeting the load demand and the transmission line losses of the system. G represents the total number of hydro units [99,100]. τ represents the time delay from the upstream reservoir m to the downstream reservoir j. R_{uj} shows the total upstream reservoirs immediately located above the j plant. The equation of continuity defined in the last constraint summarizes the volume of the j plant in terms of its inflow, spillage, and discharge rate coupled with the parameters of the upstream reservoirs. The hydro power of a particular unit j is defined in terms of its discharge rate. The transmission losses of the network are modeled as the function of the hydro power for a particular scheduling interval i [101–103].

4.3. Scheduling of Thermal Unit with Pumped Hydro Storage

Another important optimization problem which deals with the optimum dispatch of the thermal and hydro unit is the pumped hydrothermal storage problem. In this type of problem, the scheduling intervals are categorized into two major types, the off-peak intervals in which the demand value of the system is low and the peak intervals in which the demand is high. In off-peak intervals, the water is pumped back to the reservoir, while in the peak intervals, the combined optimum dispatch of hydro and thermal units is computed to meet the demand value [104,105]. The objective function aims to minimize the total thermal cost generation, and it is given as follows:

$$f = \sum_{i=1}^{n_s} N_i F(P_T) \qquad (\$) \tag{28}$$

The constraints for the pumped hydrothermal storage are defined as follows:

$$= \begin{cases} P_{T,min} \le P_{T,i} \le P_{T,max} \\ P_{H,min} \le P_{H,i} \le P_{H,max} \\ V_{min} \le V_i \le V_{max} \\ d_{min,i} \le d_i \le d_{max,i} \\ \sum_{i=1}^{n_s} N_i d_i = d_T \\ V_i = V_{i-1} + N_i(inf_i - d_i - sp_i) \end{cases} \tag{29}$$

The difference lies in the magnitude of the discharge rate d for the pumped hydrothermal storage problem. For off-peak intervals, where the water is pumped back to the reservoir, the magnitude of the discharge rate is taken as negative. For non-pumping intervals (peak intervals) or intervals where both the combined dispatch of hydro and thermal units is determined, the magnitude of the discharge rate is taken as positive [106]. In the case of the pumped hydrothermal scheduling problem, the power balance equation can be written as follows:

$$= \begin{cases} P_{D,g} + P_{L,g} - P_{T,g} - P_{H,g} = 0 & (Generating\ \ Intervals) \\ P_{D,p} + P_{L,p} - P_{T,p} + P_{H,p} = 0 & (Pumped\ \ Intervals) \end{cases} \tag{30}$$

In the above equation, for generating intervals g, the combined dispatch of the hydro power $P_{H,g}$ and thermal power $P_{T,p}$ is taken to meet the demand value and the transmission losses of the system. Figure 5 shows the equivalent circuit model of the pumped hydrothermal model highlighting the power balance constraint equations for different types of sub-intervals [107]. Table 4 summarizes the different dispatch problems for hydro and thermal units.

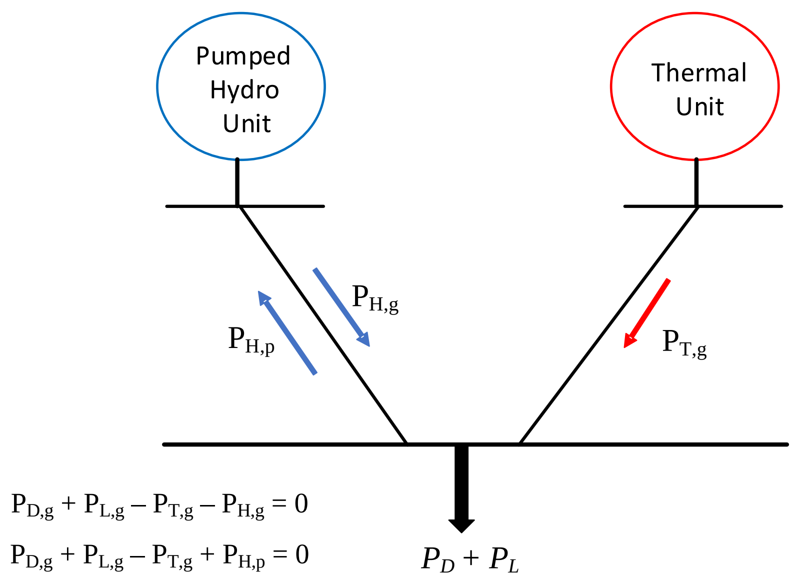

Figure 5. Equivalent circuit model of the pumped hydrothermal scheduling problem while considering the transmission losses of the system.

