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Scheduling a Wind Hydro-Pumped-Storage Unit Considering the Economical Optimization

Milad Ghaisi Rad[1], Milad Rahmani[2], Pedram Gharghabi[3,*], Ali Zoghi[2], Seyed Hossein Hosseinian[2]

[1]Electrical and Computer Engineering Department, University of Nebraska-Lincoln, Lincoln, United States
[2]Department of Electrical Engineering, Amirkabir University of Technology, Tehran, Iran
[3]Department of Computer and Electrical Engineering, Mississippi State University, Starkville, United States
*Corresponding author: Pg377@msstate.edu

Abstract In this paper a new approach has been introduced to find the optimum capacity of a wind farm to cooperate with a hydro-pumped-storage in order to maximize the income and optimize the payback period of their combination. First, Monte Carlo method has been used to generate the annual price and wind speed values. Then, an operating policy has been considered to schedule each unit generating and saving the produced energy by the wind farm. Subsequently, simulations have been carried out in MATLAB M-File environment to show the effectiveness of the presented method. Finally, results are presented in various circumstances to help the owner to select the optimum condition for constructing a wind hydro-pumped-storage system.

Keywords: *wind farm, pumped-storage, wind hydro-pumped-storage, optimize the payback period, Monte Carlo*

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1. Introduction

Energy production in most countries is depended on fossil fuels producing 85% of all consumed energy [1]. In recent years, so many concerns about relieving greenhouse gases, air pollutions, and the high cost of fossil fuels made decision makers to replace the traditional power plants with sustainable energy resources such as wind, solar, hydropower, and etc. Because of stochastic behavior of these types of energy, it is better not to utilize them as the direct and also main sources of electrical energy consumed in power systems. Using a storage system and managing its output energy can improve the total system's reliability and ameliorate the total income. One of the largest storage systems widely used in many countries is hydro-pumped-storage (HPS).

A HPS unit has many advantages such as peak shaving, quick response, and also low capital cost [2]. A HPS normally buys electrical power to charge its upper reservoir in off-peak hours and discharges the saved energy in peak hours. Combination of HPS with a renewable energy resource not only solves the reliability problem of the renewable unit but also benefits the availability of free energy to charge the HPS in order to maximize the total income. One of the major renewable energy resources which can produce energy in such a large scale to cooperate with HPS is wind.

In the last few years, many approaches have been suggested to integrate HPS and wind farms. Some of them concentrated on wind hydro-pumped-storage (WHPS) role in power market. Also, they have brought out the issue of increasing the penetration of renewable energy in power systems [3,4,5,6,7]. The WHPS has been analyzed from two points of view. One of them studies this combination as an economical issue while the other one focuses on compensation of wind farm output active power fluctuations. In [8,9,10] various scheduling strategies to optimize the integration of wind farm and HPS unit are suggested such as neural network (NN) and other innovative algorithms. Besides, there are some methods to consider the network's transmission level harmonics effect on the local marginal prices [11] which are useful in the placement of HPS. Some other papers have scheduled the WHPS operation to minimize the system's total cost [12,13,14]. On the other hand, due to stochastic behavior of wind speed, wind farm output power varies time to time which may cause power quality problems in the case of direct connection to the network [15,16,17,18].

Using the method proposed in this paper, capital cost payback period of the WHPS has been improved. Thus, the HPS owner would be motivated to use a wind farm along with the HPS unit. First, wind and electricity price have been generated for a year-ahead using Monte Carlo method. Then, based on achieved values, a scheduled operation has been presented.

In section 2, the characteristics of a wind farm and a HPS unit have been demonstrated. section 3 describes the proposed method and discusses the probable operational scenarios for the WHPS. Also the required data have been generated in this section using Monte Carlo method. Finally, a case study has been carried out and simulated in section 4 to prove the validity of the proposed method.

