Journal of Solar Energy Research (JSER)

Journal homepage: jser.ut.ac.ir

Economic Impacts of Long-Term Wind Speed Changes on Optimal Planning of a Hybrid Renewable Energy System (HRES)

Mohsen Aryan Nezhad[a]

[a]Department of Electrical and Computer Engineering, Faculty of Imam Mohammad Bagher, Sari Branch, Technical and Vocational University (TVU), Mazandaran, Iran.

Received: 2020-12-15
Accepted: 2021-04-03

Abstract

Long-term wind speed changes have a direct impact on optimal planning and economic parameters of the HRES. This study was conducted to determine the effects of long-term wind speed variations on optimal equipment layout and planning of a Hybrid Renewable Energy System (HRES). For this purpose, integrated and comprehensive studies and collected data on wind speed changes, from 40 meteorology stations from 1975 to 2005 across Iran in four different seasons are used. To evaluate the wind potential of different regions and assess the effects of wind speed changes on wind turbine production, average seasonal wind speed changes in each decade is considered in the optimal planning of a specific HRES for eight selected cities in different regions of Iran. Homer software is used to calculate the effects of wind speed changes on the annual production of wind turbines, cost of energy (COE (\$/kW)), total Net Present Cost (NPC (\$)), operating cost (OC (\$/yr)), and diesel generator fuel consumption (Litter/yr). For most cities that have a major change in the long-term wind speed, the optimal number of equipment, rating power of HRES equipment, and annual production of wind turbines changed. Therefore, the COE, total NPC, and diesel generator fuel consumption change more than the initial estimation considering the stable climate condition. The study results showed that, due to changes in the annual wind speed, the annual production of wind turbines for different regions changes between -28% and +10%. For this wide range in the power production of wind turbines, the COE changes between 0.203 (\$/kWh) and 0.34 (\$/kWh).

Keywords: Homer, Optimal Planning, Hybrid Renewable Energy System (HRES), Wind Energy, Wind Speed Changes.

1. Introduction

The use of renewable energy sources has been increased due to economic and health problems and massive investments in traditional power generation and construction of transmission lines [1, 2]. If societies emphasize on traditional methods for energy production based on fossil fuels, it resu lts in extra financial consequences and many environmental impacts such as pollution and global warming[3, 4].

Renewable energy resources are intermittent energy resources that are not continuously available due to uncontrolled inputs [5, 6]. Therefore, their output power cannot be accurately predicted. To cover the uncertainties of renewable energy resources, these resources are integrated with

*m-aryannezhad@tvu.ac.ir, Mohsen.aryannezhad@gmail.com

traditional resources and storages and create the HRES [7, 8]. One of the important issues in the HRES design is optimal planning of its components such as the number and rating power of the wind turbines, photovoltaic modules, batteries, diesel generators, and converters so that they meet the requirements of the load with the minimum cost [9-12]. By changing in global climate condition, the annual generation of renewable energy will be changed and this issue is capable of fundamental changes in the economic performance of the HRES [13].

Due to changes in the earth's climate that occurs because of earth's internal processes, and greenhouse gases, regional climate changes over time. This makes the average annual amount of energy produced by wind turbines have a wide variation than the HRES planning obtained in stable climate condition. Long-term change in global climate is a key parameter influencing renewable energy production and this issue takes usually less consideration at the optimal planning of the HRES. To determine the economic and environmental consequences of climate changes, the evaluation of climate changes on HRES operation is essential.

Homer is the advanced simulation software developed by U.S. National Renewable Energy Laboratory (NREL). This software is used by many researchers around the world for technical and economic analysis of the HRES. Simulation, optimization, and sensitivity analysis are three tasks that can be easily done by this software [14]. Homer's optimization and sensitivity analysis algorithms make it easier to evaluate system configurations [14]. This software has a high potential in the choice and analysis of the different types of energy sources such as diesel generator, solar photovoltaic, wind turbine, fuel cell, hydropower, and battery with the different types of loads. Homer can model the HRES in both standalone and grid-connected modes. Homer sorts feasible and optimized HRES based on total NPC taking into account most economic and reliable items [14].