Table 4. Summary of different types of ED problems involving thermal unit and hydro unit as generating sources. The nature of the optimization problem and the decision variables are highlighted for each type.

Optimization Problem	Objective Function	Constraints	Decision Variables	Nature of Objective Function
Economic dispatch problem for single thermal and hydro unit [83–92]	$f = \sum_{i=1}^{n_s} N_i F(P_T)$	Power balance constraint, power limits constraint, volume constraints, equation of continuity, discharge rate constraints	V	The objective function is non-linear and multi-modal in nature. The cost characteristics can be modeled with or without considering the valve point effect
Economic dispatch problem for single thermal and multiple hydro units connected in cascaded connection [93–103]	$f = \sum_{i=1}^{n_s} N_i F(P_T)$	Power balance constraint, power limits constraint, volume constraints, equation of continuity, discharge rate constraints	V	The objective function is non-linear and multi-modal in nature. The cost characteristics can be modeled with or without considering the valve point effect
Economic dispatch problem for thermal unit and pumped hydro storage unit [104–107]	$f = \sum_{i=1}^{n_s} N_i F(P_T)$	Power balance constraint (depends upon the nature of the scheduling interval), power limits constraint, volume constraints, equation of continuity, discharge rate constraints	V	The objective function is non-linear and multi-modal in nature. The cost characteristics can be modeled with or without considering the valve point effect

5. Economic Dispatch Problem for Conventional and Non-Conventional Sources

The recent shift in the paradigm from conventional to green energy demands the reformulation of sophisticated optimization problems to optimally utilize both conventional and distributed energy sources. The major reasons for opting for renewable sources are their negligible emissions and environmental constraints. However, the production of such sources largely depends on external atmospheric conditions, and the power output can fluctuate in nature for different scheduling intervals [108,109]. To deal with this intermittent nature of renewable sources, researchers have developed various optimization models and forecasting algorithms to effectively coordinate different energy sources in a hybrid power system. This section describes the basic forms of different objective functions and constraints associated with such optimization problems and highlights various additions to augment the nature of the practical problem [110,111].

5.1. Economic Dispatch of Conventional and Photovoltaic Energy Source

Owing to negligible environmental constraints and fossil fuel dependence, the photovoltaic (PV) energy source has gained popularity in generating a clean form of energy. Researchers have developed several dispatch models to incorporate the PV energy source to the conventional grid to fulfill the demand value over certain scheduling intervals. The major challenge in the optimization problem including both PV and conventional sources is the dependence of the PV source on the external atmosphere parameters. The intermittent nature of the PV source introduces certain limitations in predicting its power output for different intervals. The output power of the PV plant is significantly influenced by two atmospheric parameters, irradiance and temperature levels. Therefore, the first step in solving the dispatch problem is to forecast the PV source parameters. Figure 6 shows the basic block diagram for the hydro-solar-thermal scheduling problem.

