

Discrete optimization algorithm for optimal design of a solar/wind/battery hybrid energy conversion scheme

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Abstract

Renewable energy technologies have been developed in recent years due to the limited sources of fossil fuels, the possibility of depletion of fossil fuels and the related environmental issues. In these types of systems, it is crucial to reach optimum sizing in order to have an affordable system based on solar and wind energy and energy storage. In this study, a powerful optimization scheme based on tabu search, called discrete tabu search, has been proposed for sizing three stand-alone solar/wind/energy storage (battery) hybrid systems. For validating the applied algorithm effectiveness, the results are compared with the results found by the discrete harmony search. The obtained outcomes are compared on the basis of total annual cost. The components of the scheme are analyzed in different operating conditions by applying meteorological data in addition to real time information from three typical regions of Iran. According to the obtained data, applying 'discrete tabu search' leads to better outputs on the basis of mean, standard deviation and worst indexes.

Keywords: hybrid solar/wind//battery system; stand-alone scheme; different operating conditions; optimum sizing; discrete tabu search

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1. INTRODUCTION

Several factors including the limitations of fossil fuel resources, global warming due to the combustion of fossil fuels and their environmental issues necessitate using renewable energy sources (RES) [1]. There are several advantages in utilizing RES in addition to their potential for providing the present demand of world's energy [2, 3]. Development in renewable energy systems leads to higher sustainability and reduction of greenhouse gases production [4–9]. According to International Energy Agency [10], electricity final consumption of the world has increased

from ~1983 TWh in 2010 to >23 695 TWh in 2017. Renewable energy technologies can be used for clean generation of electricity. Among various RES, wind turbines (WTs) and photovoltaic (PV) have the highest potential to provide the required energy load in isolated area [11–13]. The main problem of utilizing single-renewable energy schemes is the dependency of generated power on the conditions of environment such as speed of wind and solar irradiation. Combining RES (hybrid systems) is a conventional solution to overcome the mentioned problem. By using the hybrid systems, reliability of the electricity generation increases [14–17]. Since the nature of wind and solar energies are fluctuating,

Table 1. Literature review summary.

Reference/Year	PV	WT	Battery	Hydrogen	Diesel	Other	Method
Ekren [22]/2010	✓	✓	✓	—	—	—	SA*
Calderón <i>et al.</i> [23]/2010	✓	✓	—	✓	—	—	S*
Khatib <i>et al.</i> [24]/2011	✓	—	—	—	✓	—	S
Dufo-López <i>et al.</i> [25]/2011	✓	✓	✓	—	✓	—	Pareto evolutionary algorithm
Belfkira <i>et al.</i> [26]/2011	✓	✓	✓/—	—	✓	—	S
Raj and Ghosh [27]/2012	✓	—	—	✓/—	✓/—	—	S
Valdés <i>et al.</i> [28]/2012	✓	—	—	✓	—	—	Experimental/S
Merei <i>et al.</i> [29]/2013	✓	✓	✓	—	✓	—	GA
Castañeda <i>et al.</i> [30]/2013	✓	—	✓	✓	—	—	S
Hiendro <i>et al.</i> [14]/2013	✓	✓	✓	—	—	—	HOMER software
Rekioua <i>et al.</i> [31]/2014	✓	—	—	✓	—	—	S
Bensmail <i>et al.</i> [32]/2015	✓	—	—	✓	—	—	S
Tsuanyo <i>et al.</i> [33]/2015	✓	—	—	✓	—	—	HOMER software
Chauhan and Saini [34]/2016	✓	✓	—	—	—	✓	HS*
Shankar and Mukherjee [35]/2016	✓	✓	—	—	—	✓	HS
Halabi <i>et al.</i> [36]/2017	✓	—	✓	—	✓	—	HOMER software
Nadjemi <i>et al.</i> [37]/2017	✓	✓	✓	—	—	—	Cuckoo search
Hatata <i>et al.</i> [38]/2018	✓	✓	✓	—	—	—	GA
Ahmad <i>et al.</i> [39]/2018	✓	✓	—	—	—	✓	HOMER software
Eteiba <i>et al.</i> [40]/2018	✓	—	—	—	—	✓	HS
Khiareddine <i>et al.</i> [41]/2018	✓	✓	✓	✓	—	—	S; energy management strategy
Chakir <i>et al.</i> [42]/2019	✓	✓	—	—	—	—	S
Bawazir and Cetin [43]/2020	✓	—	—	—	✓	—	S and overview

HS, harmony search; SA, simulated annealing; S, simulation.

energy storage units are required for PV/WT hybrid schemes. Generally, deep-cycle lead acid batteries are applied for storing the generated power.

Analyzing and investigating the off-grid hybrid schemes using RES have attracted scientists' attention in recent years (Table 1). Optimal sizing of these systems is necessary to produce cost-effective power. System optimal sizing refers to finding the numbers of components to reach the minimum total annual cost (TAC). Since the input variables and numbers of components are discrete, this procedure for these types of systems is dependent on combinatorial optimization problems. In order to determine the optimal size of the schemes, an appropriate algorithm with the ability of finding the ideal combination of the components should be applied. Various methods are suggested in the previous studies [18, 19]. For instance, Roy [20] proposed an optimization model that can be applied for planning installation of WT over a worldwide energy scenario. In another research [21], a simple numerical approach was developed to size a generation unit. This algorithm was utilized to calculate the optimum capacity of generation and required storage for PV/WT hybrid systems for a remote area with residential load. Hiendro *et al.* [14] techno-economically analyzed WT and PV panel for a PV/WT hybrid system. It was found that WT and batteries are the most important units to provide the required power at night hours. Kaabeche *et al.* [5] suggested iterative approach for optimal sizing to reach the optimal capacities of the components of a PV/WT/battery system. Belmili *et al.* [11] used a detailed sizing approach for off-grid PV/WT schemes.

Owing to the growing interest in stand-alone PV/WT/battery hybrid system (SHS) deployment, the research on different

aspects of SHS has significantly increased over the past few years. Among different aspects, optimum capacity of generation is an important area of research in SHS. The optimum capacity of generation is a complex non-linear optimization problem that is subject to a variety of operational constraints. To effectively solve this vital problem, it is essential to use a powerful optimization method. Heuristic algorithms, which are inspired by natural phenomena, are efficient and appropriate optimization tools that are broadly used for solving complicated optimization problems. These algorithms can be used for hybrid systems.