2. Wind Farm and HPS Characteristics

2.1. HPS

Your A HPS contains two water reservoirs placed at different altitudes. In generation mode, flowing water from the upper reservoir produces power by passing through hydro-turbines; then the flowing water will be accumulated into the lower reservoir. This operation mode normally takes place at peak load periods. In off-peak periods, electricity energy is purchased from the grid to provide the required energy for pumping the water into the upper reservoir by electric turbo-pumps which work as hydro-turbines in the peak periods. The HPS advantages can be classified as below:

- It can be used in peak periods as a peak shaving unit due to its fast start-up similar to diesel generators and gas-turbines.
- Its efficiency is much higher compared with diesel generators and gas-turbines.
- Using HPS can lead to decrease the spinning reserve capacity and warm start-up in the system.
- The HPS can help the flat generator to regulate the network's frequency.

The HPS parameters play important role on how it works and force some constraints to it. The maximum output power is one of these parameters restricting the HPS generation.

$$0 \le P_{PS} \le P_{PS\max} \quad (1)$$

Where, P_{PSmax}[kW] is the maximum HPS output power and P_{PS}[kW] is the real time HPS output power.

Total energy discharged by the HPS into the grid in one period is limited to the upper reservoir minimum and maximum levels. These limitations have been modeled by energy levels in this paper as it is presented in equation (2).

$$\begin{aligned} & h_{low} \le h \le h_{high} \\ & 0 \le E_{PS} \le E_{PS\max} \end{aligned} \quad (2)$$

Where h_{low}[m] and h_{high}[m] are the upper reservoir minimum and maximum levels respectively, h[m] is the remaining water's level, E_{PSmax}[kWh] is the maximum HPS stored energy and E_{PS}[kWh] is the remaining HPS energy.

Each period is divided into two time periods. T_{peak}[hours] consists of the peak hours in which HPS energy is allocated to generation; While, $T_{off\text{-}peak}$[hours] consists of non-peak hours when energy is consumed to charge the upper reservoir. Based on the amount of stored water in upper reservoir, the charge and discharge times alter. These times are constrained as follows:

$$\begin{aligned} & 0 \le T_{disch.} \le T_{peak} \\ & 0 \le T_{charge} \le T_{off-peak} \end{aligned} \quad (3)$$

Where T_{disch}.[hours] and T_{charge}[hours] are discharge and charge times respectively. To achieve the maximum profit, it is better to charge and discharge the HPS by the maximum possible rates. T_{disch} and T_{peak} also can be defined as follows:

$$\begin{aligned} & T_{disch} = \frac{E_{PS}}{P_{PS\max}} \\ & T_{peak} = \frac{E_{PS\max}}{P_{PS\max}}. \end{aligned} \quad (4)$$

2.2. Wind Farm

Wind high variability and its random availability make wind prediction necessary to decrease economic payback period. Inappropriate wind farm design may cause financial damage due to use the large number of wind turbines requiring a large area to be installed [19]. Large area of wind farm might lead to higher likelihood wind turbine outage due to natural phenomenon [20,21]. Also, wind turbines have many positive and negative impacts on environment. Positive wind turbines' effects can be classified as reduction of water consumption, reduction of carbon dioxide emission [22] and minor payback time compared with other kinds of generation plants [21]; while negative impacts including effects on wildlife, noise effects and visual impacts [22] cannot restrict the usage of wind turbines.

The amount of wind turbine output power (P_{wt}[kw]) depends on some variables such as wind speed, power coefficient, turbine diameter and air density formulated as equation (5) [23]:

$$P_{wt} = 0.5\rho A C_P V^3 \times 10^{-3} \quad (5)$$

Where ρ is air density [kg/m^3], A is area swept by the rotor blade [m^2], C_P is power coefficient and V describes wind speed [m/sec].

3. Proposed Method

In this paper, it is assumed that an owner has invested and also constructed a HPS unit with the maximum capacity of E_{PSmax} and the maximum charge and discharge time of $T_{off\text{-}peak}$ and T_{peak} respectively. The amount of investment required for a HPS unit is shown by D [$/kW].