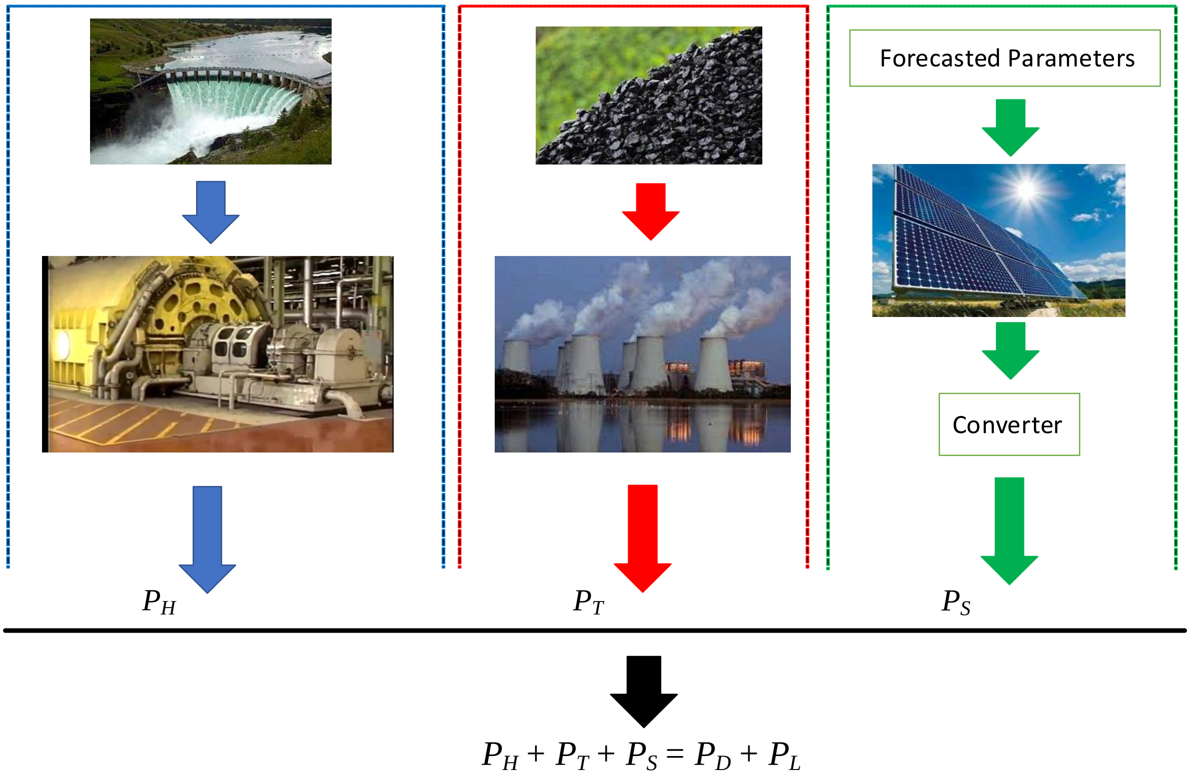

Figure 6. Block diagram representation for hydrothermal solar scheduling problem including single hydro and thermal unit.

5.1.1. Forecasting of the PV Energy Source Parameters

The first step in the power output modeling of the PV source is to forecast or determine the irradiance and temperature levels for different scheduling intervals. The authors in the literature have suggested different methodologies to predict these parameters. The authors in [112,113] have discussed the Box–Jenkins methodology to forecast the irradiance and temperature values over different scheduling intervals based on certain training data. The basic intuition behind the Box–Jenkins method is to tune the parameters of the auto-regressive integrated moving average (ARIMA) model based on the training data to compute the forecast results [114,115]. The main parts—auto-regressive (AR indicated by the order p), moving average (MA indicated by the order q), and differentiation (indicated by the order d)—of the ARIMA model are listed as follows:

$$X_t = \begin{cases} \alpha + +\epsilon_t + \sum_{k=1}^{p} \theta_k \, X_{t-k}, & AR\ Model \\ \epsilon_t + \sum_{k=1}^{q} \delta_k \, \epsilon_{t-k}, & MAModel \\ \alpha + \sum_{k=1}^{p} \theta_k \, X_{k-n} + \epsilon_t & ARMAModel \\ + \sum_{k=1}^{q} \delta_k \, \epsilon_{t-k} & \end{cases} \tag{31}$$

where $\theta_k \, \forall \, k \in \{1, 2, 3, \ldots, p\}$ shows the parameters of the AR model. $\delta_k \, \forall \, k \in \{1, 2, 3, ..., q\}$ represent the parameters of the MA model. ϵ_t shows the white noise term. To handle non-stationary time series, the ARIMA model having order d [116] can be given as follows:

$$(1 - \sum_{k=1}^{p} \theta_k \, L^k)(1 - L^d)X_t = (1 + \sum_{k=1}^{q} \delta_k \, L^k)\epsilon_t \tag{32}$$

where the lag operation L is given as $(L^k(X_t) = X_{t-k})$.

The second popular method of predicting the irradiance and temperature values for different scheduling intervals is to compute the probability distribution function for these parameters [117]. The commonly used distribution in the literature for the temperature and irradiance levels is the beta distribution due to its flexibility in adjusting the curve using different shape parameters. The probability density function for the beta distribution is given as follows:

$$f(r;\alpha,\beta) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} r^{\alpha-1}(1-r)^{\beta-1}, \qquad \alpha,\beta \geq 0,\ 0 \leq r \leq 1 \tag{33}$$

where α, β are the shape parameters, r represents the random variable for the parameters, and $\Gamma(.)$ shows the gamma function. $f(r;\alpha,\beta)$ shows the beta distribution function [118]. The parameters α and β depend upon the mean μ and standard deviation σ [119] as follows:

$$\beta = (1-\mu)\left(\frac{(\mu+1)\mu}{\sigma^2} - 1\right) \tag{34}$$

$$\alpha = \frac{\beta\mu}{1-\mu} \tag{35}$$

These two techniques are most commonly used in the literature to compute the irradiance and temperature levels for the dispatch problems of hybrid energy systems. Other distributions such as Weibull distribution [120] can also be used. The next step in the dispatch problem for the system consisting of solar and conventional sources is to compute the PV power based on the forecasted parameters. Figure 7 shows the overall forecasting and power computation model for the PV energy source.

