Hindawi Publishing Corporation
Journal of Wind Energy
Volume 2013, Article ID 735693, 7 pages
http://dx.doi.org/10.1155/2013/735693

Research Article

Power Generation Expansion Planning Including Large Scale Wind Integration: A Case Study of Oman

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Received 25 April 2013; Accepted 28 June 2013

Academic Editor: Janaka Ekanayake

Many options can be effectively used to meet the future power needs of a country in ways which would be more economically viable, environmentally sound, and socially just. A least-cost generation expansion planning study is conducted to find the economic feasibility of large scale integration of wind farms in the main interconnected transmission system of Oman. The generation expansion planning software used is WASP which is restricted in its ability to model intermittent nature of wind. Therefore, a wind turbine is modeled as a thermal plant with high forced outage rate related to its capacity factor. The result of the study has shown that wind turbines are economically viable option in the overall least-cost generation expansion plan for the Main Interconnected System of Oman.

1. Introduction

In the planning of a power system, it is essential to estimate the operating cost and reliability of the system. To make these estimations, it is important to model the system load and generation units in an appropriate way. Power system planning is made up of the electrical load forecast, generation planning, and electrical network planning [1, 2]. The electrical load forecast forms the basis of power system planning and provides information on expected consumption increase, load curve profiles, and load distribution. The result of generation planning and electrical network can also conversely exert an influence on electrical load curve or distribution via marginal cost effort. In the planning process, major decisions in expansion planning of the generation system must consider alternative generating unit sizes, types of capacity, timing of addition, and locations. The main sources of uncertainty in strategic planning are forecasts of electricity demand, fuel prices and availability, availability and performance of new technology, governmental policies toward privatization and regulations, and public attitudes [3].

This paper reports a study that was aimed to find a least-cost generation expansion plan for the Main Interconnected System (MIS) of Oman considering the large scale integration of wind energy. The importance of the study is to show how wind turbines can be modeled in generation expansion planning software models that are based on load duration curve technique and that wind energy system can form part of the least-cost plan in Oman while keeping the same planning standard of minimum reserve margin and cost of unserved energy.

The study is limited by its scope as no detailed investigation of wind energy sites and their true potential is estimated. However, ample literature on wind energy potential and its application in Oman is available which suggests that there is a significant potential available in the southern part and the coastal area of the country [4–10]. The study also does not consider the cost related to wind power evacuation from the south to the north of the country where the major load exists. The load and generation data used is taken from Oman Power and Water Procurement (OPWP) company's report [11] and private communications to OPWP personnel. The candidate plants used for expanding the generation system are taken those which are presently in the Omani power system with the exception of wind plants. The generation expansion planning is done using Wien Automatic System

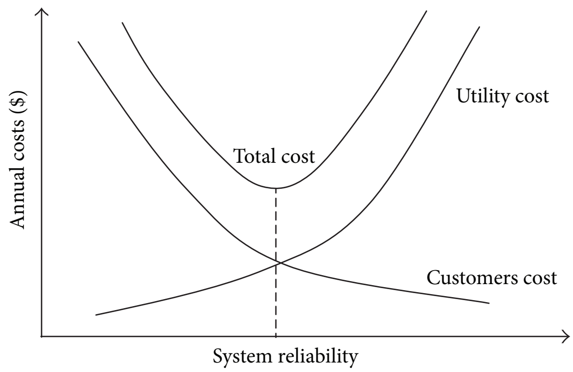

Figure 1: Relationship between consumers, utility, and total annual cost with respect to reliability.

Planning (WASP) software [12]. The software has its own modeling limitations; for example, the load model is based on the load duration curve (LDC). LDC model provides information about the percentage of time the load equals or exceeds a certain MW value and gives the same energy information as the actual chronological load curve; however, the chronology of the events is lost which poses modeling limitations to nondispatchable technologies such as wind.

This paper is arranged in six sections. Section 1 is an introduction. Section 2 is a theoretical review of power planning concepts. Section 3 is a review of wind energy potential in Oman. Section 4 discusses how wind plants can be modeled in WASP. Section 5 provides generation and load data of MIS system. Section 6 presents the results of the generation expansion planning. And the last section concludes the paper.

2. Electric Power System Planning

2.1. Objective of Power Planning Study. The objective of electric planning study is to meet the *load forecast* with high *reliability* at a minimum *cost*. There are three keywords in the previous statement, that is, load forecast, reliability, and cost. A brief discussion on these three keywords is followed. The cost is minimized depending on the financial resources, technical, environmental, and political considerations. Four questions must be answered when the study of capacity planning is done [1].

