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Hybrid wind-diesel-battery system planning considering multiple different wind turbine technologies installation

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ABSTRACT

Today, renewable resources have become one of the main pillars of electricity generation because of the constant reduction in their costs. In this regard, wind energy possesses the highest share in installed capacity and total energy output. Adopting a well-structured planning model is one of the most effective ways to further reduce costs and been the focus of research in the past decades. The previously models use a generic model for the wind turbine and its related parameters while only the optimal number is determined. In this context, this paper presents a novel approach for optimally planning of wind-diesel-battery systems which optimizes the wind turbine technology as a decision variable from the different types already commercially available. For this purpose, an optimization problem is introduced with the possibility of choosing a single type of turbine technology. The proposed model is then modified to optimize and simultaneously select multiple different wind turbine technologies. Results of the case study demonstrate a significant reduction in the planning cost, namely above 5 percent depend on the wind speed. Furthermore, the total yearly energy generated by diesel generator is decreased by 700 kWh, meaning higher renewable penetration and less emissions.

1. Introduction

Depletion of the fossil fuels in addition to their dramatic price rise have emphasized necessity to utilize alternative energy sources. Furthermore, the environmental pollution caused by their use is another limiting factor to their deployment. According to their nature, renewable energy resources have the overcome above-mentioned problems during a period started from the initial days of development to date (Moriarty and Honnery, 2016). Due to the reduced costs of their installation, these resources can be a promising alternative for fossil fuels in the long run. Today, renewable energy resources are competitive with fossil fuels due to the constant reduction in installation, operation, and maintenance cost. The statistics demonstrate a significant increase in the installation and production of energy from these technologies in the last decade (Bhattacharya et al., 2016). Fig. 1 displays the fuel shares in world total primary energy supply for 2017. As it can be observed, over 13% of the energy needed in 2017 is supplied by the renewable resources. The wind and solar energy have a distinct status because of their high potential and also environmental friendliness.

Fig. 2 shows the status of each renewable technology from the total amount of energy produced by renewable resource in 2017. As the figure shows, wind and solar energy each accounted for 5.1% and 3.9% of the total generated energy, respectively (Renewables Information Ov, 2019).

Figs. 3 and 4 depict the share of the wind and solar energy from the total installed renewable capacity and total generated power from 2009 to 2018. As the figures demonstrate, share of the wind energy in the renewable energy basket has always been greater than the solar during this period (Renewable Capacity Statis, 2019; Renewable Energy Statisti, 2019).

One of the effective ways to enhance affordability and cost competitiveness of the wind energy with respect to the conventional resources and also other renewable ones is to adopt a proper planning and investment plan. This is performed in the past decades by proposing various wind supply system configurations and planning methods for independent (Kaldellis and Th Vlachos, 2006; Saad et al., 2018; Raooft et al., 2018; Mehrjerdi, 2020; Kellogg et al., 1998) or hybrid wind-based (Badwawi et al., 2015; Khare et al., 2016; Mehrjerdi and Hemmati, 2020; Mehrjerdi and Rakhshani,

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Nomenclature

Sets

Ψ_T	Turbine technologies
Ψ_H	Hours
Ψ_M	Months

Parameters

E_0^{BS}	Initial energy stored in battery (kWh)
F_{DG}^{Cost}	Unit cost of diesel generator fuel ($/Liter)
$IC_{(t)}^{WT}$	Investment cost of wind turbine technology t ($)
IC^{DG}	Unit investment cost of diesel generator ($/kW)
IC_{BS}^{P}	Unit investment cost of battery power rating ($/kW)
IC_{BS}^{E}	Unit investment cost of battery energy capacity ($/kWh)
I_r	Interest rate
K_{DG}^{Fix}	Fixed fuel consumption coefficient of the diesel generator (Liter/kW)
K_{DG}^{Var}	Variable fuel consumption coefficient of the diesel generator (Liter/kWh)
L_f	Life time
M	Lager enough constant used for integer modeling
M_{WT}^{Max}	Maximum allowable number of installed turbine technologies
N_{WT}^{Min}	Minimum number of each turbine technology installed
$OM_{(t)}^{WT}$	Unit O$M cost of wind turbine technology t ($)
OM^{DG}	Unit O$M cost of diesel generator ($/kW)
OM_{BS}^{P}	Unit O$M cost of battery power rating ($/kW)
OM_{BS}^{E}	Unit O$M cost of battery energy capacity ($/kWh)
P_{WT}^{Min}	Minimum power share of each turbine technology installed
$P_{(h,m)}^{Load}$	Load consumption at hour t and month m (kW)
$P_{(t)}^{WTR}$	Rated power of turbine technology t (kW)
$v_{(t)}^{ci}$	Cut-in speed of turbine technology t (m/s)
$v_{(t)}^{ci}$	Cut-out speed of turbine technology t (m/s)
$v_{(t)}^{r}$	Rated speed of turbine technology t (m/s)
λ	Economic converting factor
η^{Cha}	Charging efficiency of the battery storage
η^{Dis}	Discharging efficiency of the battery storage

Variables

NPC	Net present cost
IC_{WT}^{Tot}	Total investment cost of wind turbines ($)
IC_{DG}^{Tot}	Total investment cost of diesel generator ($)
IC_{BS}^{Tot}	Total investment cost of battery storage ($)
PR_{DG}	Optimal power rating of diesel generator (kW)
$N_{(t)}^{WT}$	Optimal number of wind turbine technology t
R_{BS}^{P}	Optimal power rating of battery storage (kW)
R_{BS}^{E}	Optimal energy capacity of battery storage (kWh)
OM_{WT}^{Tot}	Total O&M cost of wind turbines ($/year)
OM_{DG}^{Tot}	Total O&M cost of diesel generator ($/year)
OM_{BS}^{Tot}	Total O&M cost of battery storage ($/year)
C_{DG}^{Fuel}	Total fuel cost of diesel generator ($)
$F_{(h,m)}^{DG}$	Fuel consumption of diesel generator at hour t and month m (Liter)
$P_{(h,m)}^{DG}$	Generated power by diesel generator at hour t and month m (kW)
$P_{(h,m)}^{Wind}$	Total generated power by wind turbines at hour t and month m (kW)
$P_{(h,m)}^{WT}$	Useful generated power by wind turbines at hour t and month m (kW)
$Q_{(h,m)}^{WT}$	Curtailed generated power by wind turbines at hour t and month m (kW)
$P_{(h,m)}^{BS}$	Net generated power by battery storage at hour t and month m (kW)
$P_{(h,m)}^{Dis}$	Discharge power of battery storage at hour t and month m (kW)
$P_{(h,m)}^{Cha}$	Charged power of battery storage at hour t and month m (kW)
$E_{(h,m)}^{BS}$	Stored energy in the battery storage at hour t and month m (kWh)
$B_{(t)}^{WT}$	Binary variable indicating installation of wind turbine technology t
$B_{(h,m)}^{Cha}$	Binary variable indicating charging status of battery storage
$B_{(h,m)}^{Dis}$	Binary variable indicating discharging status of battery storage

2019; Sinha and Chandel, 2015) renewable plants (Hemmati et al., 2017). In the proposed methods, it is recommended to use a diesel generator to produce power in the cases with negligible wind speed. Also, in order to smoothing generated power and also shifting generated energy in time to be used at time periods with no wind power, an energy storage system is used along with the turbines. The utilized energy storage system is usually a battery because of having various advantages over other storage technologies especially for the wind power applications (Saboori Rezaet al., 2017). The Resulting wind-diesel-battery system relies on the wind power to generate electric energy and possesses a predefined level of the supply considering size of the components. Optimal planning and component sizing of such a supply system is investigated by many researchers in the autonomous configuration or hybridized with the PV panels in the past decades (Nema et al., 2009). Although other objectives have been addressed in the problem, i.e. emission reduction and/or enhancing reliability level, minimizing system costs have been the primary goal of the system planning (Luna-Rubio et al., 2012; Fadaee and Radzi, 2012).