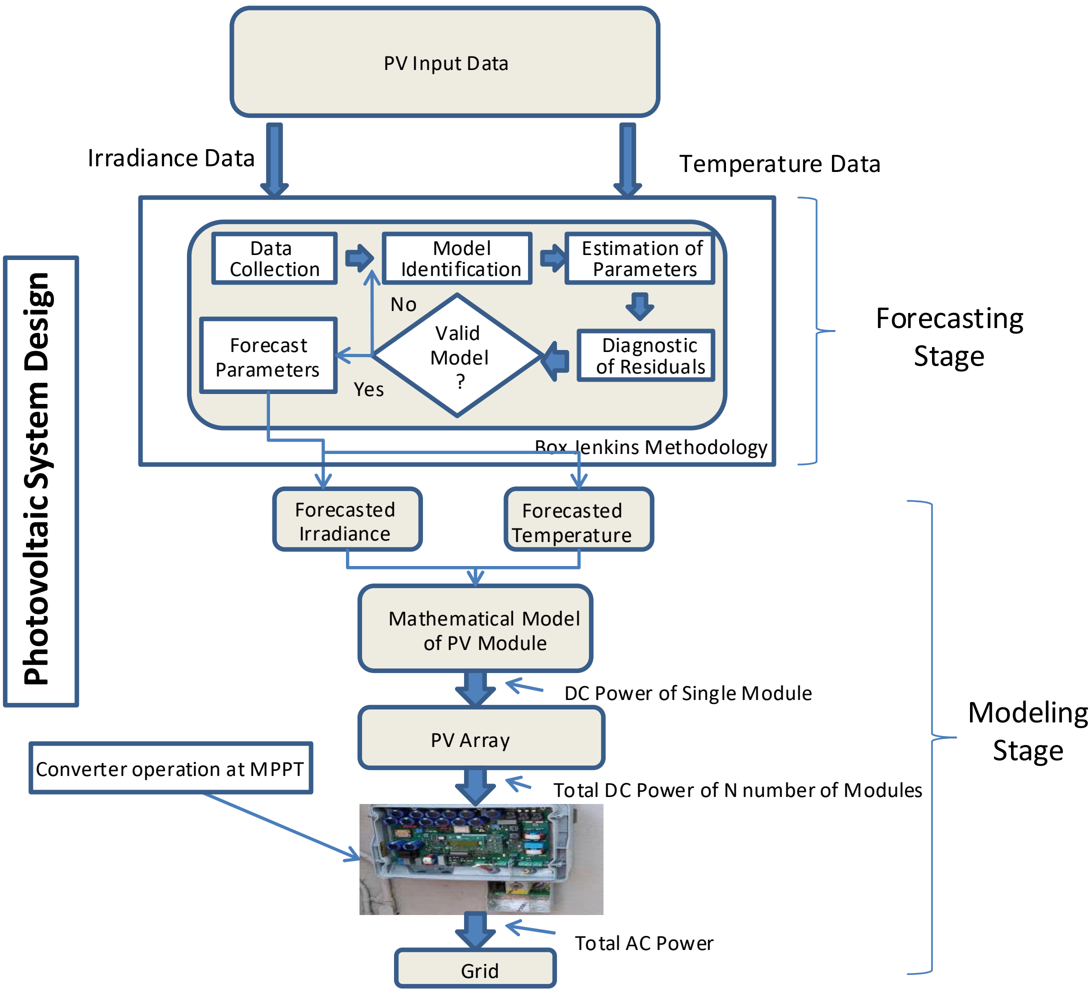

Figure 7. Basic flow chart for determining the PV power output for the economic dispatch problem.

5.1.2. Dispatch Problem Modeling

The output power of the PV module is determined using the irradiance and temperature levels for different scheduling intervals. Different mathematical models are suggested in the literature to compute the output power of the PV plant based on external parameters. The most common method used to determine the characteristics of the PV module is the single diode model [121,122]. However, the single diode model introduces a challenge to optimally selecting the different parameters for the equivalent circuit [123]. The other methods involve modeling the characteristics of the PV module using the fractional integral polynomial method [124] or using the double diode model to augment the efficiency of the single-diode-based circuit [125,126]. The selection for the model depends upon the requirement of the dispatch problem and can be selected based on the system parameters.