In [10], based on the obtained meteorology information from NASA and Ethiopian National Meteorological Services Agency (NMSA) on 4 different cities, COE, OC, and NPC were calculated.

In [15], the author provides a design and optimization method for determining the optimal size of components of an HRES based on minimization of initial equipment cost.

The authors in [16] presented a relative analysis between different types of diesel and photovoltaic compound based on data collected from a rural area in the province of Jujuy. In [17], a new technique to enhance optimal control and performances of PV-diesel microgrid in stand-alone mode with the means of control and data acquisition software, LabVIEW, is presented.

In [10, 18, 19], the wind speed is considered constant in the whole process of the projects. The wind speed variation is defined for the sensitivity analysis in some articles, and it is only performed to investigate the variation in costs. But, it is not based on the reality of climate change.

In this paper, the consequences of long term wind speed changes on optimal planning of the HRES are investigated. For this purpose, this article addresses the optimal sizing of a specific standalone HRES in 8 windy points of Iran in both cases of stable climate and long-term climate changes. Finally, the effects of seasonal long-term wind speed changes are analyzed on an HRES equipment layout, wind turbine power production, total NPC, the COE, and diesel generator fuel consumption. Homer software is also used in all simulations.

2. The long-term trend of wind speed in Iran

To determine the effect of climate changes on wind energy, integrated and comprehensive studies on climate changes and meteorological data conducted by the Department of Land and Water at the University of Tehran are used. These studies are focused on data obtained from 40 meteorological stations distributed in the whole part of the country from 1975 to 2005 in four different seasons of the year. These studies and collected data showed that 75% of stations have an increase and 25 % of them have a decrease in wind speed from 1975 to 2005. Most of reducing changes in wind speed occurred in Abadan with an average change of 0.52 (m/s) per decade and the most increasing changes are for Zabol with an average value of 0.81(m/s) per decade. Table 1 shows changes in wind speed per decade $(m.s^{-1}.dec^{-1})$ and Figure 1 shows the location of some meteorological stations and understudy cities on Iran's map [13].

Table 1. Seasonal changes in the average wind speed in meter per second over each decade $(m.s^{-1}.dec^{-1})$ [13].

City	Winter	Spring	Summer	Autumn
Abadan	-0.42	-0.04	-0.99	-0.61
Tabriz	0.13	-0.18	0.22	0.11
Zabol	0.42	0.86	1.28	0.45
Mashhad	0.28	0.37	0.37	0.22
Gorgan	0.08	0.11	0.1	0.1
Tehran	-0.1	-0.14	-0.1	0.07
Sanandaj	0.03	0.04	0.02	0.01
Hamedan	0.15	0.19	0.13	-0.12

According to the mentioned studies, it is identified that the maximum wind speed decreasing trend is in a temperate semi-arid climate. In this type of climate, wind speed reduces with an average rate of 0.045 (m/s) each decade. The cold semi-arid climate had the highest increase in wind speed with an average rate of 0.145 (m/s) for each decade [13].

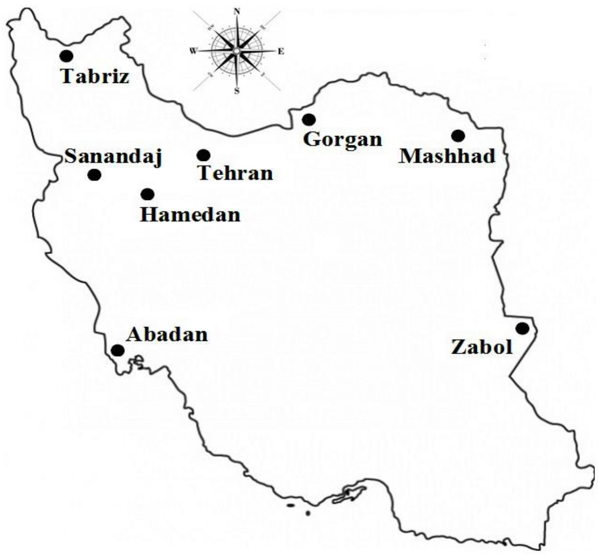

Figure 1. Geographic distribution of the cities.