In the proposed models presented so far, typical values are used for the wind turbine parameters and then only the optimal number of turbines is optimized based on the turbine rating. In other words, the technical and economic parameters related to the wind turbine including turbine speeds (cut-in, rated, and cut-out), rated power, and turbine costs (capital and yearly operation and maintenance) are considered based on generic values and not for a specific technology. Therefore, the results of mathematical optimization may not be completely applicable in the practice. The solution to this issue is to build a mathematical model based on the parameters of the actual turbines already presented in the market. In other words, in addition to the optimal number of each turbine, optimal planning should also determine the optimal turbine technology to take into account the spectrum of the wind speed. In this case, the best results in terms of wind energy extraction and planning cost minimization will be yielded considering the matching of the optimization results with the market turbines. In this case, not only

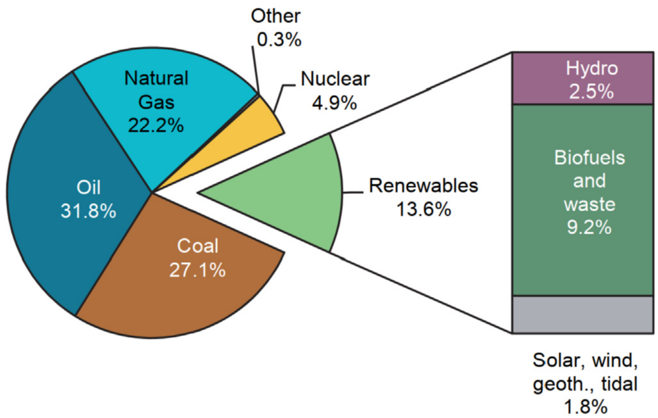

Fig. 1. Fuel shares in world total primary energy supply for 2017 (Renewables Information Ov, 2019).

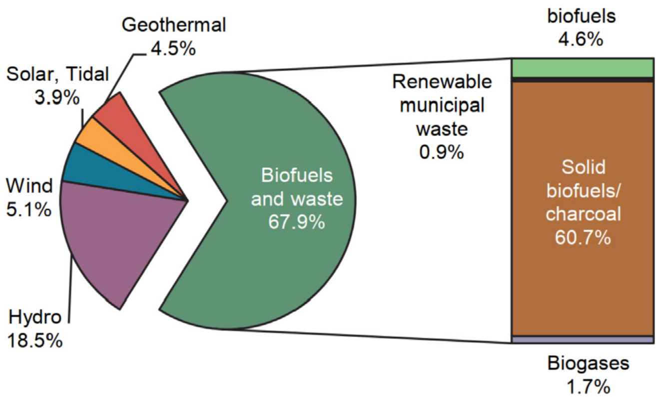

Fig. 2. Product shares in world renewable energy supply for 2017 (Renewable Capacity Statis, 2019).

the optimal number of the turbines but also the optimal technology will be determined from a large number of the available commercial turbines. This issue has not been addressed in the previous studies.

The next issue is the impact of considering simultaneous installation of several different turbines is not taken into account. In other words, the effect of installation of multiple different types of turbines with different parameters in the same paper has neither been modeled nor investigated. This is especially important if the wind speed is varied over a wide range. Because in these conditions, only one type of turbine cannot capture all wind energy in a wide range of speed variations. In this case, maximum wind energy extraction with minimum planning cost can be achieved by utilizing multiple diverse turbines with different characteristics. To do this, a mathematical optimization model should first be formulated so that multiple various turbines can be simultaneously selected. In this regard, the model will determine both the number and type of technologies required and also the optimal number of each selected technology. This has also not yet been addressed in the literature.

The research gaps mentioned above are targeted in this paper. Accordingly, in this paper, a novel optimization model for optimal planning of wind-diesel-battery systems will be presented. The proposed model makes it possible to optimally determine the optimal turbine technology from a wide range of turbines available in the market. Then the proposed model is modified so that multiple different turbines can be simultaneously and optimally determined according to the different novel criteria. The proposed model is a Mixed Integer Linear Programming (MILP) problem that seeks to minimize the Net Present Cost (NPC). The results of the simulations indicate considerable cost reduction achieved by the optimal multiple turbine modeling and selection. The contributions of this work can be summarized as follows.

1 Proposing a new approach for modeling, integration, and selection optimization of the turbine technology in the wind-diesel-battery system planning (single-turbine optimization).
2 Modeling and optimization of the multiple different turbine technology selection based on various mathematically modeled criteria (multiple-turbine optimization).
3 Linear planning model without convergence problems, easily solvable by available market packages, and ensuring finding global optima.
4 Modeling based on monthly data to capture most of the wind energy by considering wind speed variation range
5 Flexible and interactive model in terms of planning preferences (turbine selection constraints)

The paper is structured as follows. In section 2, the proposed mathematical models for optimal wind-diesel-battery system

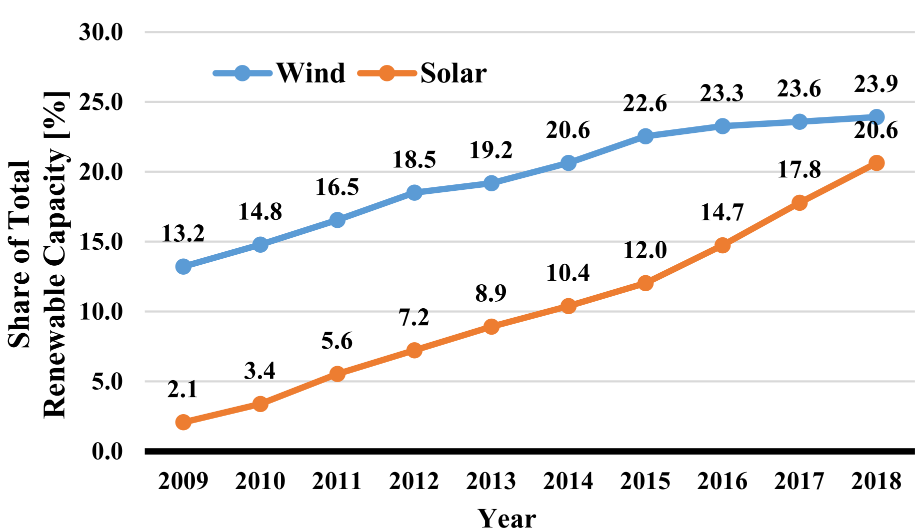

Fig. 3. Wind and solar share in world renewable-based plant capacity (Renewable Energy Statisti, 2019).