The next step in modeling the dispatch problem is to define the objective function and discuss the different constraints associated with the PV power. The constraints for hydro and thermal generation remain the same as previously discussed in the respective sections. Therefore, we will only highlight the basic cost function for solar power and discuss the possible PV constraints. The basic objective function which models the cost equation for the PV plant represents a linear relation between a defined tariff rate and the output power [112,113], given as follows:

$$f_{s,j} = \sum_{i=1}^{n_s} C_j H_i P_{s_j,i} \tag{36}$$

where $f_{s,j}$ represents the cost of the j^{th} PV plant. C_j represents the cost coefficient given in $\$/kWhr$ for the j^{th} plant, H_i represents the duration of particular scheduling interval i given in hours, and $P_{s_j,i}$ represents the output power of the j^{th} plant given in kilowatts or the i scheduling interval. The total cost or the objective function for S number of PV plants is given as follows:

$$f_2 = \sum_{m=1}^{S} f_{s,m} \tag{37}$$

The overall cost function for the combined dispatch of hydro, thermal, and solar energy sources is given as follows:

$$C_T = f_1 + f_2 \tag{38}$$

where f_1 represents the cost function for the hydro and thermal units as described previously. The typical constraint related to the solar power is the power limit constraint, given [119] as follows:

$$P_{s_j,min} \leq P_{s_j,i} \leq P_{s_j,max} \tag{39}$$

The remaining constraints remain the same for the hydro and thermal units as discussed previously in the respective sections. This represents the simplest form of the solar-hydrothermal dispatch problem discussed in the literature. The basic objective function introduced can be modified by taking into consideration different practical constraints. For instance, the authors in [127,128] have updated the objective function for thermal generation by including the emission values while considering the PV energy source. This modification introduces an additional emission cost for the thermal plant which has already been described in the previous sections. The authors in [129] have suggested the economic dispatch of the system consisting of solar and electric vehicles. The authors in [130] consider the pumped hydro storage in addition to the solar and thermal energy sources. The basic modification in the objective function is in accordance with the previously defined generating and pumping intervals for the pumped hydro storage problem. The authors in [131] modify the problem by considering the wind energy source in addition to solar, thermal, and hydro energy sources. The details of incorporating the wind energy source into the dispatch problem are discussed in the next section. This concludes the dispatch for the PV energy source with conventional sources. A large number of objective functions have been discussed for this particular dispatch problem by introducing small changes in the original objective function. However, these changes are in accordance with the different dispatch objective functions already discussed in the paper.

5.2. Economic Dispatch of Conventional and Wind Energy Source

Another renewable energy source which has gained popularity for generating clean power is the wind energy system [132,133]. The output power of the wind system depends primarily on the wind speed for different scheduling intervals. This again introduces a challenge to handling the intermittent nature of the system [134,135]. For solving the dispatch problem including a wind energy source, a similar procedure is required as described previously for the PV system. Therefore, we will only discuss the changes required to model the wind energy system. Figure 8 shows the basic configuration diagram for the dispatch problem consisting of the conventional and wind energy system.

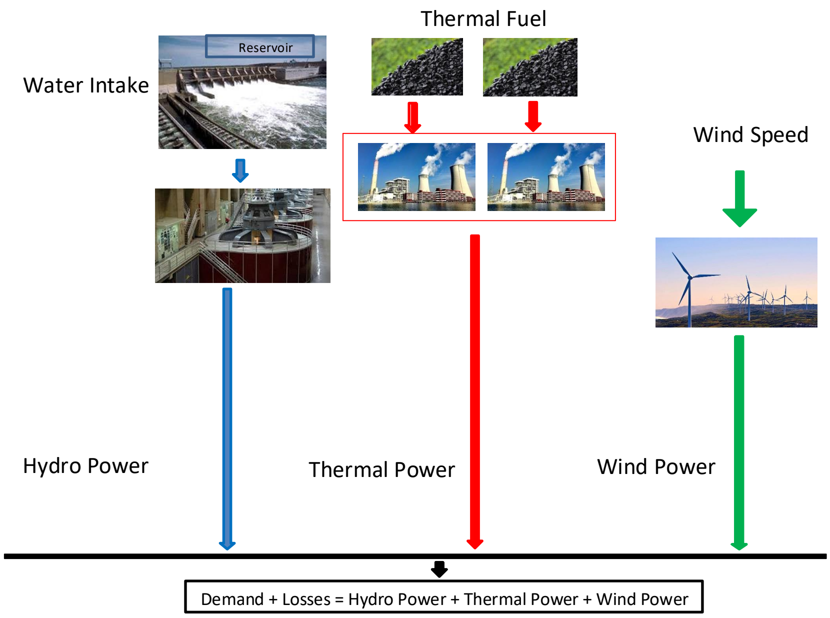

Figure 8. System configuration for the dispatch problem consisting of wind and conventional sources.