In the present article, discrete tabu search (DTS), as powerful optimization approach, is employed for optimizing three stand-alone hybrid systems and consists of PV, WT, and battery as the storage unit, in various regions of Iran, namely, PV/WT/battery, WT/battery and PV/battery. The components of the scheme are analyzed in different operating conditions by applying meteorological data in addition to real-time information from three typical regions of Iran. The objective is total cost minimization subject to the operational limitations. In addition to optimization of the hybrid energy systems for the case studies by applying DTS, comparing the results of the current work with the ones achieved by discrete harmony search (DHS) [34] is another novelty of the current research. In other words, in the present paper, an SHS is considered and investigated. Wind and PV are the primary sources of energy for power generation and batteries are utilized for storing the generated energy. In the first step, the system is modeled to obtain the formulation of TAC. Afterwards, TAC is used as objective function and the optimization is performed to determine the ideal numbers of SHS. Then, the performances of powerful algorithm in obtaining the hybrid system optimal size

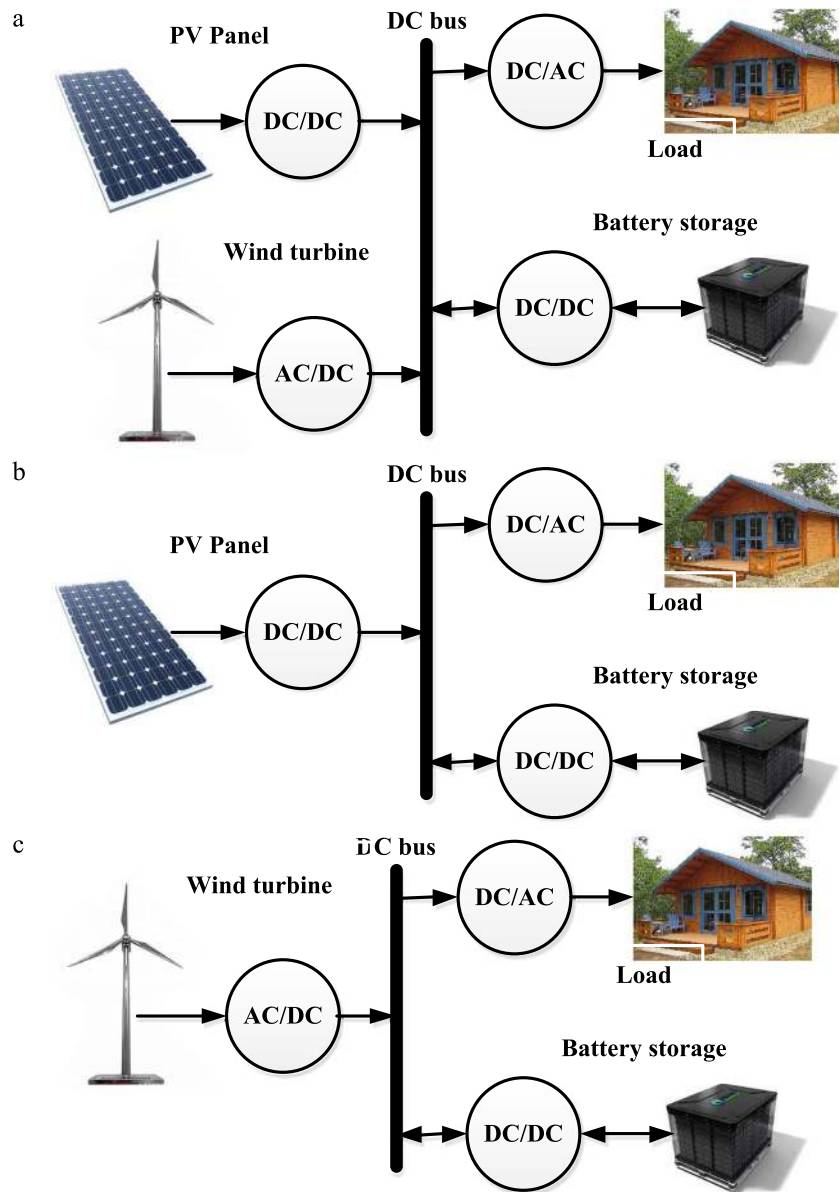


Figure 1. Schematic of stand-alone hybrid scheme: a) PV/WT/battery; b) PV/ battery; c) WT/battery.

are evaluated. The details of the methods and their performance are represented in the following sections.

2. UNIT SIZING

In [Figure 1](#) the schematics of the investigated system including solar, WT and battery are illustrated. The chargers of the battery are connected to DC/DC and AC/DC buses for storing PV and WT generated electricity, respectively. Determination of the optimal size of this system is very crucial to achieve an appropriate ratio between the cost and performance. In order to achieve this goal, the difference between the generated power (P_{Gen}^t) and the energy demands (P_{Dmd}^t) must be minimized as indicated in

Eq. (1). The operating strategy of the stand-alone hybrid scheme for each hour is represented by the flow chart provided in [Figure 2](#).

$$\Delta P = P_{Gen}^t - P_{Dmd}^t \quad (1)$$

2.1. Resource and load information

In order to analyze the system, hourly data of solar irradiation, speed of wind and ambient temperature are gathered in a 1-year period. The case studies are located in north-east, south and north-west of Iran, respectively, as shown in [Figures 3 to 5](#) [44]. The mean hourly energy demand of a conventional building, located in the case studies, is represented in [Figure 6](#). The mentioned data are utilized for determination of the outputs of the current study.