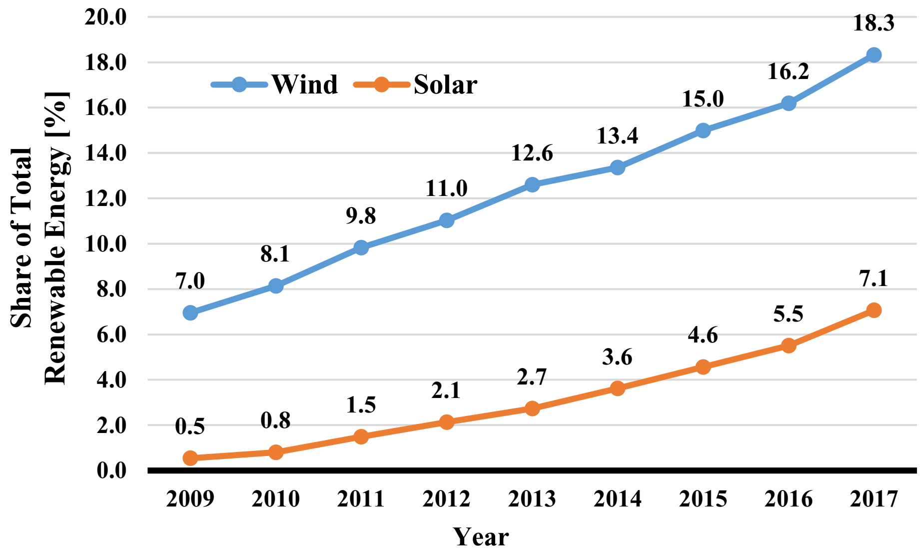

Fig. 4. Wind and solar share in world renewable-based energy generated (Renewable Energy Statisti, 2019).

planning is introduced in detail. The section starts with the conceptual configuration of the system, continues with the single-turbine optimization model, and finally ends with the proposed multiple-turbine optimization model. Then, in Section 3, the proposed models are implemented on a test case to evaluate the effectiveness and functionality. In this section, various cases are simulated and sensitivity of the result with respect to the key input parameters of the problem is evaluated. Finally, conclusion remarks of the study are presented in Section 4.

2. The proposed models

In this section, the proposed models for optimal wind-diesel-battery system planning considering single and multiple turbine technology selection optimization are introduced in details. First, the general structure of the proposed system is presented and its operation modes are described. Then, the main model for minimizing the system costs by considering the turbine selection optimization from existing technologies is introduced. Afterward, the proposed model is simultaneously modified to enable selection and optimization of multiple different turbines based on different criteria.

2.1. System structure

General layout of the system is displayed in Fig. 5. As in the figure, it composed of four main components, namely wind farm, diesel generator (s), Battery Energy Storage System (BESS), and load center. The wind farm is the main source of the energy by converting wind energy to the electric energy through turbines.

The electric energy produced by the wind farm will be directly injected to the load center bus. Given that wind speed is not as enough as needed to generate electricity at all hours of the day, required energy for those hours should be supplied from other sources. This energy can be supplied by either an independent source or a storage facility that has previously stored energy. These are both considered in the system to enhance reliability of the supply. As it can be observed from the figure, the diesel generator is directly connected to the load center bus to produce power when needed. The diesel generator based on the required power may consist of several independent machines. In meanwhile, the BESS which is bidirectional device is also connected to the load center bus. The role of the BESS is to store the energy generated by the wind farm at hours with extra power than the load demand. Then, the stored energy can be applied to the load center when needed. In this way, the BESS performs a time shift task for the energy generated by the wind farm. This will help to offset the time mismatch between load demand peak hours and wind-based maximum energy generation. The archived renewable energy time shift will result in the reducing of required power rating of the diesel generator. Considering three sources of supply injecting power to the load center bus, a priority list or operation modes should be established.

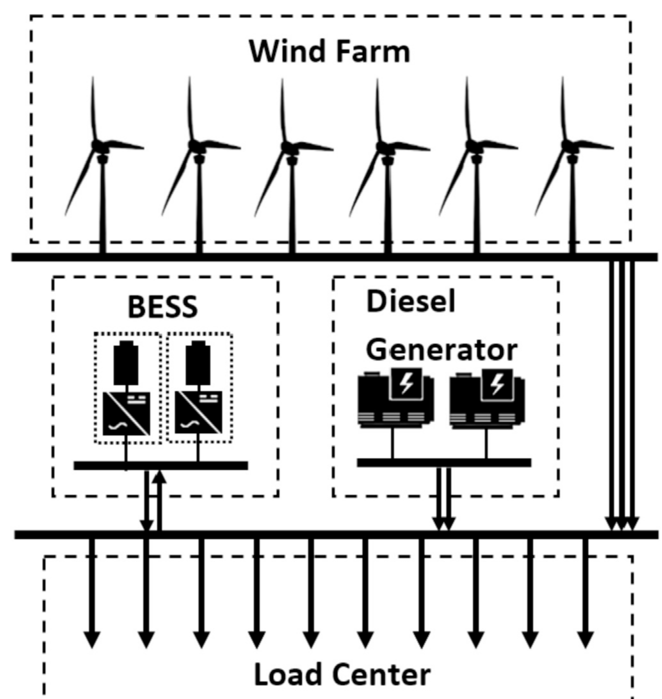

Fig. 5. Conceptual layout of the system.

Considering the abovementioned different sources of supply, the system can work at a specific operation mode with respect to

Table 1
Different operation modes of the system.

#	Modes	Resources	Priority
1	**Mode W**	Wind Only	1
2	**Mode B**	Battery Only	3
3	**Mode D**	Generator Only	7
4	**Mode WB**	Wind + Battery	2
5	**Mode WD**	Wind + Generator	5
6	**Mode BD**	Battery + Generator	6
7	**Mode WBD**	Wind + Battery + Generator	4

the status of the generated, stored, and demanded energies. Different operation modes of the system along with the required conditions are introduced in Table 1. As the table presents, the system may work in one of the seven operation modes, namely W, B, D, WB, WD, and WBD. The words W, B, and G, stand for wind energy, battery storage, and diesel generator, respectively. The priority of power injection in single-source mode means if the power is available, it will be supplied first by the wind turbines, then by the battery stored energy, and finally by the diesel generator. In double and triple-source modes, resource priority will be also the same.

2.2. Single-turbine selection and optimization

The aim of the problem is to define an optimal size of the system components introduced to completely supply the load but with the minimum cost. This means that finding optimal power rating of the diesel generator, power rating and energy capacity of the BESS, and optimal technology and also the number of the wind turbines among a large number of the commercial models already available in the market. At first, a single-turbine model is developed and then it is enhanced to account for multiple-turbine selection optimization in the following. The optimization trend is based on minimizing the costs of the system planning. To this end, the Net Present Cost (NPC) is defined as the objective function as denoted by (1). The NPC is composed of the present capital cost and the converted yearly Operation and Maintenance (O&M) cost to the present value. Each cost term in the NPC is elaborated over all of the system components, as denoted by (1). The factor λ is used to equalize dimensions of both cost terms and is formulated in (2).

$$NPC = IC_{WT}^{Tot} + IC_{DG}^{Tot} + IC_{BS}^{Tot} + \lambda \left(OM_{WT}^{Tot} + OM_{DG}^{Tot} + OM_{BS}^{Tot} \right) \tag{1}$$

$$\lambda = \frac{(1+I_r)^{L_f} - 1}{i_r (1+I_r)^{L_f}} \tag{2}$$

The costs of each component of the system, i.e. investment and O&M, is a function of the per-unit equipment cost and rating of the installation. This is mathematically modeled for various parts of the system in the following equations. For the wind turbines, investment and O&M costs are calculated in (3) and (4), respectively. As in the equations, considering that there is a set of various turbines, the costs are elaborated over the turbines which are installed.

$$IC_{WT}^{Tot} = \sum_t N_{(t)}^{WT} IC_{(t)}^{WT} \tag{3}$$

$$OM_{WT}^{Tot} = \sum_t N_{(t)}^{WT} \, OM_{(t)}^{WT} \tag{4}$$

The cost terms for battery storage is calculated in (5) and (6). It should be noted that the BESS is characterized by two nominal values, namely power rating and energy capacity. Thus, related cost terms are also proportional to both values. As it can be observed from (5) and (6), the cost terms are a function of the rating of the installation in addition to the per-unit cost of the power rating and energy capacity.