The first step is to approximate the wind speed for different intervals. Among the different techniques discussed in the literature [136], the simplest and most conventional method is to use a probability density function for determining the wind speed statistics. The most commonly used probability density function for the wind speed is the Weibull p.d.f. [137], given as follows:

$$f(v) = \frac{a}{b}(\frac{v}{b})^{a-1}exp[-(\frac{v}{b})^{a}] \quad \text{(Weibull p.d.f)} \tag{40}$$

where a represents the shape parameter, and b represents the scale parameter. When the shape parameter a is taken as 2, another p.d.f. known as the Rayleigh p.d.f. [138] can be written as follows:

$$f(v) = \frac{2v}{b^2}exp[-(\frac{v}{b})^{2}] \quad \text{(Rayleigh p.d.f)} \tag{41}$$

where $b = \frac{2}{\sqrt{\pi}}v_{ag}$ (v_{ag} represents the average wind speed). Based on the type of distribution used, the value of v_{ag} can be determined as follows:

$$v_{ag} = \int_0^{\infty} v.f(v)\, dv = \frac{\sqrt{\pi}}{2}b \quad \text{(Rayleigh Statistics)} \tag{42}$$

The output power of the wind energy system is usually determined based on the average of the cubic wind speed. Therefore, the above relation can be modified to give the average wind speed as follows:

$$(v^3)_{ag} = \int_0^\infty v^3.f(v)\,dv = \frac{3}{4}b^3\sqrt{\pi} \tag{43}$$

By substituting the value of the b, the above equation can be written as follows:

$$(v^3)_{ag} = \frac{3}{4}\sqrt{\pi}(\frac{2}{\sqrt{\pi}}v_{ag})^3 = \frac{6}{\pi}v_{ag}^3 \tag{44}$$

The average power of the wind can then be determined as follows:

$$P_{ag} = \frac{6}{\pi}.\frac{1}{2}\rho A v_{ag}^3 \quad \text{(Rayleigh Statistics)} \tag{45}$$

where ρ represents the density of the air given in kg/m^3, and A represents the swept area of the rotor given in m^2 [139]. Additional terms such as efficiency of the system η and coefficient of performance C_p can also be included in the above equation to provide a more realistic approach. The objective function for the overall dispatch problem including conventional and wind energy power can then be formulated by taking relations similar to those discussed for the solar energy source (a linear relationship between a defined tariff and the power output of the wind system). The constraints defined for the dispatch problem are same as previously defined for the hydro and thermal units with the addition of the power limits constraint for the wind energy source [140,141].

Figure 9 shows the basic block diagram showing the major steps involved in solving the dispatch problem consisting of conventional and distributed generation sources.

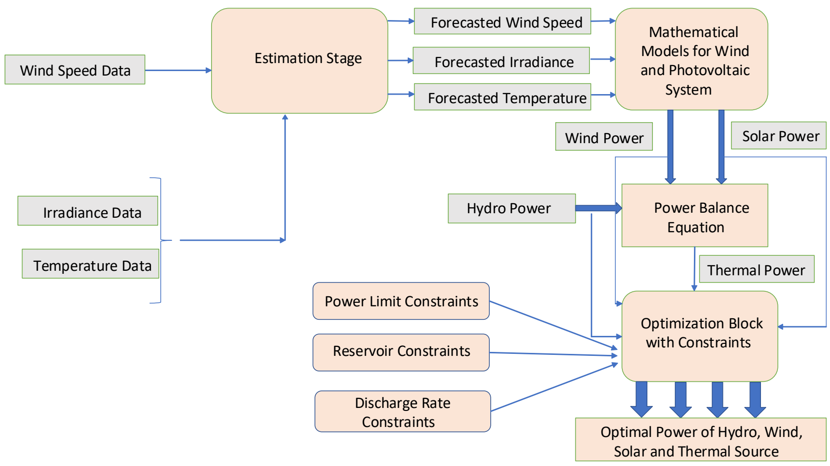

Figure 9. Overall block diagram for computing the dispatch problem for hybrid energy systems consisting of conventional and renewable sources.