(1) What type of capacities will be added to the system?

(2) How much capacities will be added?

(3) When these capacities will be added?

(4) Where these capacities will be located?

The first three questions can be answered by using any generation expansion planning software. However, for the question where to locate the new facilities a detailed feasibility study has to be carried out considering the load center, availability of fuel, water, manpower, transmission corridors, and so forth. The objective function of the least-cost-planning software is normally the following.

Minimize for all j,

$$B_j = \sum_{i=1}^{n} \left(\overline{\mathrm{CC}_i} - \overline{\mathrm{SV}_i} + \overline{\mathrm{FC}_i} + \overline{\mathrm{O}_i\&\mathrm{M}_i} + \overline{\mathrm{UE}_i} \right), \qquad (1)$$

where

CC is the capital cost;

SV is the salvage value;

FC is the fuel cost;

O&M is the operating and maintenance cost;

UE is the energy not served cost;

n is number of years in study period;

And over bar ($\overline{\ }$) on the above costs represents present worth of all the costs.

The capital costs of only candidate generating plants considered for expansion are added in the objective function. The capital costs of existing plants and those in the construction phase (committed plants) in the system are considered sunk and are thus not considered in the objective function.

2.2. Generation Planning Study Period. The study period normally spans from twenty to twenty-five years. The study period consists of three subperiods: preplanning period, planning period, and postplanning period [13]. Preplanning period is the first 3-4 years in which the planning was done earlier. This is included in the study period to see the energy production cost and reliability of the system. The planning period is between 4 and 10 years in which the decision has to be taken now about the plants that have to be added in the future to meet the forecast. The post-planning period is added in the study period to avoid the end effects by making the calculations continue for another 10 years or more so that a proper tradeoff between construction costs and operating costs is found. Therefore, the long-term forecasts of 20–25 years of electricity consumption and demand are used in the planning of investment in generating capacity and the development of fuel supplies.

2.3. Reliability. Reliability is the ability of a system or component to perform its required functions under stated conditions for a specified period of time [14, 15]. In (1) the reliability is also embedded in terms of cost of energy not served. This cost is basically customers' electricity outages cost and is the penalty for unreliability. If more capacity is added in the system, the capital cost would be high but because of more capacity in the system the total unserved energy cost would be low as the system would be more reliable. On the other hand, if the capacity added is less than the actual required, then there would be more customer outages and hence higher unserved energy cost. The basic concept of reliability-cost/reliability-worth evaluation is relatively simple and can be presented by the cost/reliability curves, as shown in Figure 1 [14, 15]. These curves show that the investment cost generally increases with higher reliability, that is, capital investment is augmented in order to improve

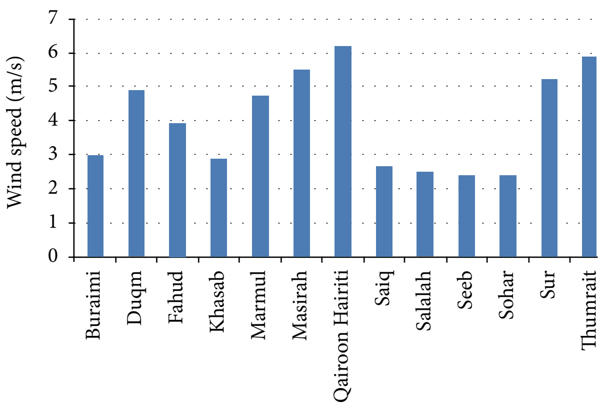

Figure 2: Annual average wind speeds of some sites in Oman at 10 m height.

the reliability. On the other hand, the customers' outages cost decreases as the reliability increases. Furthermore, the total cost of the two curves is the sum of the utility cost and the customers cost, and the minimum exhibits the optimal cost.

3. Wind Energy Potential in Oman

The wind speed in Oman is relatively high compared with other gulf countries. Oman's southern region appears to have the highest wind potential. Figure 2 shows the average wind speed in some of the cities in Oman. The highest wind potential is in Quiroon Hariti and Thumrait and both are in the South of Oman. A brief literature review on wind energy potential in Oman is presented in the following paragraphs.