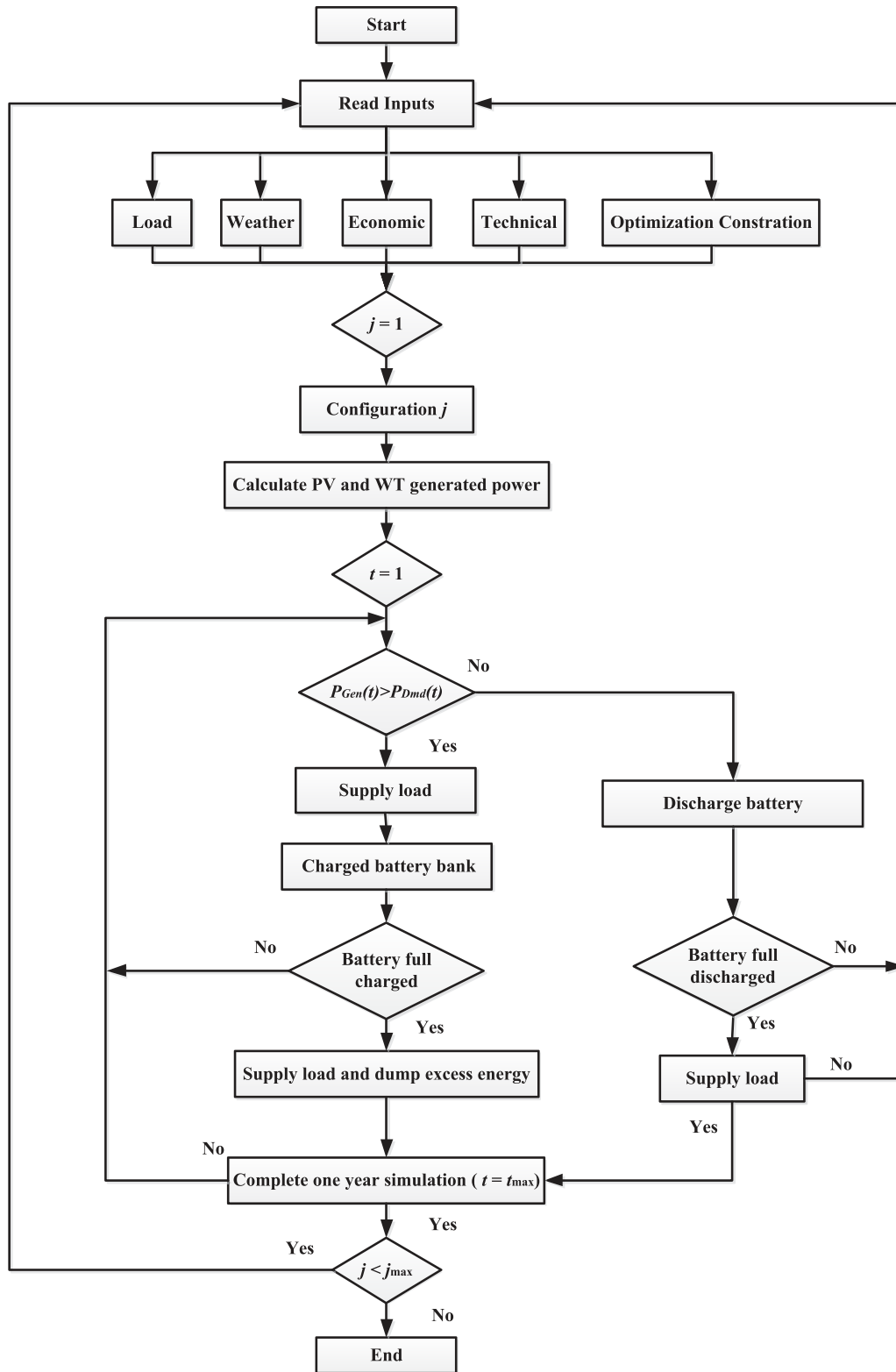


Figure 2. Operating strategy of the hybrid scheme.

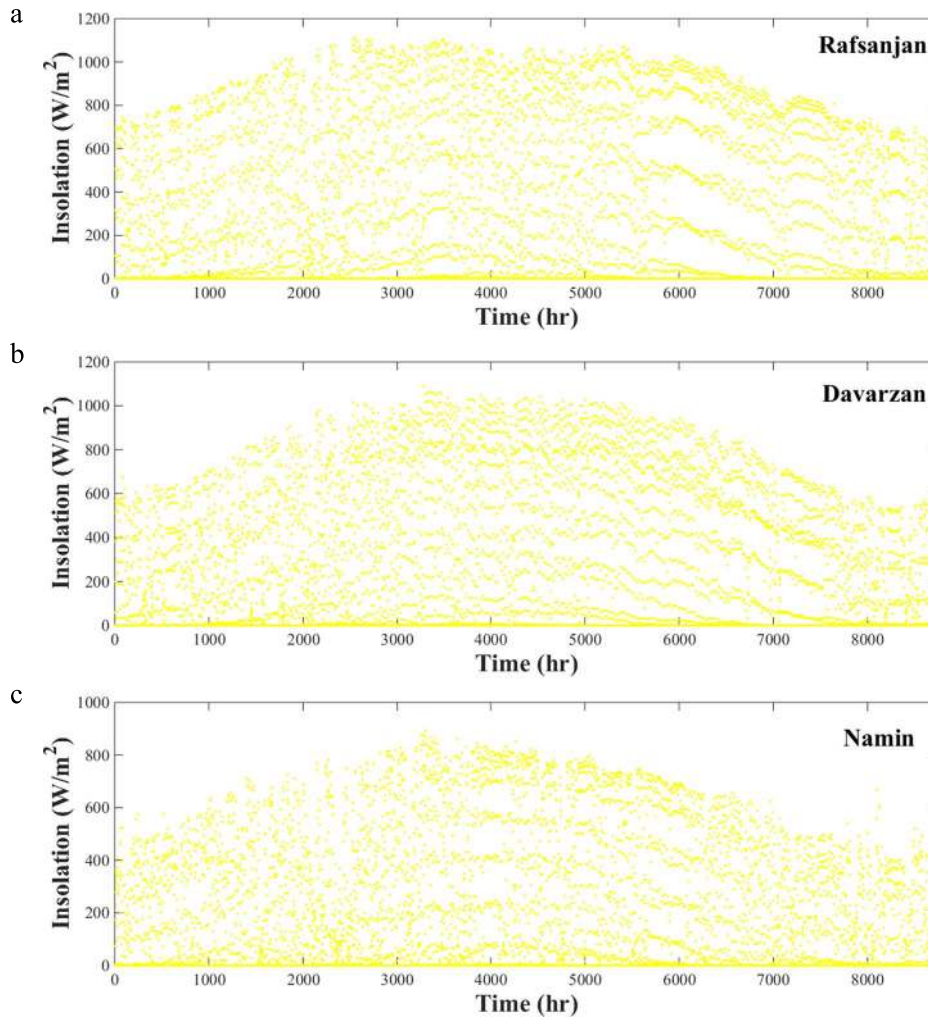


Figure 3. Insolation profile in a year.

2.2. Wind turbine

In Eq. (2), the generated power of turbine is indicated based on the wind speed [45]. The features of the considered WT in the current study are represented in Table 2.

$$P_{Wind-Each}^t = \begin{cases} 0 & \text{if } v \leq V_i \text{ or } v \geq V_o \\ P_r \frac{v - V_i}{V_r - V_i} & \text{if } V_i < v < V_r \\ P_r & \text{if } V_r \leq v < V_o \end{cases} \quad (2)$$

In Eq.(2), $P_{Wind-Each}^t$ refers to the generated power by each turbine, v is the speed of wind and V_o , V_i and V_r , indicate cut-out, cut-in and rated, or nominal turbine speed, respectively. P_r denotes the rated power of each WT.

2.3. PV

PV generated power, by considering the solar irradiation (R_a , in kW/m^2), and ambient temperature, can be determined by using Eq. (3) [46, 47]. The features of PV panels applied in this paper

are indicated in Table 2.

$$P_{PV-Each}^t = R_a(t)A_{pv}\eta_{pv} \quad (3)$$

Here, A_{pv} refers to PV surface area (in m^2) and η_{pv} is the PV efficiency, which can be obtained by applying Eq. (4) as follows:

$$\eta_{pv} = \eta_r \eta_{pc} [1 - N_T ((T_j) - T_{ref})] \quad (4)$$

$$T_j = T_{air}(t) + \frac{R_a(t)}{800} (NOCT - 20) \quad (5)$$

Where η_{pc} , η_r , T_{air} , T_j , T_{ref} , $NOCT$ and N_T are the efficiencies of power conditioning and reference module, ambient air temperature ($^{\circ}\text{C}$), temperature ($^{\circ}\text{C}$) coefficient, reference temperature of the cell, PV nominal working temperature (43°C) and temperature coefficient in the PV panel efficiency, respectively.

The generated electricity by a panel and a WT are given in Figures 7 and 8. The utilized data are hourly average, which is applicable for sizing the units.