3. The effect of seasonal variations in wind speed

To evaluate the long-term wind speed changes on the main parameters of an HRES, simulation of an HRES with a peak power of 280 (kW) in eight windy points of Iran is performed. For this purpose, an HRES model based on the monthly wind speed was simulated according to Iran meteorological organization information. The wind speed is not constant over the project due to climate change. Therefore, to model the average of these wind changes, according to Figure 2, the average rate of wind speed changes in the middle of the project, the 15th year, was considered. For example, Zabol has an average wind speed of 8.55 (m/s) in July and its average wind speed changes 1.28 (m/s) for each decade in summer, then the average mean of its wind speed changes during the project is:

1.5×1.28=1.92.

Therefore, the average wind speed in summer is 8.55+1.92=10.47 $(m.s^{-1}.dec^{-1})$ that is considered for HRES optimal planning to model average wind speed change during the total time of the project.

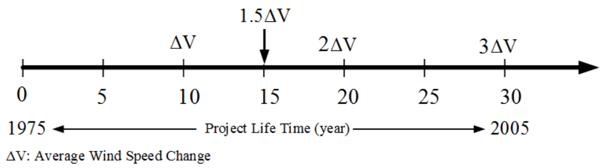

Figure 2. Determination of mean change in wind speed per decade during the project

In this case, according to Figure 2 and Tables 1-2, the percentage changes of seasonal wind speed are calculated as shown in Table 3.

Table 2. The average wind speed for the eight cities under study used in the stable climate condition (m/s)

	Jan	Apr	July	Oct
Abadan	4.50	4.70	5.55	4.61
Tabriz	5.18	6.65	9.30	5.65
Zabol	5.35	5.69	8.55	6.52
Mashhad	5.24	4.87	6.40	5.28
Gorgan	4.62	4.29	5.24	4.45
Tehran	5.00	5.65	6.74	5.15
Sanandaj	4.68	7.02	8.11	5.28
Hamedan	4.88	7.94	8.73	5.54

Table 3. Percentage changes in wind speed due to the long-term climate change

	Jan	Apr	July	Oct
Abadan	-1.33	-31.6	-16.5	-13.7
Tabriz	-5.21	4.96	1.77	3.45
Zabol	24.11	33.74	7.9	9.66
Mashhad	10.6	11.4	5.15	7.95
Gorgan	3.57	3.5	2.86	2.7
Tehran	-4.2	-2.65	1.56	-2.91
Sanandaj	1.3	0.4	0.185	0.85
Hamedan	5.84	2.46	-2.06	4.06

The HRES model which is considered in this article is shown in Figure 3. The HRES includes different components like the diesel generator, wind turbine, photovoltaic panel, battery bank, and converter. Solar panel and wind turbine are non-dispatchable sources and have highly intermittent nature that their output power cannot be controlled. So, such sources are usually integrated with the battery and diesel generator to supply the load demand with high flexibility.

According to the state of charge (SOC) of the battery, Homer software estimates the maximum discharge power of the battery to supply load demand. So, available energy (kWh), total amount of energy (kWh), load demand (kWh), and length of time are main elements that determine the maximum discharge power of the battery. As well, the battery charging power is directly proportional to the amount of empty capacity of the battery bank. According to the maximum charge rate, charge current limitation, and unfilled capacity of the battery bank, the battery charge current can be obtained.