The proposed method has studied the feasibility of building a wind farm by the HPS owner in parallel with the HPS unit to maximize the total profit of the system. Besides, in spite of other approaches, in this method the HPS does not use the grid energy to pump the water and all the required energy is supplied by the wind farm connected to it.

Each of the HPS unit elements has its efficiency demonstrated by η_j, where j represents the j_{th} element. Due to series performance of the HPS elements, overall efficiency which is shown by η_t can be calculated by multiplying all of the elements' efficiencies as it is written in equation(6); where J represents the total number of the HPS unit elements.

$$\eta_t = \prod_{j=1}^{J} \eta_j, j \in J. \quad (6)$$

3.1. Data Generation

Data used in this paper have been generated using Monte Carlo method due to stochastic behavior of wind and variable real time electricity price ($price_t$[\$/kWh]) and maximum price value of ($price_{max}$ [\$/kWh]). The Monte Carlo method uses random numbers to simulate stochastic behavior. This method can be used to estimate the anticipated or average variables' values and also the frequency distribution of the parameters if needed [22].

The price value follows a three steps pricing policy considering the peak, mid-peak and off-peak hours. Due to having two consumption patterns in the year, price values as well are divided into two high and low price seasons; which is demonstrated in Figure 1. Monte Carlo method has been used to determine the annual price values using the arithmetic mean values which are shown in Figure 1.

As well as the price, the wind speed also has been determined by Monte Carlo method. The values has been estimated around two mean speeds of 10.5m/sec and 6m/sec which are representing the arithmetic mean value speeds in high and low wind speed seasons. Figure 2 demonstrates the seasonal mean values and two examples of determined daily wind speeds.

3.2. Operational Scenarios

In this paper, a comparison has been made between $price_{max}$ and $price_t$ affected by η_t. This comparison results lead to various operational scenarios as follows:

1. Wind farm pumps water to charge the HPS unit and HPS is in idle state.
2. Wind farm sells all of its power generation and HPS unit is idle.
3. Both wind farm and HPS unit sell the generated power to the grid.

A fair selection between these scenarios depends on the ratio of $price_{max}$ and $price_t$. If the difference between them compensates the HPS cycle loss, wind farm produced energy is stored in upper reservoir. Therefore, if $price_{\max} \geq \frac{price_t}{\eta_t}$ then the HPS starts to pump; conversely, if $price_{\max} < \frac{price_t}{\eta_t}$ then, wind farm energy will be sold directly. In peak price hours both wind farm and HPS units are scheduled to inject all their produced and stored energy into the grid. Table 1 shows a proper example for proposed method. Where, income I and II represent the total income with and without using proposed method respectively.

3.3. Methodology

Due to variable price values in day-ahead market, the ratio of $price_{max}$ and $price_t$ can help to choose between the scenarios represented before. Based on inequality (3), the HPS is scheduled to inject all of its stored power in T_{disch}. The discharge process must occur during T_{peak} to gain the maximum income. Price vector can be written as equation (7).

$$price = [\,price_1, price_2, ..., price_H\,] \tag{7}$$

Where H is the number of time intervals of price announcement. Considering a scheduling period of one hour, the total number of periods for the day ahead would be 24. By sorting the price vector, price'vector would be generated.

$$price' = [\,price'_1, price'_2, ..., price'_H\,] \tag{8}$$

The $price_{dis}$ vector consists of the last T_{disch} members of price'vector.

$$price_{dis} = [\,price'_{H-T_{disch}+1}, price'_{H-T_{disch}+2}, ..., price'_H\,]. \tag{9}$$