$$IC_{BS}^{Tot} = R_{BS}^{P} IC_{BS}^{P} + \ R_{BS}^{E} IC_{BS}^{E} \tag{5}$$

$$OM_{BS}^{Tot} = R_{BS}^{P} OM_{BS}^{P} + R_{BS}^{E} OM_{BS}^{E} \tag{6}$$

The investment cost equation for the diesel generator is same as the other system components. In other words, it is a linear function of the installation rating and also per-unit cost of the equipment, as it is denoted by (7). Dissimilar to the wind turbines and battery storage, the diesel generator consumes fuel. Therefore, its operation should be considered for this issues in addition to the constant costs which is mathematically modeled in (8). As in the equation, the O&M cost is composed of two terms. The first is the constant O&M cost which is a linear function of the installation rating and per-unit cost. The second term which is variable value and depends on the hours of the operation is the cost for fuel consumption. This cost term is calculated in (9) and is function of the unit fuel price and total consumed fuel over the year. The fuel consumption can be calculated by using variable and fixed fuel consumption coefficients, as denoted by (10). The equation declares that the amount of the fuel required to generate a specific value of the power at a certain hour is a function of the rated power of the diesel generator and also the generated power at that hour.

$$IC_{DG}^{Tot} = \ PR_{DG} IC^{DG} \tag{7}$$

$$OM_{DG}^{Tot} = PR_{DG} OM^{DG} + C_{DG}^{Fuel} \tag{8}$$

$$C_{DG}^{Fuel} = F_{DG}^{Cost} * \sum_h \sum_m N_m F_{(h,m)}^{DG} \tag{9}$$

$$F_{(h,m)}^{DG} = K_{DG}^{Fix} \, PR_{DG} + K_{DG}^{Var} \, P_{(h,m)}^{DG} \quad \forall \ h \in \Psi_H \ , \ m \in \Psi_M \tag{10}$$

The balance between generated and consumed powers in the system should be kept at any time period and for each month of the operation. This is mathematically established in (11). As in this equations, left-hand-side entries denote injects or generation resources while right-hand-side term stands for the withdrawal or consumption of the power. The generation resources are diesel generator, battery storage, and wind turbines, respectively. Load demand consumption is a predefined value while generation resources are variables which are related to the system status. Equations related to each generation resources are defined as follows.

$$P_{(h,m)}^{DG} + P_{(h,m)}^{BS} + P_{(h,m)}^{WT} = P_{(h,m)}^{Load} \quad \forall \ h \in \Psi_H \ , \ m \in \Psi_M \tag{11}$$

The largest generation resource is the energy produced by the wind through the turbines. Considering that there are various turbines with different parameters, energy obtained from the same wind speed and regime will be different. To model various wind turbine technologies, it is essential to consider independent representative hourly wind speed regimes for all months of the year. In other words, in order to capture maximum wind energy as possible, it is necessary to incorporate the monthly changes into the modeling. This is due to the wide range of speed variations from month to month. Fig. 6 depicts a typical wind regime for all months of the year. As figure shows, probability distribution function of the wind speed is different from month to month. Therefore, it is essential to consider these variations in problem modeling.

Considering a linear power curve for the wind turbine, which is common practice (Mehrjerdi, 2019a), the amount of the power produced from each wind speed value is a function of the power rating of the turbine, wind speed, and cut-in, rated, and cut-out speed of the turbine. This is mathematically formulated in (12) where produced power from the wind energy falls into four categories. For the wind speeds below cut-in and also above cut-out, generated power is equal to zero. For the wind speeds higher than the rated and at the same time lower than the cut-off speed, the generated power will be a constant value equal to the rated power of the turbine. Finally, for the wind speeds higher than the cut-in and also lower than the rated speed, generated power is a linear function of the speeds and also rated power.

$$P^{Tur}_{(h,m,t)} = \begin{cases} 0 & , \quad v_{(h,m)} \le v^{ci}_{(t)} \\ P^{WTR}_{(t)} \left(\dfrac{v_{(h,m)} - v^{ci}_{(t)}}{v^{r}_{(t)} - v^{ci}_{(t)}} \right) & , \quad v^{ci}_{(t)} \le v_{(h,m)} \le v^{r}_{(t)} \\ P^{WTR}_{(t)} & , \quad v^{r}_{(t)} \le v_{(h,m)} \le v^{co}_{(t)} \\ 0 & , \quad v^{co}_{(t)} \le v_{(h,m)} \end{cases} \quad \forall\ h \in \Psi_H,\ m \in \Psi_M,\ t \in \Psi_T \tag{12}$$

To model turbine selection in the optimization, an indicating binary variable is used, namely $B^{WT}_{(t)}$. index t denotes a set of the wind turbines with different parameters. This auxiliary binary variable helps to control the number of the technologies selected for the installation. Also, number of each technology installed is represented by an integer variable, namely $N^{WT}_{(t)}$. An accurate mathematical relation should be established between these two variables. This relation is modeled by introducing (13) and (14). Constant M is a large enough value which is used to model the situation. The value must be large enough to not limit the maximum number of turbine installations.

$$N^{WT}_{(t)} \le MB^{WT}_{(t)} \quad \forall \quad t \in \Psi_T \tag{13}$$

$$N^{WT}_{(t)} \ge B^{WT}_{(t)} \quad \forall \quad t \in \Psi_T \tag{14}$$

These two relations indicate that a turbine technology t can only be installed when the relevant binary variable is turned on. Conversely, if a binary variable which is related to the installation of a turbine is turned on, at least one turbine of that technology must be installed. A truth table for these relations is presented in Table 2. As the table indicates, if the binary variable related to a specific turbine technology is switched on, then that type of turbine can be installed from one to M numbers.

Considering that only one type of turbine technology selection is allowed, an extra relation is needed. Non-equality (15) performs this task by limiting indicator binary variables. The equation denotes that only one binary variable or equivalently only one turbine

Table 2
Truth-table for the turbine installation number and installation indicator binary variable.

$B_{WT}(t)$	$N_{WT}(t)$	
	Value	Equations
0	0	$N_{WT}(t) \le 0 N_{WT}(t) \ge 0$
1		$N_{WT}(t) \le M N_{WT}(t) \ge 1$

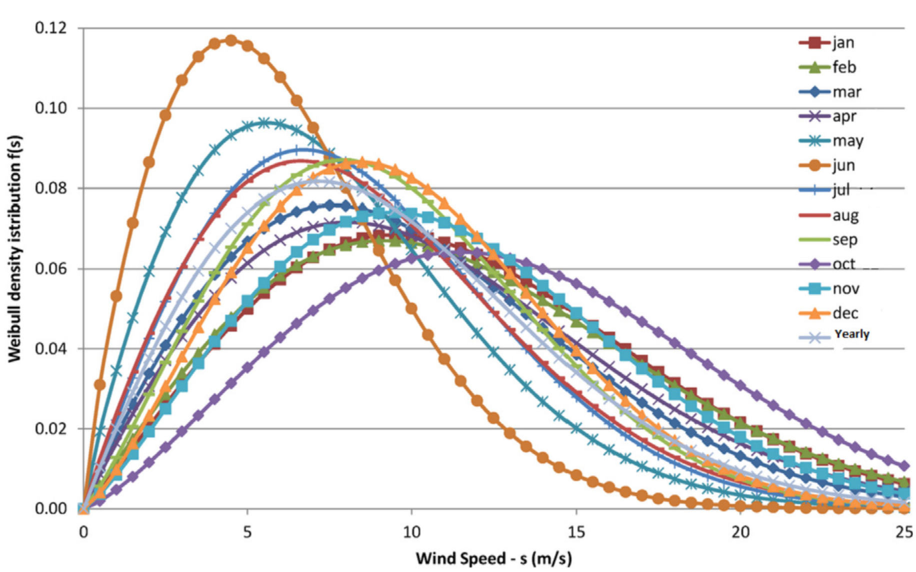

Fig. 6. Weibull probability distribution function of the wind speed for representative day of the month.

technology can be selected during the optimization process.