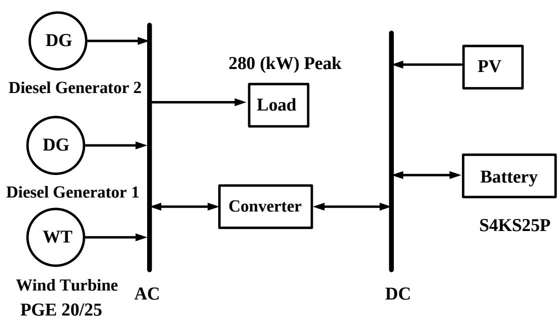

Figure 3. Detailed model of PV-wind -diesel-battery system

To determine the effect of climate changes on optimal sizing and planning of HRES for selected cities in islanded mode, it is assumed that the case study belongs to remote areas. So, HRES is enough far away from the main network that it is not economical for grid extension. In Iran, the peak load demand occurs in the summer season due to the high consumption of cooling equipment. The power consumption of a typical remote area in summer is as shown in Figure 4. The load profile is considered constant for all selected cities.

The large size diesel generator has a low efficiency at low power generation. So, two diesel generators with different ratings are used to cover a long range of power generation with higher efficiency than a large diesel generator. In Figure 3, the DC bus voltage is the number of batteries per string multiplied by battery's voltage. In this case, the nominal voltage for S4KS25P is 4 (V) and batteries per string are 10. So the Dc bus voltage is: 4×10= 40 (V).

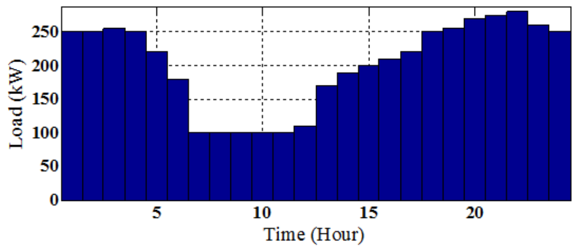

Figure 4. Power consumption of the HRES in the summer season

In this case, the costs of the HRES equipment are as shown in Table 4 [20].

The price of fuel is 1($/Liter) and the project lifetime is 30 years [21]. First, simulation is run for constant wind speed considering no climate change. To investigate the effect of seasonal wind speed changes on the optimal planning of HRES, the seasonal wind speed changes are applied to the HRES. Then, the effect of these changes on optimal sizing of the HRES is investigated. For this purpose, some indices such as COE, NPC, diesel generators fuel consumption, and average generation of wind turbines are used.

Table 4. Price of equipment used in the Homer software [20].

	CC	RC	O&M
WT	5000 $/Kw	4000 $/ Kw	100 $/Yr
DG	500$/ Kw	400 $/ Kw	0.025$/Hr
Battery	1600 $	1600 $	10 $/Yr
Converter	900$/ Kw	900 $/ Kw	0
PV	6000$/ Kw	6000$/ Kw	0

4. Simulation results

4.1. Stable climate-based optimal planning of HRES

Based on data presented in Table 4, and system configuration shown in Figure 3, Homer simulates the HRES components with every feasible combination of defined components that the user specifies in the inputs. Then, based on the optimization process, Homer sorts the different combination of the HRES components like PV, DG, batteries, and … with minimum total NPC and initial capital. After simulation, Zabol with the stable climate condition and minimum NPC needs 10 wind turbines with 25 (kW-AC) nominal power, two diesel generators with a nominal power of 100 and 200 (kW), one 60 (kW) converter, and 80 batteries for the mentioned HRES. As shown in row A of Table 5 and Figure 5, the total energy production of HRES is about 1,721,100 (kWh/yr). 75% of the total energy production of HRES is the share of wind turbines, and 25% is the share of two 100 and 200 (kW) diesel generators.

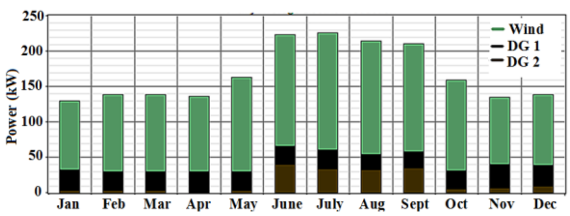

Figure 5. Monthly average power production of HRES installed in Zabol considering stable climate condition

For Abadan with minimum NPC, HRES needs 12 wind turbines with 25 (kW-AC) nominal power, two diesel generators with the nominal power of 100 and 200 (kW), one 50 (kW) converter, and 70 batteries. In this situation, the total energy production of HRES is about 1,478,000 (kWh/yr) and 65% of this amount is the share of wind turbine production and 35% is the share of two 100 and 200 (kW) diesel generators. In the stable climate condition, the NPC, COE, OC, and other HRES planning parameters for different cities are shown in rows A of Tables 5. Rows A of Table 6 show the number of equipment obtained from planning for different cities in the stable climate condition.