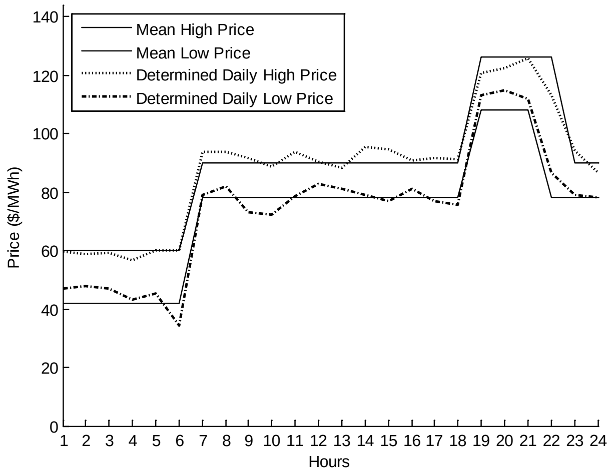

Figure 1. The price seasonal mean value and an example daily price

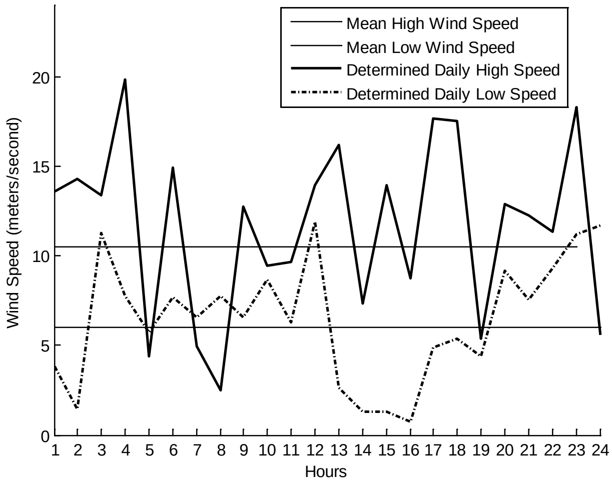

Figure 2. The wind speed seasonal mean value and an example daily wind speed

Table 1. An example solved using the proposed method

Wind Farm Output Power (MW)	Real Time Price (\$/MWh)	Maximum Price (\$/MWh)	Total Efficiency	Selected Scenario	Income I (\$) & II (\$)
100	10	13	0.8	pumping	1040 -1000
100	11	13	0.8	direct sell	1100-1040

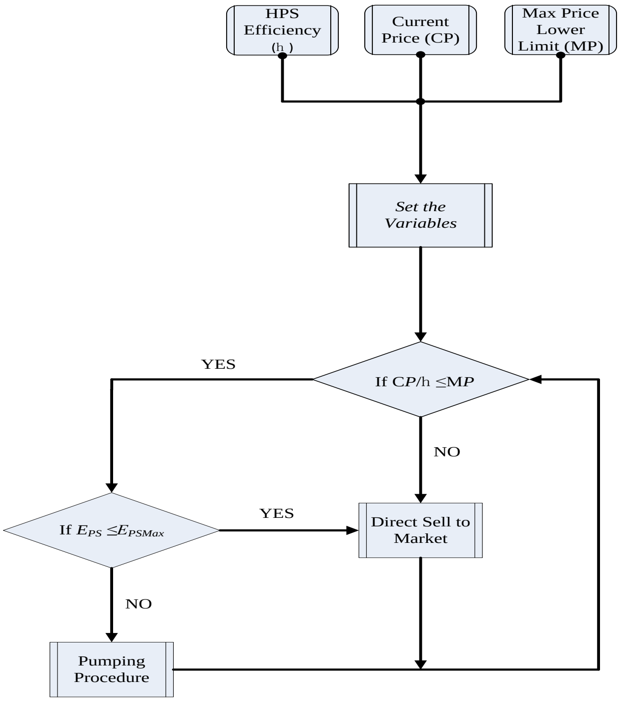

Figure 3. The WHPS operational procedure flowchart

Figure 3 stands for the illustrated algorithm which contains the operational procedure for the WHPS unit.