$$\sum_t B^{WT}_{(t)} \leq 1 \tag{15}$$

Now, the power generated by the wind turbines can be calculated. The total generated power by the turbines is calculated in (16). In (16), the power generated by each turbine technology for each wind speed (each hour of each month), i.e. $P^{Tur}_{(h,m,t)}$, is a constant value and previously calculated by (12) based on the turbine parameters and also wind speed. In this way, the model seeks to find the turbine technology with the most wind power capture over the whole year considering wide range of the wind speed variations.

$$P^{Wind}_{(h,m)} = \sum_t N^{WT}_{(t)} P^{Tur}_{(h,m,t)} \quad \forall\ h \in \Psi_H\ ,\ m \in \Psi_M \tag{16}$$

Whole of the generated wind power may not be completely injected to the load bus. Considering hourly load demand, extra generated wind power will be used to charge the battery. The Charging status will be continued until fulling the battery storage. If the load is completely supplied with the wind power and also the battery is fully charged, the surplus wind energy will be unused and therefore will be curtailed. Thus, total generated wind power at any time period is divided to the used portion in addition to the curtailed one, as denoted by (17).

$$P^{Wind}_{(h,m)} = P^{WT}_{(h,m)} + Q^{WT}_{(h,m)} \quad \forall\ h \in \Psi_H\ ,\ m \in \Psi_M \tag{17}$$

For the diesel generator, generated power cannot exceed the rated installed value. This is mathematically expressed in (18). Also, the power produced by the battery is the difference between the discharge power and the charge power, as modeled in (19). Additionally, stored energy in the battery at any time period is a function of the previously stored energy and also charging/discharging actions take place considering related efficiencies, as denoted by (20).

$$P^{DG}_{(h,m)} \leq PR_{DG} \quad \forall\ h \in \Psi_H\ ,\ m \in \Psi_M \tag{18}$$

$$P^{BS}_{(h,m)} = P^{Dis}_{(h,m)} - P^{Cha}_{(h,m)} \quad \forall\ h \in \Psi_H\ ,\ m \in \Psi_M \tag{19}$$

$$E^{BS}_{(h,m)} = E^{BS}_{(h-1,m)} + P^{Cha}_{(h,m)} \eta^{Cha} - \frac{P^{Dis}_{(h,m)}}{\eta^{Dis}} \quad \forall\ h \in \Psi_H\ ,\ m \in \Psi_M \tag{20}$$

Finally, the equations governing battery charge/discharge limitation and relations are introduced in (21) to (29). The equations declare that charging and discharging power and also stored energy are limited to the installed power rating and energy capacity, respectively. Furthermore, only one of the charging or discharging actions can be performed at any time period. Moreover, discharge power from the battery cannot go beyond the stored energy multiplied by the discharging efficiency. Finally, the initial and final state of the charge of the battery should be the same (Mehrjerdi et al., 2020; Mehrjerdi and Hemmati, 2019; Mehrjerdi, 2019b).

$$P^{Cha}_{(h,m)} \leq PR^{P}_{BS} \quad \forall\ h \in \Psi_H\ ,\ m \in \Psi_M \tag{21}$$

$$P^{Dis}_{(h,m)} \leq PR^{P}_{BS} \quad \forall\ h \in \Psi_H\ ,\ m \in \Psi_M \tag{22}$$

$$E^{BS}_{(h,m)} \leq PR^{E}_{BS} \quad \forall\ h \in \Psi_H\ ,\ m \in \Psi_M \tag{23}$$

$$B^{Cha}_{(h,m)} + B^{Dis}_{(h,m)} \leq 1 \quad \forall\ h \in \Psi_H\ ,\ m \in \Psi_M \tag{24}$$

$$P^{Cha}_{(h,m)} \leq B^{Cha}_{(h,m)} M \quad \forall\ h \in \Psi_H\ ,\ m \in \Psi_M \tag{25}$$

$$P^{Dis}_{(h,m)} \leq B^{Dis}_{(h,m)} M \quad \forall\ h \in \Psi_H\ ,\ m \in \Psi_M \tag{26}$$

$$P^{Dis}_{(h,m)} \leq E^{BS}_{(h-1,m)}\ \eta^{Dis} \quad \forall\ h \in \Psi_H\ ,\ m \in \Psi_M \tag{27}$$

$$E^{BS}_{(h,m)} = E^{BS}_{0} \quad \forall\ h = 1\ ,\ m \in \Psi_M \tag{28}$$

$$E^{BS}_{(h,m)} = E^{BS}_{0} \quad \forall\ h = 24\ ,\ m \in \Psi_M \tag{29}$$

2.3. Multiple-turbine selection and optimization

In the previous subsection, the proposed model for optimal wind-diesel-battery system planning with single-turbine technology selection optimization has been developed. For summarization, the final model can be expressed as:

$$\begin{array}{l} Min\ NPC \\ Subjected\ \ to: \quad \begin{cases} (1-11) \\ (13-29) \end{cases} \end{array} \tag{30}$$

In order to considering the multiple-turbine selection optimization, some new constraints should be added to the model and some others may need to be modified. The only change to relax the problem with respect to the number of turbine technologies selection is to eliminate Equation (15) from the model. In this way, the resulting model will be as follows.

$$\begin{array}{l} Min\ NPC \\ Subjected\ \ to: \quad \begin{cases} (1-11) \\ (13-14) \\ (16-29) \end{cases} \end{array} \tag{31}$$

In the model proposed in (31), the problem seeks to find a combination of the turbine technologies among a set of the candidate so that the NPC will be minimized. Although the goal of multiple-turbine selection is mathematically precisely modeled, the number of technologies selected may be so high that the results are not practically applicable. Therefore, a binding conditions should be established to limit the number of the technologies selected. To do this, three different criteria are established to limit the number and also power of the technologies installed. These criteria and their mathematical formula are described in the following.

1 Maximum number of technologies installed (M^{Max}_{WT})

The system planner may not be interested in choosing too many different turbine technologies for some reasons. For example, the greater number of different turbine technologies means the need for skilled manpower familiar with all technologies in terms of service and maintenance. As a result, smaller numbers of different technologies of turbines may result in lower costs for manpower, service, and also maintenance. To limit the model to consider this situation, Equation (15) must be changed as follows. In (32), the maximum number of turbine technologies to be selected is shown with M^{Max}_{WT} and stands for the predefined maximum number of turbine technologies to be selected.

$$\sum_t B_{(t)}^{WT} \le M_{WT}^{Max} \tag{32}$$

2 Minimum number of each turbine technologies installed (N_{WT}^{Min})

Another constraint is that the number of each technology selected cannot be smaller than a predefined value. This constraint helps to eliminate the unrealistic states of selecting just one or a very small number of turbine technologies. This constraint can be established by changing Equation (14) as follows. In (33), N_{WT}^{Min} denotes predefined minimum number of each turbine technologies which can be installed.

$$N_{(t)}^{WT} \ge N_{WT}^{Min} B_{(t)}^{WT} \quad \forall \quad t \in \Psi_T \tag{33}$$

3 Minimum power share of total wind turbines installed (P_{WT}^{Min})

In addition to the number of turbine technologies selected and also number of each selected technology, their selections can be limited by the percentage of installed power of each technology. For example, relation of the total installed power of a particular turbine technology with respect to the total installed wind power cannot be less than a certain percentage. This can be mathematically shown as follows. In (34), P_{WT}^{Min} represents minimum share of each technology selected among total wind installation.

$$N_{(t)}^{WT} P_{(t)}^{WTR} \ge P_{WT}^{Min} \sum_t \left(N_{(t)}^{WT} P_{(t)}^{WTR} \right) \quad \forall \quad t \in \Psi_T \tag{34}$$

Considering the changes made to the single-turbine selection models, the final multiple-turbine selection model can be summarized as follows.

$$\begin{array}{l} Min\ NPC \\ Subjected\ \ to: \begin{cases} (1-11) \\ (13) \\ (16-29) \\ (31-34) \end{cases} \end{array} \tag{35}$$

3. Case study

Introduced models in the previous section are implemented in a test case to evaluate their efficiency. The resulting models, (30) and (34), are mixed integer linear programming (MILP) optimization problem. The proposed MILP models are implemented in the GAMS software (Rosenthal, 2017) and are solved by using CPLEX (Cplex, 2015) solver. Inputs and parameters used in the simulations and also results of the running various cases along with the relevant discussion are presented in the following.