In [6], it is concluded that with the existing gas price of 1.5 US$/MMBtu wind energy is not economical for grid application. The wind energy at Quiroon Hariti, (see Figure 2) the highest wind potential in Oman, becomes marginally economical at a gas price of 6 $/MMBtu. At the opportunity cost of natural gas price of approximately 3 $/MMBtu and adding a depletion premium of 3% per annum, the cost of wind energy become comparable to open cycle gas-turbine (GT) power plants. The combined cycle (CCGT) power plants remain cheaper, however. The comparison is made by assuming the economic life of assets (GT, CCGT, and 20 MW wind farm) to be 25 years and the real discount rate at 7.55%.

In [7], the electricity generation from wind energy for Duqm, a coastal region, was investigated based on the monthly mean wind speed observations. A technoeconomic evaluation was also presented using V90-1.8 turbine. It was concluded that the power generation cost is higher than the current existing system, due to the highly subsidized price of natural gas. In [8], a single 50 kW wind turbine of TekVal was used to demonstrate the economical utilization of the wind energy at the site. It was concluded that the operating cost of the diesel generation was 1.7–1.8 times the specific cost of wind turbine. It was also concluded that the simple payback period of the turbine was about five years.

In [9], five-year hourly wind data is analyzed from twenty-nine weather stations to identify the potential location for wind energy applications in Oman. Different criteria including theoretical wind power output, vertical profile, turbulence, and peak demand fitness were considered to identify the potential locations. Air density and roughness length, which play an important role in the calculation of the wind power density potential, are derived for each station site. Due to the seasonal power demand, a seasonal approach is also introduced to identify the wind potential on different seasons. Finally, a scoring approach was introduced in order to classify the potential sites based on the different factors mentioned previously. It is concluded that Qairoon Hairiti, Thumrait, Masirah, and Ras Alhad have high wind power potential and that Quiroon Hariti is the most suitable site for wind power generation.

Table 1: Technical data of wind turbine.

Wind mach.	Rated power (kW)	Cut-in (m/s)	Cut-out (m/s)	Rated speed (m/s)	Hub height (m)	Rotor Dia (m)	Expected life (yrs)
V80	2000	4	25	16	67	80	20

In [10], the article assessed wind power cost per kWh of energy produced using four types of wind machines at 27 locations within Oman. These sites cover all regions in Oman. Hourly values of wind speed recorded between 2000 and 2009, in most cases, were used for all 27 locations. Wind duration curves were developed and utilized to calculate the cost per kWh of energy generated from four chosen wind machines. It was found that the cost of energy is low in the south and middle regions of Oman compared with that in the north region. According to the study, the most promising sites for the economic harnessing of wind power are Thumrait, Qairoon Hairiti, Masirah, and Sur, with an energy cost of less than 0.117 US$/kWh when 2000 kW, 1500 kW, 850 kW, or 250 kW wind turbines are used.

4. Wind Plant Modeling in WASP

As mentioned in the introduction that the load model in WASP software is based on the load duration curve (LDC) technique. LDC model provides information about the percentage of time the load equals or exceeds a certain MW value and gives the same energy information as the actual chronological load curve. However, the chronology of the events is lost in LDC models which pose modeling limitations for nondispatchable technologies such as wind which are inherently chronological devices that operate according to the availability of wind. There are several ways to model wind turbine/plant in WASP and all have some kind of approximation. Here are some of the ways to handle it.

(1) Wind turbine/plant can be modeled as a thermal plant with zero fuel cost and increased forced outage rate to reflect the variability of wind and reduced capacity credit of wind turbine. With zero fuel cost, the economic loading order of wind turbine is first in the merit and can be considered as a base load plant.

(2) Wind turbine is modeled as negative load. The expected energy produced by a wind turbine can first

Table 2: Data of wind turbine for WASP.

Type	Max. capacity (MW)	Forced outage rate	Sch. maintenance days	Fixed O&M cost $/kW-month	Capital cost $/kW	Life (yrs)	Construction time (yr)
Wind	20	75.4%	10	1.46	1500	20	1

Table 3: Technical and cost data of thermal plants in the year 2012.