6. Methods and Simulation Tools to Solve the ED for Integrated Systems

After highlighting the major types of dispatch problems along with discussing the nature of the involved objective functions and constraints, the authors provide a brief introduction of different optimization techniques used in the literature to find the optimum solution. The two major sets of algorithms used in the literature are deterministic and heuristic optimization algorithms. Deterministic algorithms try to achieve a global solution by using a well-defined set of update equations. Such algorithms can be difficult to implement for highly non-linear, multi-modal, and non-convex objective functions. On the contrary, meta-heuristic optimization algorithms have a certain randomness in their update equation and provide good approximates to the global solution for non-linear and multi-modal problems. Some review papers have already been discussed in the Introduction which compare the performance of different optimization algorithms for various types of ED problems. Here, we will briefly highlight the major techniques used for each type of ED problem. Among meta-heuristic optimization algorithms, promising techniques used to solve the ED problem are the firefly algorithm (FA) [142,143], PSO [144], accelerated particle swarm optimization (APSO) [145], harmony search algorithm [146], and stochastic techniques [147]. A large set of different conventional techniques has also been studied for solving different types of dispatch problems, such as the Lagrangian relaxation method [148], mixed integer programming [149], dynamic programming [79], and interior point programming [150]. Figure 10 shows the breakdown of different optimization algorithms. Table 5 summarizes the behavior of a few promising meta-heuristic techniques for each type of ED problem, while Table 6 summarizes basic features of the most commonly used simulation tools to solve the ED problem.

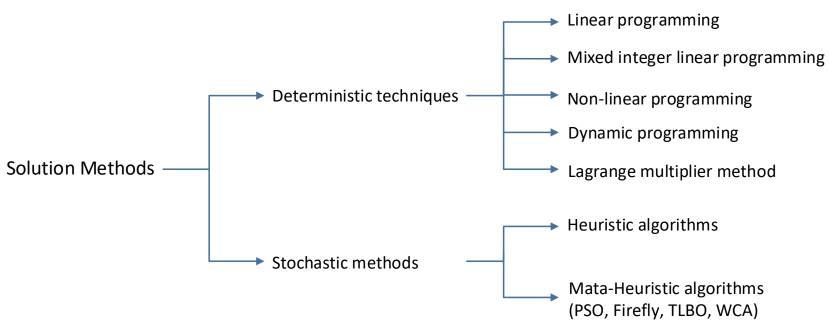

Figure 10. Breakdown of different solution methods used to solve various forms of the ED problem.

Table 5. Brief summary and analysis of different optimization algorithms for various types of economic dispatch problems.

Algorithm	Update Criteria	Test System	General Performance
Teaching Learning Based Algorithm [67]	Meta-heuristic optimization algorithm with two different phases (Teaching and Learning) having multiple update equations	Muti-objective combined economic emission dispatch problem having multiple thermal units with different cost characteristics	Higher computational time as compared to techniques such as PSO and FA. By making certain parametric modifications, the final converged solution can be improved by a substantial factor
APSO [112]	Meta-heuristic optimization algorithm with single update equation for reaching the optimum solution	Short term hydrothermal scheduling problem under the penetration of single equivalent PV source	Intermediate computational effort in reaching towards the optimal solution. Single update equation with the global best component improves the performance of the algorithm towards the optimal solution
PSO [113]	Meta-heuristic optimization algorithm with two update equations having both velocity and position components	Hydrothermal scheduling problem under the penetration of multiple PV units	Higher computational time in reaching towards the optimal solution. Two update equations with both local and global search mechanisms give promising results in terms of reaching the final solution
Firefly Algorithm [142,143]	Meta-heuristic optimization algorithm with single update equation for reaching the optimum solution	Simple ED problem with multiple thermal units of different cost characteristics having valve point loading effect	Lower execution time in reaching towards the optimal solution. The absence of global best component can result in trapping of the solution towards the local optimum. However, different parametric and structural variants can improve the convergence behaviour of the algorithm
Improved Harmony Search Algorithm [146]	Meta-heuristic optimization algorithm	Short term hydrothermal scheduling problem	Promising results in attaining the global solution. Computational time is also comparable to techniques like FA and APSO

Table 6. Brief summary and analysis of different simulation tools to compute the ED problem.