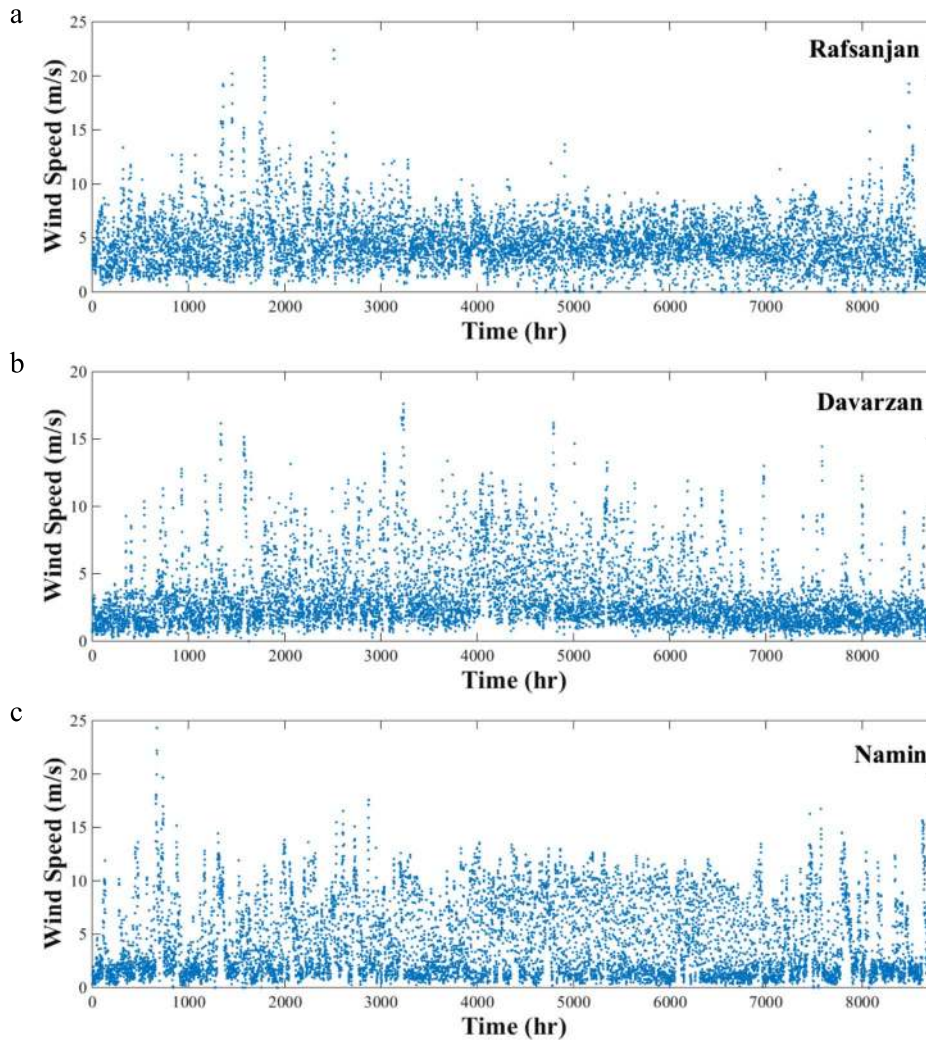


Figure 4. Hourly distribution of wind speed in a year ($h= 10$ m).

2.4. Battery

Charging or discharging of the input power may be positive or negative. In the state of charge battery, based on the determination of productivity and duration, is calculated thus:

If $P_{PV}^t + P_{Wind}^t = P_{Dmd}^t$, the capacity of the battery will be constant. In the cases, the produced power of PV panels and WTs are higher than load power, the storage system is in charging condition, which is defined as follows:

$$SOC_{Batt}^t = SOC_{Batt}^{t-1} (1 - \sigma) + \left[(P_{Wind}^t + P_{PV}^t) - \frac{P_L^t}{\eta_{Inv}} \right] \eta_{BC} \quad (6)$$

Where SOC_{Batt}^{t-1} and SOC_{Batt}^t refer to battery bank charge quantities at time $t-1$ and t , respectively. P_L^t refers to the demand of energy in a specific hour. P_{Wind}^t and P_{PV}^t denote the generated power by the WTs and PV panels, respectively. η_{Inv} is the inverter efficiency, η_{BC} is the battery bank charge efficiency and σ refers to the rate of hourly self-discharge.

In the cases $P_{PV}^t + P_{Wind}^t < P_{Dmd}^t$, the total generated power by the WTs and PV panes are lower compared with the load power, the storage system is in the discharge state. The battery charged quantity at time (t) can be determined by Eq. (7). It should be indicated that the storage system can be discharged up to a restricted value [48].

$$SOC_{Batt}^t = SOC_{Batt}^{t-1} (1 - \sigma) + \left[\frac{P_L^t}{\eta_{Inv}} - (P_{Wind}^t + P_{PV}^t) \right] / \eta_{BF} \quad (7)$$

In this equation, η_{BF} denotes the efficiency of battery storage discharging. The profiles of storage scheme utilized in the system are represented in Table 3.

3. GOVERNING EQUATIONS

3.1. Objective function

In order to obtain the solution, it is necessary to accurately define the objective function. The goal of this study is minimizing the

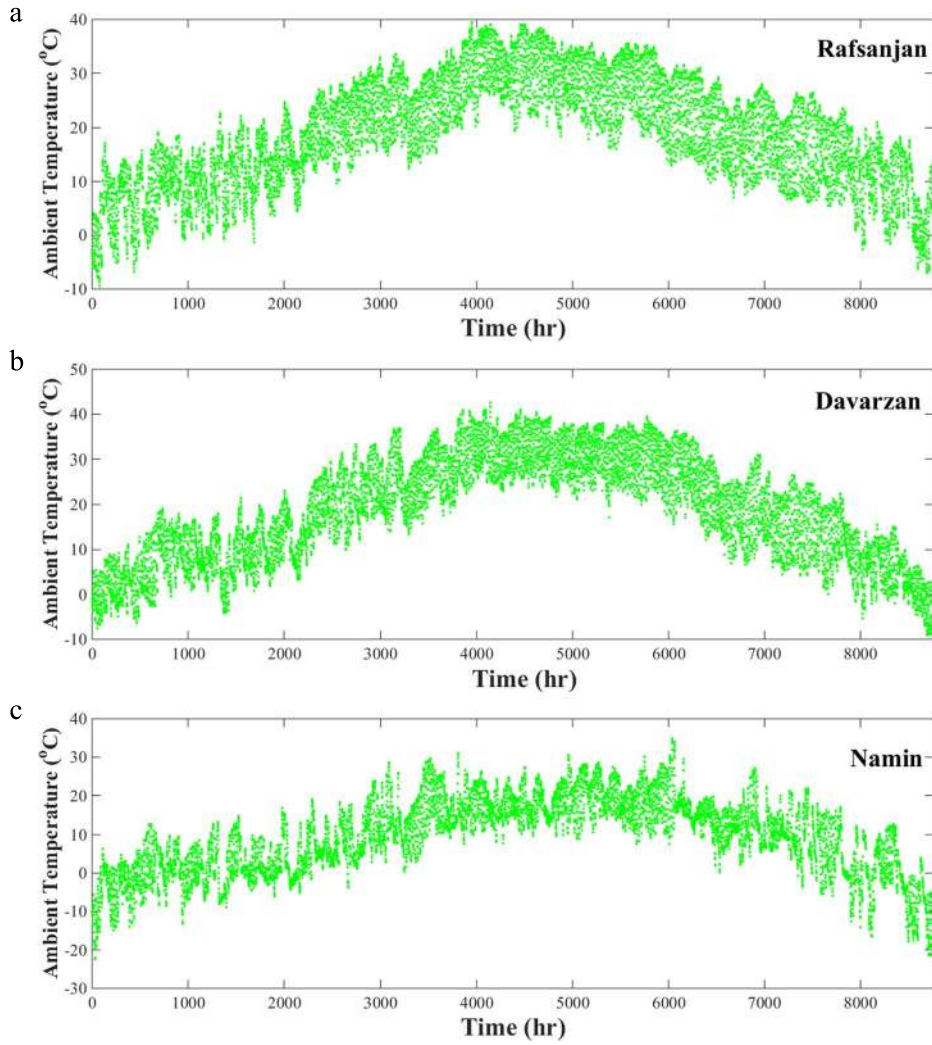


Figure 5. Hourly ambient temperature profile in a year.