No.	Plant name	No. of sets	Min. load MW	Capacity MW	Heat rates kcal/kWh		Fast spin Res %	FOR %	Sched. Maintenance days	O&M (FIX) $/kW-month	O&M (VAR) $/MWh
					Base load	Incr. load					
1	GBG5	8	6	16	4728	2434	9	10	27	3.78	0.18
2	GBG6	2	11	26	4176	2116	9	10	31	5.21	0.18
3	GBG9	2	91	91	2705	2705	0	5	31	7.17	0.18
4	GBS1	1	37	37	1811	1811	0	50	34	5.68	0.37
5	GBS2	2	30	30	1058	1058	0	20	25	8.91	0.37
6	RUSL	8	45	86	3713	2224	9	5	27	3.57	2.26
7	WJZ1	8	12	27	4204	2205	9	5	31	6.50	0.18
8	WJZ2	5	6	17	4701	2430	9	5	30	6.50	0.18
9	MNH1	3	12	29	4301	2253	9	2	20	6.52	3.24
10	MNH2	2	42	94	3455	2215	9	2	30	6.52	2.13
11	ALK	3	44	99	3515	2326	9	2	37	6.57	3.32
12	BRK1	1	108	435	3257	1756	9	3	20	9.08	1.44
13	BRK2	1	126	710	2114	1742	9	4	20	7.07	1.16
14	BRK3	2	40	247	1797	1455	9	3	20	20.05	1.04
15	SHR1	1	121	590	3467	1821	9	3	20	5.84	1.28
16	SHR2	2	40	247	1797	1455	9	3	20	20.05	1.04
17	SURa	0	400	799	1771	1316	9	3	20	13.01	0.66
18	SURb	0	201	401	1711	1316	9	3.5	20	13.01	0.66

be subtracted from the original chronological load curve and then the load duration curve is made. The optimization is then done without considering wind turbines and the cost of wind turbine can then be added later in the optimal case.

(3) Wind turbine can be derated according to the capacity credit and modeled as a thermal plant with zero fuel cost and a normal forced outage rate of say about 4% can be assigned.

(4) Wind turbine is modeled as a hydroplant with a base load capacity and inflow energy as a constraint. The inflow energy reflects the energy the wind turbine can produce in a given load duration curve time span.

In the present study, a wind turbine is modeled as a thermal plant with high forced outage rate to investigate the economic feasibility of wind plants. This technique is closer to reality as the higher forced outage rate force the WASP model to select more plants to meet the reliability requirement. In real systems also because of poor capacity credit attributed to wind energy a lot of backup supply has to be provided. The candidate plant of 2 MW taken from [10] is used to demonstrate the economic feasibility at one of the best sites of Thumrait. Table 1 gives the technical data of wind turbine.

The annual energy produced by this wind turbine at the site is 4318 MWh from which its forced outage rate is calculated from its capacity factor using the following two formulas:

$$\text{Capacity Factor} = \frac{\text{Annual Energy Produced (MWh)}}{\text{Rated Capacity (MW)} \times 8760\,\text{hrs}}.$$

$$\text{Forced Outage Rate} = 1 - \text{Capacity Factor}. \tag{2}$$

It is assumed that 10 wind turbines of 2 MW size form a wind park of 20 MW. This 20 MW is used as a candidate plant instead of 2 MW wind turbine. The other needed data for WASP is shown in Table 2.

5. MIS Generation and Load Data

5.1. Generation Data. The generation expansion planning is carried out for the MIS from 2012 to 2034. The main Interconnected System consists of ten existing plants Ghubrah, Rusail, Wadi Al-Jizzi, Manah, Barka-I, Barka-II, Barka-III, Sohar-I, Sohar-II, and Alkamil. All the plants are either combustion turbines or combined cycle plants. The fixed or existing system consists of about 4770 MW capacity [11]. The

Table 4: Technical and cost data of candidate plants.

No.	Plant name	Min. load MW	Capacity MW	Heat rates kcal/kWh Base load	Heat rates kcal/kWh Incr load	Fast spin Res %	FOR %	Sched. maintenance days	O&M (FIX) $/kW-month	O&M (VAR) $/MWh	Capital cost $/kWh	Plant life (yrs)	Construction time
1	GBG9	91	91	2705	2705	0	5	31	7.17	0.18	795	25	3
2	BRK1	108	435	3257	1756	9	3	20	9.08	1.44	977	25	3
3	FCOL	83	250	2800	2300	10	8	35	2.92	5.00	2000	25	5

Table 5: Results of base case: costs, reliability, type, and number of units selected.