Simulation Tool	Advantages/Features	Disadvantages
Power World Simulator [151]	Economic dispatch of multi-generation thermal system can be computed using different cost functions. Power system consisting of multiple thermal units can be modeled using variable characteristics. In addition, different techniques such as Gauss–Seidel , Newton–Raphson, fast decoupled, and DC power flow can be used for power flow studies	Single line diagram of the system can only be modeled using the software. Different distributed energy sources and hydroelectric source cannot be included effectively in the system. Moreover, various advanced optimization techniques cannot be implemented for solving the objective functions
MATLAB/Simulink [152]	Different meta-heuristic and conventional optimization algorithms can be implemented for solving the dispatch problems. The mathematical models for PV energy source and wind energy system are available to analyze the hybrid energy systems	ED algorithms need to be developed from scratch. The options to compute the optimal power flow and perform the contingency analysis for the given system are not readily available
DIgSILENT [153]	The contingency analysis and the optimal power flow solution can be obtained efficiently while solving the ED and unit commitment problem. In addition, renewable energy sources and battery energy storage can be included in the dispatch model. The emission, startup, and operation cost functions can be optimized for different power sources	Advanced optimization algorithms such as heuristic and meta-heuristic techniques cannot be implemented effectively for obtaining the optimal solution for the hybrid energy systems
Electrical Transient Analyzer Program (ETAP) [154]	ED for multi-thermal power systems can be computed using robust algorithms. Fuel cost minimization along with the optimal energy management techniques provides a good platform to solve dispatch problems for non-linear cost functions	Models for renewable energy sources are not readily available for developing the dispatch scenario for hybrid energy systems. Moreover, optimization algorithms are largely limited to conventional techniques
PLEXOS [155]	Stochastic and deterministic algorithms are available to compute the ED for multi-generation system. Moreover, unit commitment and dispatch problems can be solved efficiently while considering emission and fuel constraints	Intermittent nature of renewable energy sources cannot be modeled efficiently for the dispatch problems of hybrid energy systems

7. Conclusions and Future Directions

The formulation of scheduling problems for different hybrid and multi-generation energy systems has become an important domain in the field of optimization theory. A number of optimization problems based on different objective functions depending upon the configuration of the system have been suggested by researchers to model an actual system. However, there are certain scenarios which have not been considered extensively while discussing the dispatch problems for different generating units. For instance, while discussing dispatch for the system consisting of thermal units, cost characteristics are modeled only using the quadratic cost equation in the majority of problems. However, the quadratic function can be made linear using piece-wise linear functions to formulate another type of objective function and compare its performance with conventional characteristics [156,157]. Similarly, for the hydrothermal scheduling problem, the conventional objective function takes into account only cost characteristics of thermal generation while maintaining the reservoir constraints. This approach is appreciable since the running cost of the hydro power is negligible as compared to the thermal generation. However, if we are scheduling over a long duration, then certain factors such as maintenance cost and operation and management costs should be incorporated in the conventional objective function to better formulate the optimization problem [158].

For scheduling problems involving a solar energy source, an important factor known as the partial shading effect is usually not considered while computing the output power of the PV module. The partial shading effect results in multiple local peaks for the power curves instead of a global peak; therefore, it is essential to consider this effect, as the majority of the literature suggests the operation of the PV plant at MPPT and neglects the tracking procedure for the global optimum power. By considering this fact, the output power models for the PV modules would be greatly influenced, and it would certainly introduce a research gap to formulate more realistic optimization functions [159,160]. Similarly, for renewable energy sources, the conventional cost equation can be updated to include the overestimation and underestimation penalties to better formulate the objective function.

Another important consideration while developing the optimization models for hybrid energy systems is to consider the resilience of the system. Power systems are vulnerable to different faults and natural hazards. Therefore, proper contingency analysis would be required to better schedule different energy sources while considering reliability and resilience constraints. This would introduce modified forms of the optimization problems for scheduling hybrid energy systems [161,162].

To conclude, power system optimization is extremely important for maintaining the power balance of the system. Different dispatch models are required to find the optimum power allocation of each energy source in a hybrid system. As the number of generating sources increases, the optimization problem becomes more complex, non-linear, and multi-dimensional in nature. The proper formulation of optimization functions would be required to idealize a complex physical system incorporating different energy sources. This research presents a state-of-the-art review of the major types of dispatch problems for different energy sources while presenting the nature of each objective function and the generating constraints involved.

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Abbreviations

The following abbreviations are used in this manuscript:

ED	Economic Dispatch
STHTS	Short Term Hydrothermal Scheduling
EED	Economic Emission Dispatch
PV	Photovoltaic
WES	Wind Energy System
POZ	Prohibited Operating Zones

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