In order to achieve the highest amount of profit, the HPS unit should be discharged by its maximum capacity. Therefore, the total income gained by the HPS can be obtained through below equation (9).

Where HPS_{inc}[$] demonstrates the total income gained by the HPS unit.

Based on the considered schedule, wind farm would have two modes of operation. The first mode includes the peak price hours with the duration of T_{disch} in which the wind farm operator decides to sell all of its generated power regardless of the $price_t$ as it is declared in the 3rd scenario; and, in the other mode which includes the off-peak periods if $price_{\max} < \frac{price_t}{\eta_t}$ then, wind farm energy will be sold directly to the market.

$$W_{inc} = W_{inc-peak} + W_{inc-offpeak} \tag{10}$$

Where, W_{inc}[$] is the wind farm total income and $W_{inc-peak}$[$] and $W_{inc-offpeak}$[$] are wind farm incomes in peak and off-peak periods respectively. Therefore, the total income of the WHPS can be formulated as follows:

$$WHPS_{inc} = HPS_{inc} + W_{inc} \tag{11}$$

Where $WHPS_{inc}$[$] describes the total WHPS income. Assuming C [$/kW] as wind farm installation cost, the payback period (PP) for the WHPS can be defined as below:

$$C \times P_{W\max} + D \times P_{PS\max} = \int_0^{PP} WHPS_{inc} \tag{12}$$

Where $P_{W\max}$[kW] is the nominal installed power for the wind farm. Based on the economic relations between the represented parameters, it is obvious that the more the number of wind turbines, the more the income; so, it is necessary to define a constraint to have an optimum value for the number of wind turbines in order to optimize the WHPS payback period.

Having numerous wind turbines in WHPS may lead to have more power than required power to fully charge the HPS unit; accordingly, it is similar to have another wind farm in parallel with an appropriate WHPS. The extra generated power by the additional wind farm will be sold to power market regardless of the $price_t$. This parallel wind farm does not seem to have any effect on optimizing the WHPS cycle. The required constraint can be defined as the total wind turbines number in which, the HPS upper reservoir reaches its maximum capacity in one day of the year. Another factor to determine the effectiveness of the proposed algorithm is peak to average ratio (PAR), defined in equation (13). The PAR index shows the smoothness of the output power curve.

$$PAR = \frac{Output_{peak}}{Output_{average}}. \tag{13}$$

4. Case Study

To prove the validity of the proposed method in this paper, an example HPS unit with the capacity of 100 MW has been introduced with the characteristics demonstrated in Table 2. Without considering a wind farm in parallel with the HPS unit, the payback period would be equal to 7 years and 109 days. The PAR for this HPS is equal to -15 which makes it a passive energy source. The negativity comes from the negatice average produced power by HPS shown in Figure 4. It means that, the HPS uses more energy than it produces as it is clear in Figure 4.

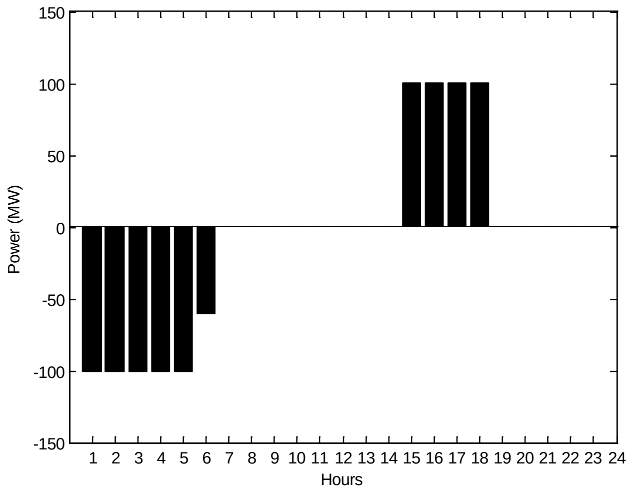

Figure 4. The stand-alone HPS schematic power curve

Table 2. The example HPS unit characteristics

Parameter	E_{PSmax} (MWh)	P_{PSmax} (MW)	η_t	T_{peak} (hours)	$T_{off\text{-}peak}$ (hours)	D ($/MW)
Value	400	100	0.71	4	20	400000