Year	Present worth cost of the year in thousands dollars: Const. cost	Salvage value	Operating cost	Energy not served cost	Total	Obj. Fn (Cumulative)	LOLP %	GBG9	BRK1	FCOL
2034	81646	73253	631261	0	639654	21847338	0.028	74	15	0
2033	104834	84241	651639	0	672232	21207684	0.024	69	15	0
2032	109827	78893	670504	0	701438	20535452	0.031	63	15	0
2031	117515	75307	689700	0	731908	19834014	0.028	63	14	0
2030	826712	471547	709039	0	1064204	19102106	0.027	63	13	0
2029	337793	171065	699590	126	866444	18037902	0.047	42	10	0
2028	143960	64548	734243	123	813778	17171458	0.046	39	8	0
2027	104885	41510	752857	235	816467	16357680	0.055	39	7	0
2026	112227	39068	777024	262	850445	15541213	0.055	35	7	0
2025	412757	125894	802078	327	1089268	14690768	0.058	31	7	0
2024	188703	50204	812510	372	951381	13601500	0.057	29	5	0
2023	708848	163664	830018	796	1375999	12650119	0.085	29	4	0
2022	252822	50358	823948	867	1027279	11274120	0.086	26	1	0
2021	157404	26859	846190	1015	977749	10246841	0.092	25	0	0
2020	252633	36626	867924	1639	1085570	9269092	0.124	21	0	0
2019	450528	54940	893340	1709	1290638	8183523	0.121	15	0	0
2018	241033	24418	910721	2313	1129649	6892885	0.144	5	0	0
2017	0	0	933210	535	933745	5763236	0.047	0	0	0
2016	0	0	961424	0	961424	4829492	0.006	0	0	0
2015	0	0	996447	0	996447	3868068	0	0	0	0
2014	0	0	997687	0	997687	2871621	0.001	0	0	0
2013	0	0	965412	965	966377	1873934	0.071	0	0	0
2012	0	0	906425	1132	907557	907557	0.076	0	0	0

committed plants and the retirements are also taken into account. Table 3 provides technical and economic data for the fixed system and committed plants. All power plants are powered by natural gas, which comes from domestic production with a fuel cost of 1189 ¢/10^6 kcal equivalent to $3/MMBtu. The last two plants with zero number of sets show the committed plants. Table 4 provides the technical and economic data of units taken as candidate plants for expansion.

5.2. Load Data. As mentioned earlier, the load model in WASP is of load duration curve. The annual chronological hourly load curve of year 2009 is used to make load duration curves (LDC) for winter and summer seasons. Figure 3 shows a summer load duration curve with inverted axes. The figure shows that load of 1100 MW or more needs to be served all times and more than 3000 MW needs to be served for around 8% of time. These summer and winter LDCs are then normalized and the shapes of LDCs are assumed the same for the whole study period. The peak load for the 2012 is 4189 MW and for year 2034 (the end of study period) is 12,617 MW with an average load growth of about 5%. Figure 4 shows the peak load from 2012 till 2034.

5.3. Economic Data. The discount rate used for the study is 7.5% and the cost of unserved energy as 1.6 $/kWh. The discount rate of 7.5% has been used in earlier official studies; see for example [6]. The cost of unserved energy was worked

Table 6: Results of base case: costs, reliability, type, and number of units selected.

Year	Present worth cost of the year in thousands dollars						LOLP %	GBG9	BRK1	Wind
	Const. cost	Salvage value	Operating cost	Energy not served cost	Total	Obj. Fn (cumulative)				
2034	112256	100716	604143	1883	617566	21721956	0.284	63	15	51
2033	113361	90334	619355	2361	644744	21104390	0.328	62	14	51
2032	125332	89652	640912	1968	678560	20459646	0.276	58	14	45
2031	125810	80370	658514	2096	706050	19781086	0.282	58	13	43
2030	846035	480353	675986	2353	1044020	19075036	0.299	58	12	42
2029	333885	168326	669359	2367	837284	18031016	0.26	39	9	35
2028	143960	64549	706327	1849	787588	17193732	0.207	37	7	33
2027	154038	60963	723468	2484	819027	16406144	0.25	37	6	33
2026	190940	58496	740582	3493	876519	15587117	0.317	37	5	33
2025	411400	124215	775462	1787	1064434	14710598	0.177	36	5	19
2024	128488	34184	787557	2170	884031	13646164	0.187	29	4	17
2023	739292	158541	810692	2817	1394260	12762133	0.219	25	4	17
2022	216046	43033	829179	1085	1003277	11367873	0.098	16	3	1
2021	231169	39447	853933	792	1046448	10364596	0.076	16	2	1
2020	306917	43548	869463	1793	1134626	9318148	0.131	16	1	1
2019	450528	54940	893340	1709	1290638	8183523	0.121	15	0	0
2018	241033	24418	910721	2313	1129649	6892885	0.144	5	0	0
2017	0	0	933210	535	933745	5763236	0.047	0	0	0