3.1. Inputs and parameters

The inputs parameters used in the simulations including interest rate and life time, together with the various technical and cost parameters related to the battery storage and also diesel generators are presented in Table 3. The technical and cost parameters related to the wind turbine technologies are shown in Table 4. The table offers cut-in, rated, and cut-out speeds in addition to the investment and O&M cost for 35 different turbine technologies already available in the market. The unit investment and yearly O&M cost of a typical wind turbine is equal to 1500 $/kW and 40 $/kW-year, respectively (IRENA, 2019; Stehly et al., 2018).

Regarding limited access to the cost of the various turbine technologies, it is supposed that the investment and O&M cost of each turbine is inversely proportional to the rated power. The investment and O&M cost of a 1 kW turbine are set to 1500 $/kW and 40 $/kW-year and then for each turbine each cost term is proportionally decreased to the rated power. The last columns of Table 3 show the calculated investment and O&M cost for each turbine technology.

The hourly wind speed for representative data of the month for all months of the year is depicted in Fig. 7. Also, Fig. 8 demonstrates representative hourly load demand for each month of the year (Grigg et al., 1999). Finally, it is supposed that at most three different turbine technologies can be selected while the number of each technology installed must be greater than five. Furthermore, it is assumed that the total power of each technology selected exceeds at least 20 percent of the total power of the wind turbine installed In other words, M_{WT}^{Max}, N_{WT}^{Min}, and P_{WT}^{Min} are equal to 4, 5, and 0.2, respectively.

4. Results and discussions

Firstly, two different cases are simulated and compared. The first one is the single-turbine model summarized in (30) and the other one is the multiple-turbine represented by (34). Simulation results for both cases are presented in Table 5. The table shows the total cost of planning in addition to the optimal component sizes for each case. Additionally, it reports difference between total cost of the cases in dollars and percentage. As the results demonstrate, single-turbine model imposes a 21,084,370 $ planning cost while for the multiple-turbine case this value is equal to 20,183,010 $. Therefore, the results demonstrate a 901,364 $ reduction in the total cost of the system planning equal to the 4.466 percent which is a considerable amount.

The table also reports the optimal size of the components for both cases. As it can be observed from the results, optimal size of the components in the multiple-turbine case is reduced with respect to the single-turbine expect for the battery power rating. It should be noted that the resulted planning cost reduction is achieved by means of reducing required size of the components. In other words, reduction in the optimal size of the system components results in the reduction of the investment and O&M costs and total cost reduction.

The results of the optimal turbine technology selection are reported in Table 6. The table shows the technologies selected, number of each technology, power raring of each technology, total power installed, and also percentage of the installation with respect to the total wind power for both cases. Considering binding conditions in the single-turbine model, only one technology is selected which is wt6 and with a total number of 153 turbines. On the contrary, in the multiple-turbine model, wt5, wt6, and wt11 technologies are selected as optimal choices each with 30, 30, and 44 turbines, respectively. Moreover, installation percentage of two first technologies is a bit more than 20 while the last one is about 60 percent. This shows accuracy of the model to keep the binding conditions established on the percentage of each technology installation which was equal to 20 (P_{WT}^{Min}). Another point to be noted is that other binding conditions on the number of the turbines are also taken into account in the results. In other words, for all three selected turbines, number of installation for each one is more than 5 (N_{WT}^{Min}) and the total number of 3 technologies is selected with is lower than the 4 (M_{WT}^{Max}).

Fig. 9 illustrates the share of each turbine technology in the

Table 3
Various input parameters of the simulation.

Item			Unit	Value
Total system		Interest rate	%	5
		Life time	Year	15
Battery	**Planning Cost**	Power Inv.	$/kW	200
		Energy Inv.	$/kWh	200
		Power O&M	$/kW/Year	2
		Energy O&M	$/kWh/Year	2
	Efficiency	Round-Trip	%	90
DG	**Planning Cost**	Investment	$/kW	300
		O&M	$/kW/Year	10
	Fuel Cost	Fuel Price	$/Liter	0.5
		K_{DG}^{Fix}	$/kW	0.06
		K_{DG}^{Var}	$/kW	0.2

multi-turbine results from the total energy generated from the wind power. The figure shows cumulated energy produced by each technology over the month for each month of the year. As in the figure, considering higher power raring and also greater number of the installations, the wt11 technology possesses the highest share. Also, the figure indicated that initial and ending months of the year offer more potential in terms of energy yield from the wind.

Fig. 10 depicts the total energy generated from the wind for both cases. As in the figure, except for the first month of the year, energy produced by the wind power in the multiple-turbine case is more than the single-turbine one for all months of the year. This is achieved by optimized turbine technology selection and shows effect of the multiple-turbine selection modeling. In other words, by modeling multiple-turbine selection and also selection optimization, it is possible to extract as much of the wind energy as possible, despite vast wind speed variations. It should be noted that this is also achieved by a lower total planning cost than the single-turbine case.

It is worth to mention that the achieved higher level of the wind energy extraction by multiple-turbine selection and optimization means using less fossil fuel-fired resources to supply the load. In other words, less power is generated via diesel generator and consequently less environmental pollution and a more renewable system. This also can be observed from the diesel generator capacity installed in the cases. As Table 1 presents, power rating of the

Table 4
Parameters of the wind turbine technologies.

#	Model	Rated Power (kW)	Speed (m/s)			Cost	
			Cut in	Rated	Cut out	Investment ($)	O&M ($/Year)
wt1	JACOBS20KW	20	3	11.6	25	29,979	799
wt2	FUHRLNDER FL 30 LM 6.1	30	3	12	25	44,952	1198
wt3	EPG35	35	3	11	25	52,435	1398
wt4	EW50	50	4	11.3	23	74,868	1996
wt5	BWCXL.50	50	3	11	30	74,868	1996
wt6	PGE50	50	3	11	25	74,868	1996
wt7	NORDTANK65SAC.DSM6.12.0	65	3.6	11	25	97,278	2594
wt8	VESTAS V17-65 KW	65	4	15	25	97,278	2594
wt9	VESTAS V17-75 KW	75	3.5	14	25	112,204	2992
wt10	WES18 MK1 80 kW	80	3	15	25	119,664	3191
wt11	FL100	100	3	10	25	149,475	3986
wt12	ADES 100−1 (ADES)	100	4	9	20	149,475	3986
wt13	ADES 100−2 (ADES)	100	3.5	11	25	149,475	3986
wt14	MICON 108	108	3.5	15	27	161,387	4303
wt15	NORDTANK 130F 20.5	130	3.7	13	25	194,112	5176
wt16	BONUS150	150	4	12	25	223,818	5968
wt17	NORDTANK150SAC.DSM4.20.07	150	4	12	25	223,818	5968
wt18	NORWIN N150	150	4	12.6	25	223,818	5968
wt19	FGW (RANK TACKE) TW150	150	4	14	24	223,818	5968
wt20	ADES 200 (ADES)	200	3	10.5	25	297,900	7944
wt21	A27/225 (ACSA)	225	3.5	14.5	25	334,842	8929
wt22	A29/225 (ACSA)	225	3.5	14	25	334,842	8929
wt23	AP300 (Adventure Power)	300	3.5	12	20	445,275	11,874
wt24	ADES 335 (ADES)	335	3.5	12	25	496,608	13,242
wt25	A1000S (AAER)	1000	4	12.5	22	1,447,500	38,600
wt26	AW-1500/77 (Acciona)	1500	3.5	11.1	25	2,131,875	56,850
wt27	AW-1500/70 (Acciona)	1500	4	11.6	25	2,131,875	56,850
wt28	aM1.5/83 (AES)	1500	3.5	11	25	2,131,875	56,850
wt29	A1650-77 (AAER)	1650	3.5	12	20	2,332,068	62,188
wt30	A1650-70 (AAER)	1650	3	12	20	2,332,068	62,188
wt31	aM2.5/103 (AES)	2500	3.5	11	25	3,421,875	91,250
wt32	aM2.5/96 (AES)	2500	3.5	12	25	3,421,875	91,250
wt33	AW-3000/109 (Acciona)	3000	3.5	12	25	4,050,000	108,000
wt34	AW-3000/100 (Acciona)	3000	4	12	25	4,050,000	108,000
wt35	V112−3.45 (Vestas)	3000	3	12	25	4,050,000	108,000