A Vestas V80 wind turbine having the nominal output power of 2000 kW and the radius of 40 meters has been considered to operate in parallel with the HPS. The installation cost for this type of wind turbines is determined about 2000 $/kW. The life time for this type is estimated about 20 years. Figure 5 shows the V80 wind turbine Cp versus the different wind speeds. Using data generated by Monte Carlo method, payback period of the wind farm is equal to 9 years and 110 days regardless of the wind turbines' number.

WHPS is expected to have a longer payback period compared with the HPS unit. Besides, using the HPS along with the wind farm has the advantage of using the storage system to sell the energy in peak price hours.

The combination of a HPS and a wind farm utilizing V80 wind turbines, both introduced before, has been practiced using the proposed method. Table 3 shows the technical and economical results.

Considering the constraint declared before and using the Table 3 and Table 4, the number of wind turbines which fully charges the upper reservoir for the first time and showes benefit to cost ratio of 0.51 for the given average wind speed is the optimum number of the wind turbines required to operate in parallel with the HPS. It is observable that for this study case, 26 is the optimum number of wind turbines. In this case, the annual income is sufficient to pay the total cost back in almost 8 years. Without considering annual inflation, the benefit to cost ratio is 0.506 which can be an intensifying amount for the investors.

In Table 3 and Table 4, the payback periods (PP) of the planning has been calculated in years and days which approves that the minimum number of the wind turbines required to charge the HPS for the first time is equal to 26. Besides, in Table 4, proportionate to original wind aims to represent the average wind speeds applied to the wind farm as a proportion to the original wind speed values.

Unlike the HPS without wind farm operation, the WHPS has a positive PAR which makes it an active energy source. The schematic power curve for an example day has been presented in Figure 6.