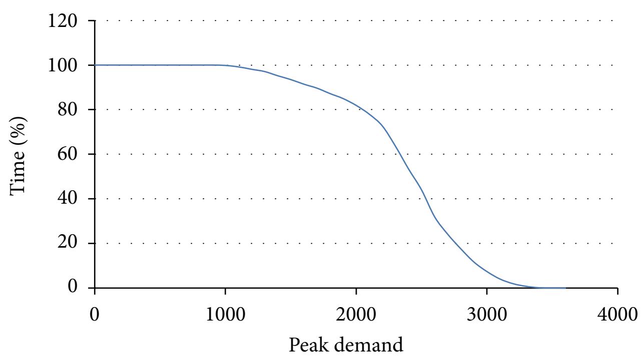

Figure 3: Load duration curve with inverted axis.

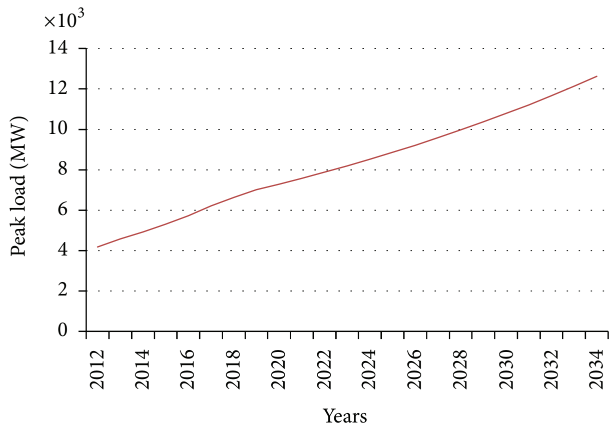

Figure 4: Annual peak demand from 2012 to 2034.

out in [15] and is consistent with the optimal reserve margins found using the cost of unserved energy and the average reserve margins existing in Oman.

6. Results and Discussions

Table 5 provides the results of a base case without the option of wind turbines. It may be noted that FCOL is not selected at all. The results show that by the year 2034 seventy-four units of GBG9 and fifteen units of BRK1 are selected with total capacity addition of 13,259 MW in the system. The existing generating units of Table 3 will all retire during the study period. The loss-of-load probability (LOLP) of 0.028% in year 2034 corresponds to loss-of-load expectation of about 0.1 day per year or 1 day in 10 years. The total objective function cost is about 21.85 billion dollars.

The result of taking 20 MW wind park as a candidate unit is shown in Table 6. It may be noted that the results are shown from 2017 onward because the results of earlier years are same as the base case. FCOL option was not taken as it was not selected in the base case. The result shows that by the year 2034 sixty-three units of GBG9, fifteen units of BRK1, and fifty one units of Wind (1020 MW) are selected with total capacity addition of 13,278 MW in the system. The total objective function cost is about 21.72 billion dollars which is about 130 million dollars less comparing to the base case. The LOLP in year 2034 is 0.284% about 1 day per year. The reliability of the system is not as good as in the base case but meets the same reserve margins limits of minimum 5% used as a constraint.

This also shows that to meet the same reliability criteria of LOLP more capacity additions are required and the reserve margin criteria are not as good measure when intermittent technology are considered in the system. It may also be noted that environmental costs are not considered in the analysis.

7. Conclusions

This paper has presented the results of a least-cost generation expansion plan using wind turbines as a candidate plant. A set of 10 wind turbines of 2 MW capacity is considered as a single unit of 20 MW capacity and modeled as a thermal unit in WASP with high forced outage rate according to the expected capacity factor at the selected site. The result shows that with minimum 5% reserve margin reliability criteria and the cost of unserved energy as $1.6/kWh the wind turbine indeed forms part of the generating system expansion economically. However, the result of reliability criteria of LOLP has shown significant difference in the two cases. Although LOLP criteria are superior to reserve margin criteria but in the presence of cost of unserved energy as balancing factor in the objective function LOLP should be automatically taken care of. On the other hand, calculating cost of unserved energy is not an easy task and needs a lot of assumptions and a reasonable sample size of survey in residential, commercial, industrial, and other sectors. As a future work it would be worthwhile to compare the high forced outage rate model of wind turbine with the negative load model. It would also be worthwhile to find the limit of maximum wind potential that can be exploited in the southern part of the country so that it can be added as a constraint to limit the number of wind turbine units selected for strategic plan.

Conflicts of Interests

The authors do not have any conflict of interests with the content of the paper.

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