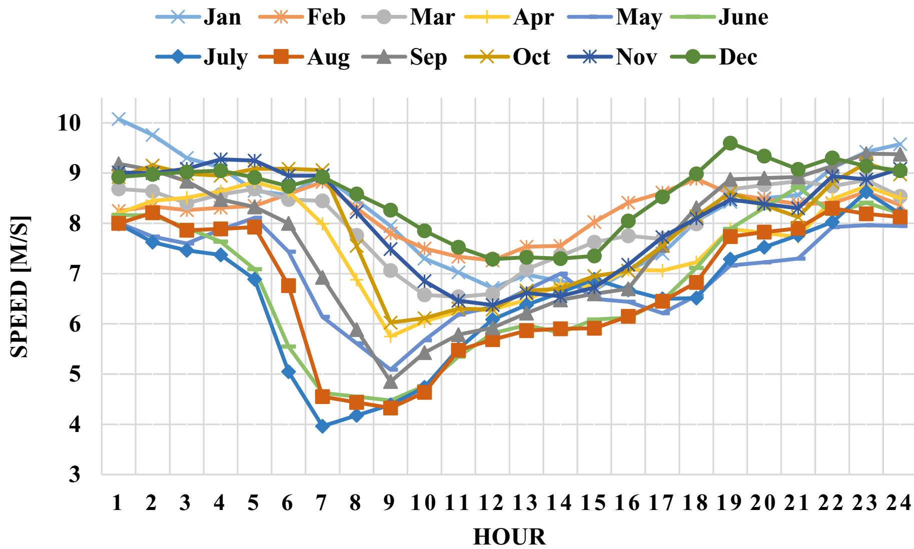

Fig. 7. Representative hourly wind speed for each month.

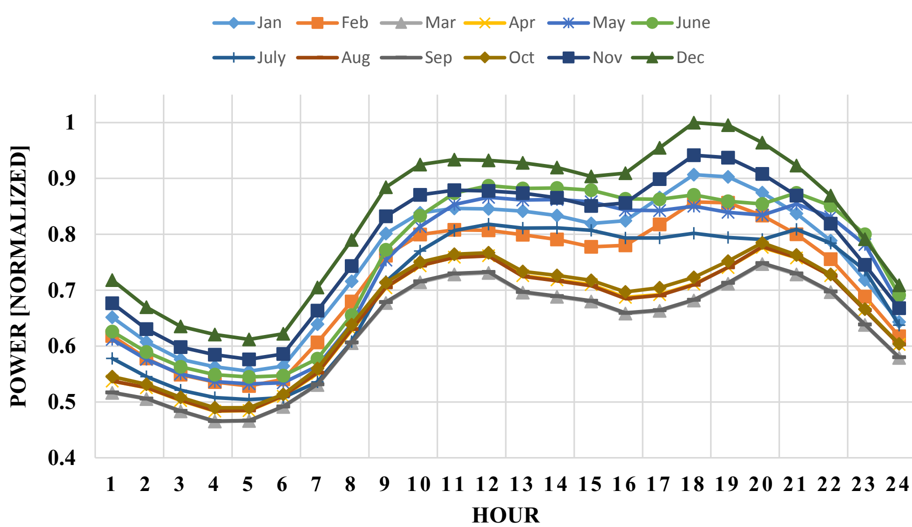

Fig. 8. Representative hourly load demand for each month.

diesel generator in the multiple-turbine case is less the same value for the single-turbine case. Besides rated power, the energy generated by the diesel generator is also proving this claim. The total energy generated at each hour elaborated over all months of the year for both cases is depicted in Fig. 11.

As the figure demonstrates, the generated energy by the diesel generator for the multi-turbine case is less than the single-turbine one. The total yearly energy generated by the diesel generator is decreased from 9824 kWh for single-turbine case to 9126 kWh for multi-turbine case which shows about an yearly reduction of about 700 kWh.

Table 7 and Table 8 represent the result of the sensitivity analysis on the two key parameters of the problem. In Table 7, the load of the system is changed in the both directions and then key results of the simulations are reported. As the results show, changing system load has not a significant impact on the percent of the cost

Table 5
Cost and optimal component size results of the simulation.

Item			Single Turbine	Multiple Turbine
Cost	Total Cost ($)		21,084,370	20,183,010
	Difference	$	901,364	
		%	**4.466**	
Component Size	Wind Turbines (kW)		7650	7400
	Diesel Generator (kW)		472	447
	Battery	Power (kW)	2602	2797
		Energy (kWh)	11,493	10,187

Table 6
Turbine selection optimization results of the simulation.

Case	Item	Value		
Multiple Turbine	Turbine Title	**wt5**	**wt6**	**wt11**
	Number of Installations	30	30	44
	Turbine Rating	50	50	100
	Total Power	1500	1500	4400
	Installation Percentage	20.27	20.27	59.46
Single Turbine	Turbine Title	**wt6**		
	Number of Installations	153		
	Turbine Rating	50		
	Total Power	7650		
	Installation Percentage	100		

difference achieved by the multi-turbine model. However, the technologies selected as the optimal choices and also number of each one is changed.

In Table 8, the effect of the wind speed variations on the results is evaluated. As the results show, changing wind speed had a considerable impact on the both percent of cost reduction and also optimal turbine selection. The percent of the cost difference is decreased in line with wind speed reduction. On the contrary, increasing wind speed is resulting in considerable growth in the cost reduction percentage. Also, by changing wind speed, various turbine technologies different from the base case are determined as the optimal choices. Strictly speaking, besides wt5, st6, and wt11 in the base case, by changing wind speed the turbine technologies wt20 and wt35 are also considered as optimal solutions.

As the simulation results show, the simultaneous employment of several types of wind turbines has several advantages. The most significant advantage is the considerable reduction in the total cost of system planning, which can be reduced from 3% to 6% depending on the various factors. In addition, the installed capacity of the diesel generator has been reduced, which has resulted in a reduction of 700 kWh yearly generated energy from fossil fuels. This in turn means increasing the penetration of renewable resources as well as reducing environmental pollutants. The reason for the aforementioned benefits is to make more use of wind energy by selecting and using several different types of turbines at the same time. In single turbine mode, the selected turbine is only capable of capturing a limited range of wind speed and the rest of the wind energy is not available. On the other hand, a wider range of wind energy is extracted when using several turbines which their types has already been selected based on their parameters. In this case, each selected turbine is responsible for extracting energy from a specific wind speed range and due to the different turbines, almost all of the wind speed variations are covered. As a result, the share of wind energy that is cheap and without fuel costs will increase in total load supply. This means less installation cost and use of the diesel generators. Ultimately, lower utilization of diesel generators will result in lower overall investment costs, increased renewable energy penetration, and reduced air pollution.