According to rows A of Table 5, Tabriz, Hamedan, and Zabol have great potential for wind power and the share of wind turbines are more than 70%. This issue causes that the COEs for Tabriz, Hamedan, and Zabol have lower values than other cities. In Gorgan due to low wind speed, the COE has higher value than other cities.

4.2 Optimal planning based on long-term wind speed changes

According to Figure 2 and Tables 2, and 3, the average of the wind speed changes is applied in the planning stage. Homer can consider the average of seasonal wind speed changes at the design stage. In this case, the HRES parameters considering seasonal wind speed changes and the optimal number of equipment are given in rows B of Tables 5, and 6.

According to Table 3, Tabriz Zabol, Mashhad, Gorgan, Hamedan, and Sanandaj have the positive wind speed changes per decade. This issue causes that share of wind turbines increase than stable climate condition. But, due to negative wind speed changes, wind turbines installed in Tehran and Abadan produce lower electrical energy than stable climate condition. So, COE for Tehran increases from 0.276 ($/kWh) to 0.282 ($/kWh), and for Abadan COE increases from 0.304 ($/kWh) to 0.34 ($/kWh).

Table 5. HRES optimal planning parameters (all costs are per 1000)
A: Stable climate condition, B: Seasonal wind speed changes

		Hamedan	Sanandaj	Tehran	Gorgan	Mashhad	Zabol	Tabriz	Abadan
IC ($)	A	1616	1591	1607	1486	1632	1632	1632	1867
	B	1730	1591	1461	1493	1600	1666	1616	1331
NPC($)	A	4050.8	4257.8	4489	5066.8	4604	3872.7	3899.4	4936
	B	3993.3	4240.2	4586	4953.7	4240.2	3293	3836.6	5532
COE ($/kWh)	A	0.249	0.262	0.276	0.312	0.283	0.238	0.24	0.304
	B	0.246	0.261	0.282	0.305	0.261	0.203	0.236	0.34
OC ($)	A	176.9	193.8	209.4	260.8	216	162.8	164.8	223
	B	164.5	192.5	227	251.4	192.5	118.2	161.3	305
DG Fuel (kL/yr)	A	107.5	121	133	174	137	95.6	98	137
	B	96.3	120.2	149	167	120	60.7	96	208
Total energy (MWh/yr)	A	1,396.6	1,381.2	1,369.3	1,281.4	1,357.8	1,721	1,315.4	1,478
	B	1,477	1,382.7	1,315.4	1,294.3	1,403.6	1,854	1,426	1,233
Wind Production	A	71%	67%	63%	49%	62%	75%	74%	65%
	B	76%	68%	57%	51%	68%	85%	75%	37%
DG Production	A	29%	33%	27%	51%	38%	25%	26%	35%
	B	24%	32%	43%	49%	32%	15%	25%	63%

Table 6. The optimal number of the HRES equipment
A: Stable climate condition, B: Seasonal wind speed changes

		Hamedan	Mashhad	Gorgan	Tabriz	Sanandaj	Zabol	Abadan	Tehran
Wind Turbine	A	10	10	9	10	10	10	12	10
	B	11	10	9	10	10	10	8	11
DG 1,2 (kW)	A	100-200	100-200	100-200	100-200	100-200	100-200	100-200	100-200
	B	100-200	100-200	100-200	100-200	100-200	100-200	100-200	100-200
Battery	A	70	70	70	80	60	80	70	70
	B	60	60	80	70	60	90	60	60
Converter (kW)	A	60	60	60	60	50	60	50	60
	B	60	60	50	60	50	80	50	60
PV (kW)	A	0	0	0	0	0	0	0	0
	B	0	0	0	0	0	0	0	0