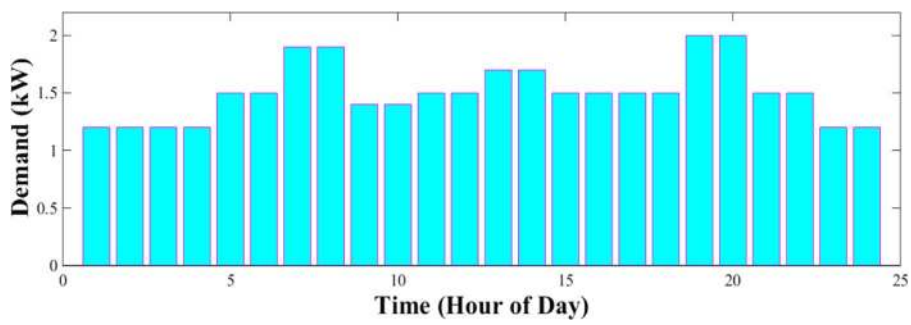


Figure 6. Mean load demand in a day.

Table 2. Wind turbine and PV panel parameters.

Wind turbine		PV panel	
P_r	1 kW	Prs	260 W
V_i	3 m/s	P_p	\$312
V_o	20 m/s	P_{if}	$0.5 \times P_p$
V_r	9 m/s	C_{Mnt}^{PV}	0.005\$/kW h
T_p	\$1443	$LSPV$	20 years
T_{if}	$0.25 \times T_p$	N_{PV}^{max}	200
N_{Wind}^{max}	200		
C_{Mnt}^{Wind}	0.02\$/kW h		
LS_{Wind}	20 years		

TAC. It contains both annual maintenance cost (C_{Mnt}) and capital cost (C_{Cap}). In order to obtain optimal design of the system, the problem of optimization stated in Eq. (8) must be solved by applying an optimization approach.

$$\begin{aligned} & \text{Minimize } (TAC(N_{PV}, N_{Wind}, N_{Batt})) \\ & = \text{Min.} \sum_{m=PV, Wind, Inv, Batt} C_{Cap,m} + C_{Mnt,m} \quad (8) \end{aligned}$$

C_{Cap} happens at the start of a project while the C_{Mnt} happens in the period of project life.

During the project life, some units of the considered system must be substituted several times. In the current research, the lifetime of the system is considered 5 years. By applying single

payment present worth factor, Eq. (9) is obtained as follows:

$$C_{Batt} = P_{Batt} \sum_{k=0,5,10,15} \frac{1}{(1+i)^k} \quad (9)$$

Where C_{Batt} refers to the battery present worth, and P_{Batt} denotes the price of the battery.

Similarly, the converter/inverter lifetime considered equal to 10 years. By utilizing the same payment, Eq. (10) is obtained as follows:

$$C_{Conv/Inv} = P_{Conv/Inv} \sum_{k=0,10} \frac{1}{(1+i)^k} \quad (10)$$

Where $C_{Conv/Inv}$ refers to the converter/inverter present worth, and $P_{Conv/Inv}$ is its price.

By disintegrating the C_{Cap} into the annual costs of all the components of the considered system, Eq. (11) is obtained as follows:

$$\begin{aligned} C_{Cap} = CRF [(N_{Wind} \cdot C_{Wind}) + (N_{PV} \cdot C_{PV}) + (N_{Batt} \cdot C_{Batt}) \\ + (N_{Conv/Inv} \cdot C_{Conv/Inv}) + C_{Backup}] \quad (11) \end{aligned}$$

$$CRF = \frac{A}{P} = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (12)$$

Where CRF is the capital recovery factor, n is the life span and i denotes the interest rate and N_{Wind} and N_{PV} indicate the number

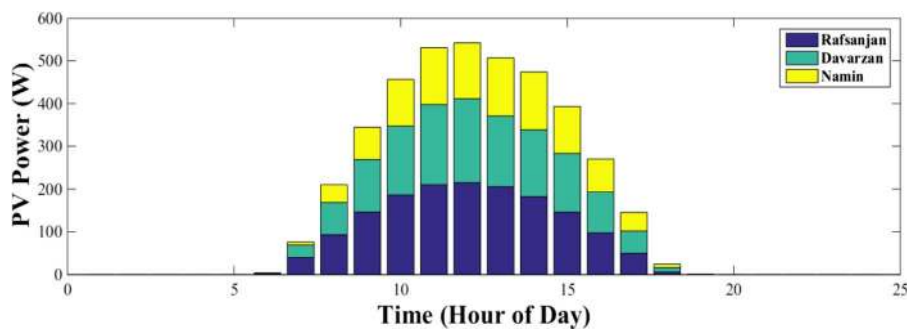


Figure 7. Mean hourly produced power by a PV panel in a day.

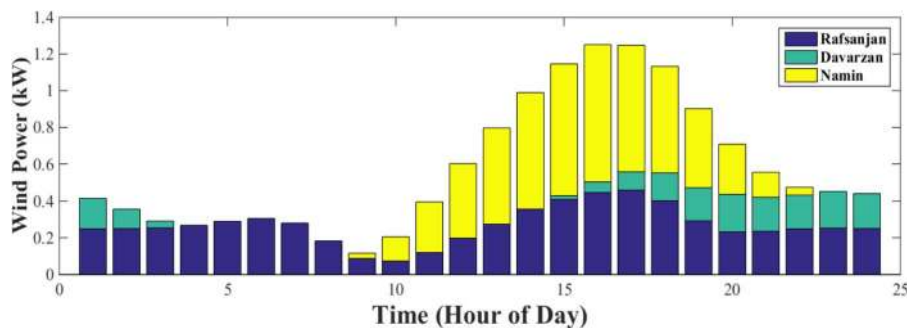


Figure 8. Mean hourly produced power by a WT in a day.

Table 3. Component parameters.

	Economic	Battery		Inverter	
j	10%	S_{Batt}	1.35 kWh	Rated power	3000 W
n	20 years	η_{BC}	85%	η_{Inv}	95%
C_{Backup}	\$2000	η_{BF}	100%	Voltage	24 V
Δt	1 h	C_{Batt}	\$130	C_{Inv}	\$2000
		LS_{Batt}	5 years	LS_{Inv}	10 years
		DOD	0.8		
		σ	0.0002		
		N_{Batt}^{max}	200		
		Voltage	12 V		

of WTs and PV panels, respectively. C_{Wind} and C_{PV} refer to the unit costs of WT and PV panels, respectively. The unit cost of components is the sum of price of the component and its installation fee. N_{Batt} and $N_{Conv/Inv}$ are the number of batteries and converter/inverter systems, respectively. C_{Backup} denotes the backup generator cost.