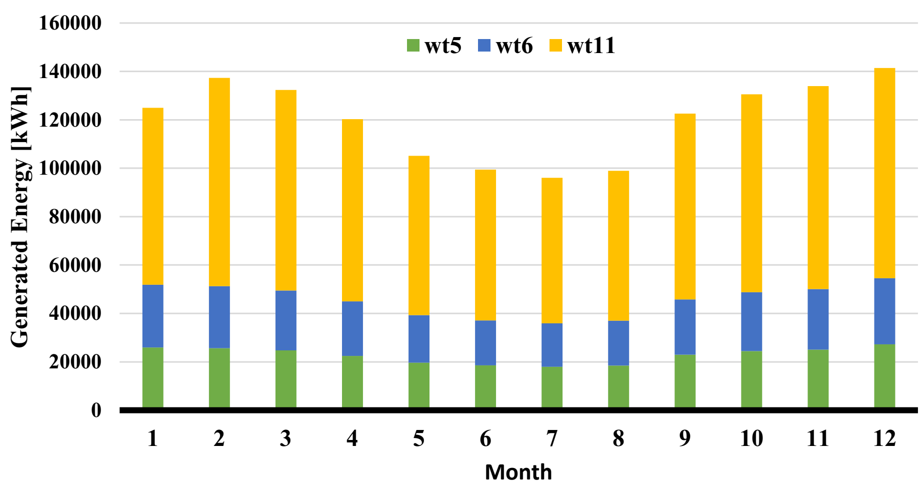

Fig. 9. Monthly total generated energy by each turbine technology for the multi-turbine case.

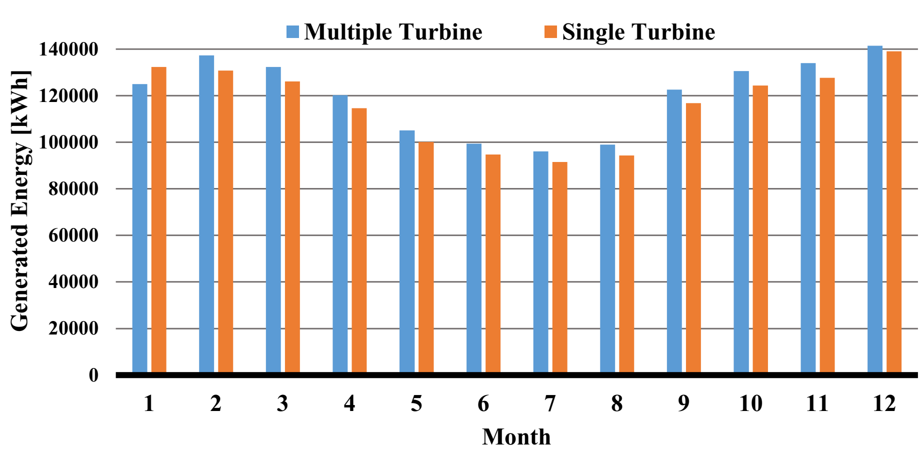

Fig. 10. Monthly total generated energy by each turbine technology for the multi-turbine case.

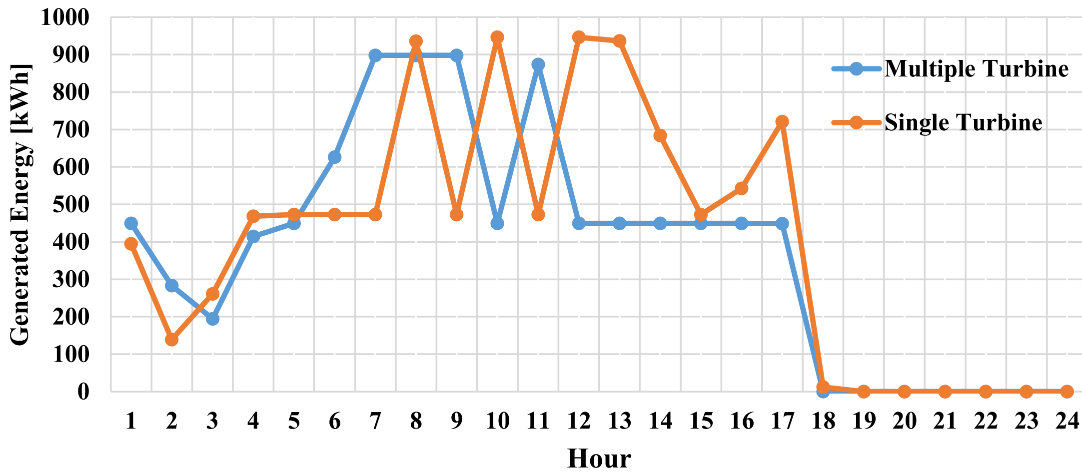

Fig. 11. Energy generated by the diesel generator for the both cases.

Table 7
Sensitivity of the turbine selection results with respect to the system load.

Load Factor	0.92	0.94	0.96	0.98	1	1.02	1.04	1.06	1.08
Cost Difference (%)	4.484	4.484	4.473	4.478	4.466	4.492	4.491	4.488	4.490
Total WT (kW)	6800	6950	7050	7200	7400	7450	7600	7800	7950
Turbine 1	54 × wt6	55 × wt6	57 × wt6	29 × wt5	30 × wt5	59 × wt5	60 × wt5	62 × wt6	63 × wt6
Turbine 2	41 × wt11	42 × wt11	42 × wt11	29 × wt6	30 × wt6	45 × wt11	46 × wt11	47 × wt11	48 × wt11
Turbine 3	–	–	–	43 × wt11	44 × wt11	–	–	–	–

Table 8
Sensitivity of the turbine selection results with respect to the wind speed.

Wind Speed	92	94	96	98	1	1.02	1.04	1.06	1.08
Cost Difference (%)	3.212	3.392	3.413	3.379	4.466	4.428	4.651	4.973	5.855
Total WT (kW)	8000	7800	7600	7500	7400	7500	7000	7000	7000
Turbine 1	26 × wt11	24 × wt11	24 × wt11	23 × wt11	30 × wt5	62 × wt5	40 × wt11	26 × wt11	26 × wt11
Turbine 2	27 × wt20	27 × wt20	26 × wt20	26 × wt20	30 × wt6	44 × wt11	1 × wt35	7 × wt20	7 × wt20
Turbine 3	–	–	–	–	44 × wt11	–	8 × wt11	1 × wt35	1 × wt35

5. Conclusions

In this paper, two novel models are developed in order to optimally plan hybrid wind-diesel-battery systems. The novelty of the proposed models is to integrate turbine technology selection in the optimization process instead of using typical parameters. In other words, besides the turbine number, optimal turbine technology is also optimally selected among a set of candidates. The first model is single-turbine optimization while the second is modified to choose multiple turbines simultaneously. Both models are MILP optimization problems and elaborated over the all month of the year. Results of the simulation on a test case demonstrate about 4.5 percent reduction in total net present cost of the planning by using multiple-turbine model with respect to the single-turbine one. This is due to the higher level of energy extraction from the wind by means of optimal planning of the multiple turbines with different parameters. Also, multiple-turbine model represents a more renewable penetration and also less operation of the fossil fuel-fired diesel generator. This will result in lower levels of environmental pollution, in turn.

Author contributions section

Elyas Rakhshani: Supervision, Writing - Review & Editing Writing - Original Draft, Conceptualization, Methodology.

Hasan Mehrjerdi: Supervision, Writing - Review & Editing, Writing - Original Draft, Conceptualization, Methodology.

Atif Iqbal: Writing - Review & Editing, Validation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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