According to Table 6, the optimal number of HRES equipment for most of the cities has changed. Meanwhile, only the optimal number of equipment in Sanandaj, due to its low seasonal wind speed changes, for both cases is the same. According to Table. 6, Zabol needs 10 wind turbines with 25 (kW-AC), two diesel generators with the nominal powers of 100 and 200 (kW), one 80 (kW) converter, and 90 batteries. This issue means that in optimal planning, due to extra wind production, the HRES needs more batteries and greater converter to save extra wind turbine energy in comparison to the stable climate condition. This issue causes the total fuel consumption of diesel generators decreases to 34,900 (Liter/yr) in comparison to the stable climate planning. As shown in Figure 6, 85% of the total energy production of HRES is the share of wind turbines, and 15% is the share of two 100 and 200 (kW) diesel generators.

According to the Table 4, the PV panel has higher capital and replacement costs than wind turbine. As well, PV panel, normally produce electrical energy approximately 10-12 hours a day. The wind turbine produce electrical energy in all day and night conditions with lower capital and replacement costs. So, in Table 6 the PV is not selected and application of wind turbine is more economic than PV panel.

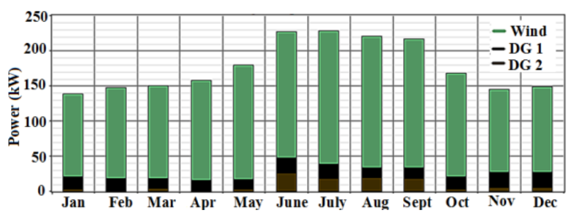

Figure 6. Monthly average power production of HRES installed in Zabol considering long-term wind speed changes

The greatest decrease in the optimal number of wind turbines belongs to Abadan. The optimal number of wind turbines has been reduced from 12 in the stable climate condition to 8 in long term climate change planning. It causes that diesel generator fuel consumptions rise dramatically. For other cities, these changes can be seen in the optimal number of equipment and the rated power of converters.

5. Conclusions

According to the obtained results, for every 1% change in the output power of wind turbine, the annual consumption of diesel fuel will change at least 1000 (Liter/yr) up to 3,500 (Liter/yr) depending on the climatic conditions of the selected area.

If the investment made in the city of Abadan with such seasonal changes, the share of the wind turbine reaches 37%. It is 28% lower than prediction with stable climate planning. This amount of wind turbine power reduction will cause an increase of 596,000 $ in total NPC.

The best points to invest on the wind energy, due to high wind power and positive seasonal wind speed change are Hamedan, Tabriz, and Zabol. In this case, more than 70% of load demand is provided by wind turbines. As well, COE, and NPC are at their lowest value in comparison to other cities. The highest fuel consumption of diesel generators belongs to Abadan due to reducing seasonal wind power. This issue causes the total NPC for Abadan raises about 596,000 ($) higher than initial evaluations in the stable climate condition. So, the COE for Abadan increases from 0.3 ($/kWh) to 0.34 ($/kWh). Due to positive seasonal wind speed changes, the highest amount of wind power production belongs to Zabol. This issue causes the total NPC decreases about 580,000 ($) lower than initial evaluations in the constant climate condition. Therefore, the COE for Zabol decreases from 0.238 ($/kWh) to 0.203 ($/kWh).

According to these studies, the reduction in the annual wind speed increases the COE and diesel generator fuel consumption. So, to make sure the low-risk investment on wind energy and avoid the additional costs, consideration of long-term climate change in the region is essential for investment on renewable energy.