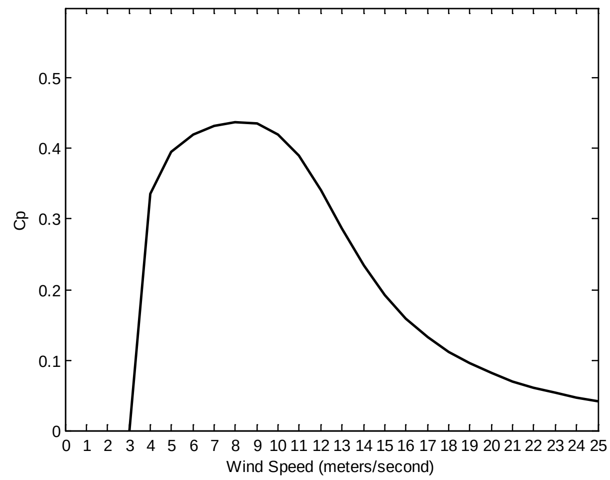

Figure 5. Cp versus wind speed diagram

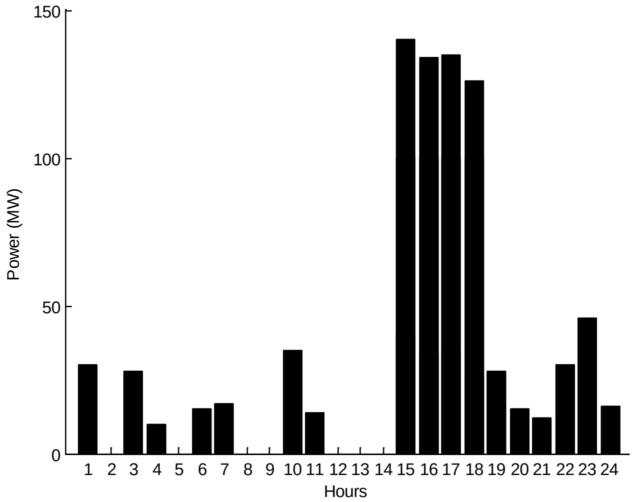

Figure 6. The WHPS schematic power curve for an example day

Table 3. Various wind farms' characteristics using the proposed method

WTs number	E_{PS} (MWh)	Annual Income (M$)	PP (years)	PP (days)	Profit per Life (M$)	Benefit to Cost Ratio
23	358	15.98	8.0	95	187.57	0.42
24	373	16.67	8.0	58	197.33	0.45
25	389	17.35	8.0	25	207.09	0.48
26	400	18.04	7.0	358	216.83	0.51
27	400	18.73	7.0	329	226.57	0.53
28	400	19.42	7.0	303	236.30	0.55

Table 4. Various wind average's impacts on the optimum operating point

Proportionate to Original Wind	Optimum *WTs* number	Annual Income (*M$*)	*PP* (years)	Profit per Life (*M$*)	Benefit to Cost Ratio
0.7	35	14.47	12	109.4	-0.39
0.8	30	15.42	10	148.4	-0.07
0.9	27	16.4	9	180	0.22
1	26	18.04	7	216.8	0.51
1.1	24	18.5	7	234	0.72
1.2	23	19.27	6	253.4	0.92
1.3	23	19.28	6	253.6	0.92

Table 5. Various price impacts on the payback period

Proportionate to Original Wind	Annual Income (*M$*)	*PP* (years)	*PP* (days)	Profit per Life (*M$*)	Benefit to Cost Ratio
0.7	12.63	11	147	109	-0.25
0.8	14.43	9	357	145	0.0
0.9	16.24	8	317	181	0.25
1	18.04	7	358	217	0.51
1.1	19.84	7	94	253	0.76
1.2	21.65	6	238	289	1.01
1.3	23.45	6	51	325	1.26

Variable wind average speed can affect the optimum wind turbine number and also annual income gained by the WHPS. Therefore, it is expected to have higher number for wind turbines as an optimum point with lower average wind profile and vice versa. Table 4 represents the calculations based on different wind averages.

The results show that, this combination would not be appropriate in low wind speeds, and the benefit to cost ratio is negative in these situations. Only if payback period is less than half of the wind turbines life time, the benefit to cost ratio would be positive and the WHPS would earn more income than its expenditures. In fact, the more the wind speeds, the more the annual income.

Varying the market price, does not have any impact on the optimal wind turbine numbers, because the optimum operating point of the WHPS would only be affected by the wind profile and the proportion of the $price_t$ and $price_{max}$. Considering the primary wind profile, and the optimum wind turbine number of 26, results have been demonstrated in Table 5 for variable prices.

As it is clear, in low prices, the benefit to cost ratio is negative similar to low wind speeds. In a power market with average daily price of 0.8 of referenced price, the benefit to cost ratio is equal to zero which means the WHPS income will not exceed the primary cost paid in the construction period.

Based on the simulations carried out in the study case, results exhibited in Table 3 help the owner to find the optimum number of wind turbines to install a wind farm in an area with specific wind and price values. Data in Table 4 can be used to site the wind farm as best as it can, because different places have different wind patterns and choosing between these possible sites needs a technical analysis. Table 5 consists of data by which the owner can understand if installing a wind farm in a specific power market zone is economically justifiable or not.

5. Conclusion

In this paper, a new approach has been introduced to find the optimum number of wind turbines required for a wind farm to operate in parallel with a HPS unit in order to maximize the income of the combination. The data needed for modeling wind and price have been generated using Monte Carlo method considering the proper averages. The shorter payback period of the HPS has ameliorated the longer payback period of the wind farm. This approach has been applied to various winds and price values using MATLAB M-File; these results can lead the WHPS owner to find the exact wind and price averages in order to gain the desired benefit.

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