At time t , the total generated power by the PV panels is obtained as follows:

$$P_{PV}^t = N_{PV} \cdot P_{PV-Each}^t \tag{13}$$

Similarly, the generated power by the WTs is obtained as follows:

$$P_{Wind}^t = N_{Wind} \cdot P_{Wind-Each}^t \tag{14}$$

The annual maintenance cost can be expressed as follows:

$$C_{Mnt} = \left[C_{Mnt-Wind} \sum_{t=1}^{24} P_{Wind}^t \cdot \Delta t + C_{Mnt-PV} \sum_{t=1}^{24} P_{PV}^t \cdot \Delta t \right] 365 \tag{15}$$

Where $C_{Mnt-Wind}$ is the maintenance cost of WTs, Δt refers to the time interval between the samples and C_{Mnt-PV} denotes maintenance cost of the PV panels.

3.2. Constraints

The details of the objective function are represented in Equations (1)–(15). Moreover, some restrictions are required to be considered in the process of optimization. These restrictions are represented in Eqs. (16)–(19).

$$0 \leq N_{PV} \leq N_{PV}^{max} \tag{16}$$

$$0 \leq N_{Wind} \leq N_{Wind}^{max} \tag{17}$$

$$0 \leq N_{Batt} \leq N_{Batt}^{max} \tag{18}$$

In the above equations, N_{Wind}^{max} , N_{PV}^{max} and N_{Batt}^{max} denote, respectively, the highest available quantity of WTs, PV and batteries.

Note that N_{PV}^{max} and N_{Wind}^{max} are selected according to the available land area.

The charge amount of storage system must meet the constraint of $SOC_{Batt}^{min} \leq SOC_{Batt}^t \leq SOC_{Batt}^{max}$

$$SOC_{Batt}^{min} = (1 - DOD) S_{Batt} \tag{19}$$

In Eq. (19), SOC_{Batt}^{max} refers to the highest charge amount of storage system and SOC_{Batt}^{min} denotes the lowest charge amount of the storage system. DOD is the calculated based on the discharge battery bank maximum depth, and S_{Batt} is the battery bank nominal capacity.

4. HEURISTIC OPTIMIZATION TECHNIQUE: DTS

This algorithm of optimization was introduced by Glover [49, 50], TS is an iterative process that initiates from a primary accidental result and try to obtain the best solutions. In this method, tabu list and aspiration criterion have key roles to prevent local optima. DTS procedure can be summarized as follows:

Step 1: iteration index ($iter$) is assumed to be equal to zero and the initial solution ($x_{initial}$) is arbitrary produced. The generated solution is considered as the present and the best solution of the problem, x_{best} (i.e. $x_{initial} = x_{current} = x_{best}$).

Step 2: at the vicinity of the obtained solution in previous step, some trial solutions (n_{trial}) are generated. Each of them is checked in the objective function to evaluate the quality. According to the values of the objective functions, the solutions are ranked in increasing order. Afterwards, x_{trial}^j is assumed as the j^{th} trial solution in the ranked set, where $1 \leq j \leq n_{trial}$. Therefore, x_{trial}^1 denotes the best trial solution according to the objective function calculated value.

Step 3: j is set to 1. In the case of $C_T(x_{trial}^j) > C_T(x_{best})$, Step 4 is performed; otherwise, it is considered that $x_{best} = x_{trial}^j$ and Step 4 is carried out.

Step 4: x_{trial}^j tabu status is examined. If it does not exist in the tabu list, it will be inserted in the list, and it is assumed that $x_{current} = x_{trial}^j$ and Step 7 is carried out. If it is in the list, Step 5 is performed.

Step 5: x_{trial}^j is checked based on aspiration criterion. If it is acceptable, the tabu restrictions will be overridden and the aspiration will be updated, $x_{current} = x_{trial}^j$, and Step 7 will be started. Else, $j = j + 1$ and Step 6 will be started.

Step 6: If $j > n_{trial}$, Step 7 will be started; otherwise, return Step 4.

Step 7: the finishing criterion must be checked.

Figure 9 shows the flow chart of the DTS algorithm. For validating the algorithm effectiveness, the results are compared with the outcomes reached by the DHS [34].

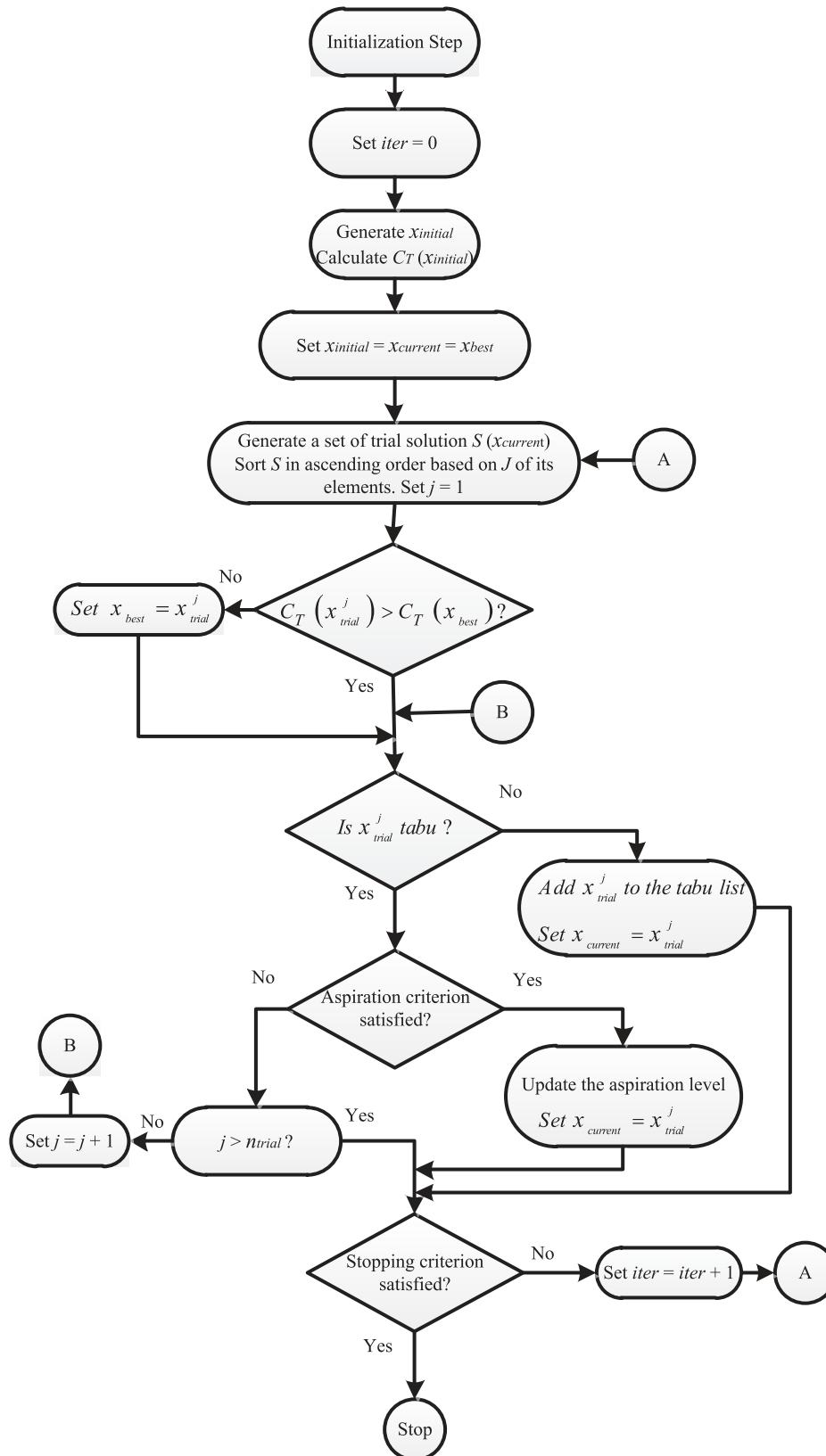


Figure 9. Flowchart of DTS algorithm used in this study.