References

1. D. D. Bineeta Mukhopadhyay, *"Optimal multi-objective expansion planning of a droop-regulated islanded microgrid,"* Energy, vol. 218, 2021.
2. C. J. Dongfeng Yang, Guowei Cai, Deyou Yang, Xiaojun Liu,, *"Interval method based optimal planning of multi-energy microgrid with uncertain renewable generation and demand,"* Applied Energy, vol. 277, 2020.
3. M. E. L. Mark Kipngetich Kiptoo, Oludamilare Bode Adewuyi, Abdul Conteh, Abdul Motin Howlader, Tomonobu Senjyu,, *"Integrated approach for optimal techno-economic planning for high renewable energy-based isolated microgrid considering cost of energy storage and demand response strategies",* Energy Conversion and Management, Energy Conversion and Management, vol. 215, 2020.
4. T. L. Vandoorn, B. Renders, L. Degroote, B. Meersman, and L. Vandevelde, "*Active load control in islanded microgrids based on the grid voltage,"* Smart Grid, IEEE Transactions on, vol. 2, pp. 139-151, 2011.
5. S. M. M. Liaqat Ali, Hamed Bizhani, Arindam Ghosh,, *"Optimal planning of clustered microgrid using a technique of cooperative game theory,"* Electric Power Systems Research, vol. 183, 2020.
6. S. y. Obara, *"Analysis of a fuel cell micro-grid with a small-scale wind turbine generator,"* International journal of Hydrogen energy, vol. 32, pp. 323-336, 2007.
7. M. Patterson, N. F. Macia, and A. M. Kannan, *"Hybrid microgrid model based on solar photovoltaic battery fuel cell system for intermittent load applications,"* IEEE Transactions on Energy Conversion, vol. 30, pp. 359-366, 2015.
8. N. Bizon, M. Oproescu, and M. Raceanu, *"Efficient energy control strategies for a standalone renewable/fuel cell hybrid power source,"* Energy Conversion and Management, vol. 90, pp. 93-110, 2015.
9. M. G. Moein Borghei, *"Optimal planning of microgrids for resilient distribution networks,,"* International Journal of Electrical Power & Energy Systems, vol. 128, 2021.
10. G. B. B. P., *"Feasibility study for a standalone solar–wind-based hybrid energy system for application in Ethiopia,"* Applied Energy vol. 87, pp. 487–495, 2010.
11. A. H. V.-H. B. H.-M. Kim, *"Resilience-Oriented Optimal Operation of Networked Hybrid Microgrids,"* IEEE Transactions on Smart Grid, vol. 10, 2019
12. N. Eghtedarpour and E. Farjah, *"Power control and management in a hybrid AC/DC microgrid,"* Smart Grid, IEEE Transactions on, vol. 5, pp. 1494-1505, 2014.
13. A. G. N Ghahreman, *"Trend analysis of mean wind speed in different climatic regions of Iran,"* Iranian Journal of irrigation and drainage vol. 4, pp. 31-43, 2010.
14. U. S. N. R. E. L. (NREL), "*Homer software* http://www.homerenergy.com/ ".
15. H. B. P Lundsager, *"A simple, robust and reliable wind diesel concept for remote power supply,"* Renew Energy vol. 5(PartI), 1994.
16. A. C. Díaz P, Peña R, Sandoval D. , *"FAR from the grid: a rural electrification field study,"* Renewable Energy vol. 35, 2010.
17. D. M. Wichert B, Lawrance W, Friese T., *"Development of a test facility for photovoltaic–diesel hybrid energy systems,"* Renew Energy vol. 22, 2001.
18. K. B. Omar H, *"Optimal planning and design of a renewable energy-based supply system for microgrids,"* Renewable Energy vol. 45, 2012.
19. K. J, *"Optimum hybrid photovoltaic-based solution for remote telecommunicationStations,"* Renewable Energy vol. 35, 2010.
20. M. F. M. Y. K.Y. Lau, S.N.M. Arshad, M. Anwari, A.H.M. Yatim *"Performance analysis of hybrid photovoltaic/diesel energy system under Malaysian conditions,"* Energy pp. 3245-3255, 2010.
21. A. K. Vallem V. V. S. N. Murty, *"Optimal Energy Management and Techno-economicAnalysis in Microgrid with Hybrid RenewableEnergy Sources,"* Journal of modern power systems and clean energy, , vol. 8, 2020.