Table 4. The performance of DHS and DTS in the determination of the optimum size of the hybrid schemes for south of Iran.

Solar/wind/battery								
Algorithm	Index							
	Mean	Max.	Min.	STD	Rank	N _{PV}	N _{Wind}	N _{Batt}
DTS	4090	4560	3800	200	1	7	5	7
DHS [34]	5250	7800	4330	704	2	8	5	21
Solar/battery								
Algorithm	Index							
	Mean	Max.	Min.	STD	Rank	N _{PV}	N _{Wind}	N _{Batt}
DTS	6040	7550	4800	787	1	20	—	71
DHS [34]	5540	6690	4860	512	2	21	—	71
Wind/battery								
Algorithm	Index							
	Mean	Max.	Min.	STD	Rank	N _{PV}	N _{Wind}	N _{Batt}
DTS	6730	11 230	3590	195	1	—	7	7
DHS [34]	4650	7720	3850	739	2	—	7	15

Table 5. The performance of DHS and DTS in the determination of the optimum size of the hybrid schemes for north-east of Iran.

Solar/wind/battery								
Algorithm	Index							
	Mean	Max.	Min.	STD	Rank	N _{PV}	N _{Wind}	N _{Batt}
DTS	5760	5980	5020	73	1	22	0	74
DHS [34]	7700	9950	5130	790	2	24	0	74
Solar/battery								
Algorithm	Index							
	Mean	Max.	Min.	STD	Rank	N _{PV}	N _{Wind}	N _{Batt}
DTS	6280	7780	5020	743	1	22	—	74
DHS [34]	5830	7150	5130	442	2	24	—	74
Wind/battery								
Algorithm	Index							
	Mean	Max.	Min.	STD	Rank	N _{PV}	N _{Wind}	N _{Batt}
DTS	11 260	15 300	9510	1677	1	—	10	167
DHS [34]	10 620	12 900	9630	828	2	—	11	164

Table 6. The performance of DHS and DTS in the determination of the optimum size of the hybrid schemes for north-west of Iran.

Solar/wind/battery								
Algorithm	Index							
	Mean	Max.	Min.	STD	Rank	N _{PV}	N _{Wind}	N _{Batt}
DTS	6350	6620	6270	72	1	23	1	83
DHS [34]	7420	9030	6360	609	2	19	2	85
Solar/battery								
Algorithm	Index							
	Mean	Max.	Min.	STD	Rank	N _{PV}	N _{Wind}	N _{Batt}
DTS	6890	8160	5660	696	1	30	—	80
DHS [34]	6590	7780	5830	532	2	30	—	85
Wind/battery								
Algorithm	Index							
	Mean	Max.	Min.	STD	Rank	N _{PV}	N _{Wind}	N _{Batt}
DTS	8210	12 750	6540	1622	1	—	5	109
DHS [34]	7550	11 520	6630	948	2	—	5	112

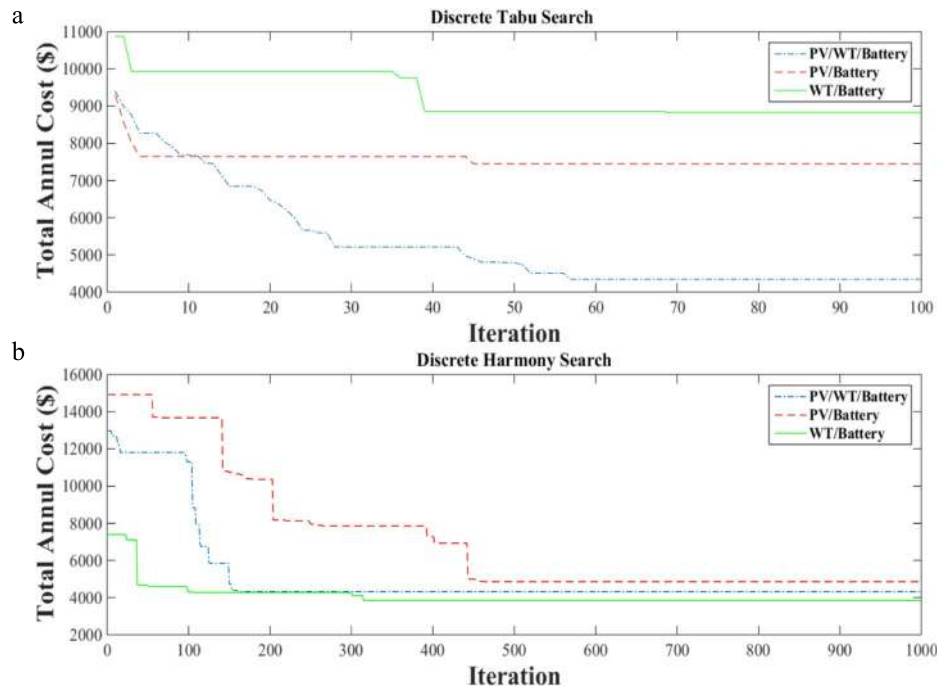


Figure 10. Convergence trend of the utilized methods in determining the ideal solution of the (a) DTS and (b) DHS algorithm (Rafsanjan).

5. RESULTS AND DISCUSSION

In order to investigate the applied approaches and the considered regions located in the considered locations for the study, which are Rafsanjan in Kerman province (south), Namin in Ardebil province (north-west) and Davarzan in Khorasan Razavi province (north-east), the mentioned hybrid system is modeled. In Tables 2 and 3, both utilized economic and technical data are represented. The profile load, for a 24-hour prototype, reveals that the minimum and maximum loads are 1.2 kW and 2 kW, respectively. The generated power by PV panels and WTs, by using the speed of wind and solar radiation, are represented in Figures 7 and 8.

In order to execute the heuristic algorithms, MATLAB software is applied. Fifty independent runs are carried out to compare the results. The algorithm's parameters are adjusted as follows:

DTS: $n_{trial} = 10$; $iter_{max} = 100$.

DHS: $HMCR = 0.9$; $PAR_{max} = 1$; $PAR_{min} = 0.1$; $bw_{max} = 1$; $bw_{min} = 0.01$; $iter_{max} = 1000$.

This algorithm tries to obtain the optimum number of WTs, panels and batteries in the investigated hybrid system. The maximum and minimum number of each unit is set to 200 and 0, respectively. Initially, the charge of batteries assumed to be equal to 30% of their nominal capacity.

The obtained results, in optimal condition, have determined for each case (Rafsanjan, Namin and Davarzan) for different hybrid system: PV(Solar)/WT/battery, PV(Solar)/battery and WT/battery. The results for each case study are shown in Tables 4 to 6. All of the required data including standard deviation (STD), best

(Min.), worst (Max.) and mean indexes in addition to the ranking are given in the mentioned tables.

Based on the data of each case study, the investigated system (PV/WT/battery) is most optimal for Rafsanjan while PV based storage is the ideal one for Namin and Davarzan. The utilized schemes for the mentioned areas are reliable and affordable. High solar irradiation in Iran is the reason of choosing PV-based storage as the ideal system for the major regions of Iran; however, for the cases when there is favorable wind speed, PV/WT/battery can be the most optimal choice.

As represented in Tables 4 to 6, the greatest index of the methods is the same, which means each method identifies the ideal solution at least once over the total runs. Comparing the performance of the algorithms indicates DTS has better results based on mean, STD and worst indexes.

In Figure 10, the convergence procedure of the utilized methods in design of various systems for Rafsanjan is illustrated. The minimum of TAC, in the case of best performance, is shown in this figure. It can be observed that the total cost reduces during the iterations, which means the reduction of total cost in the process of reaching the optimum solution. In this process, there is no information about the best size of the system, which leads to noticeable decrease in cost function, since this process leads to more information about the optimum size. In these figures, 100 iterations are considered, which is set for the DTS algorithm as the maximum number of iterative process, while the iteration number of DHS is limited to 1000.

The TACs of the investigated systems are represented in Table 4. The results reveal that the hybrid generation system is the most appropriate option for utilization and requires the lowest capacity

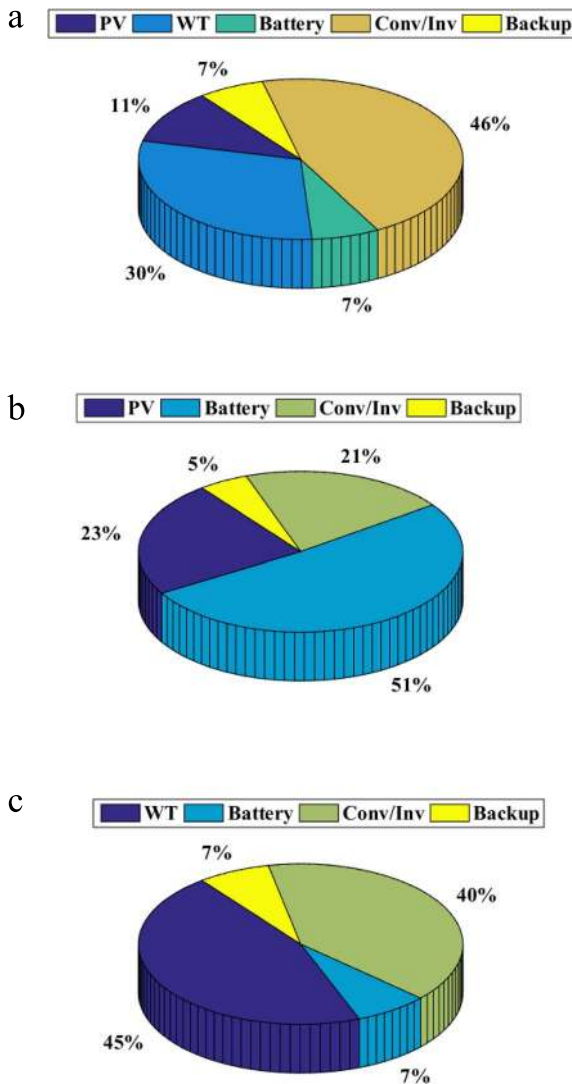


Figure 11. Annualized cost break down (Rafsanjan). (a) PV/WT/battery; (b) PV/battery; (c) WT/battery.

of storage. Also, since the nature of solar radiation and wind are unpredictable, hybrid system has more reliable performance than one system (such as PV or WT system). This configuration is

suggested for the current case study, Rafsanjan. In the case of utilizing hybrid system, respectively, the optimum sizing shows that the required numbers of PV panels, WTs and batteries are 7, 5 and 7. As shown in Table 4, the minimum TAC for Rafsanjan is \$3800.

All of the mentioned steps are applicable and true for Namin and Davarzan; however, solar based on storage system is the best option for these cities. In addition, more storage units are required for WT/battery. Increase in the required storage units is attributed to low efficiency of WT/battery in comparison with PV/battery system. In Tables 5 and 6, these steps are represented, respectively. In the case of utilizing PV/battery system for Davarzan, the optimum numbers of PV panel and battery are 22 and 74, respectively. The minimum TAC in this condition is \$5020. In addition, the optimum number of PV panels and battery for Namin is 30 and 80, respectively. The minimum TAC for this case is \$5660.

In Figure 11, the breakdown of annualized cost for different investigated configurations for Rafsanjan is represented. It is concluded that the prices of battery are different, depending on the conditions. In addition, low efficiency of the batteries increases the required numbers of it. In Figure 12, the hourly average storage level (kWh equivalent) of the battery in different investigated configurations is illustrated. The profiles of the systems are similar, which is due to the same load and generation. It should be mentioned that storage level of the batteries must not become lower than 30%. The differences between maximum and minimum peaks of storage in the case of using PV/battery are much more than the hybrid and WT/battery, which means more requirement of storage units. Increment in storage in this case is due to low efficiency of PV/battery in comparison with WT/battery and hybrid system. In this case, as shown in Table 4, the numbers of batteries equal to 7, 7 and 71 for WT/battery, hybrid system and PV/battery, respectively.

6. CONCLUSION

In this paper, a powerful optimization scheme based on tabu search (TS), called discrete TS, has been proposed for optimal sizing of the three hybrid system-based renewable energy (solar and wind). The optimal size of the components was studied

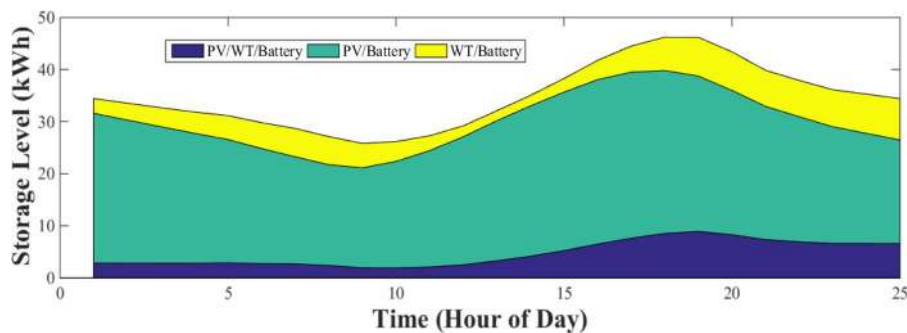


Figure 12. Level of batteries storage a typical day (Rafsanjan).

in various conditions for three case studies located in Iran. In order to investigate the systems, meteorological data and real-time information were used. For algorithm effectiveness validation, the results obtained by discrete TS are compared with those of harmony search (HS) algorithm. Based on the results of optimization, discrete TS showed better performance than discrete HS in term of TAC. According to economic analysis, hybrid systems (PV/battery) have appropriate performance in most areas of Iran, due to high solar irradiation; however, in the cases of good wind speed, PV/WT/battery can be used as an appropriate choice. It can be concluded that using discrete TS increases the possibility of obtaining the global solution of optimization problems in complex modes. Hence, discrete TS can be reliably used in hybrid system optimization problems.

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