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FUZZY LOGIC CONTROLLER FOR PREDICTING WIND TURBINE POWER GENERATION

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ABSTRACT

The utilization of wind energy for power generation purposes is occupying a great share in the electrical market worldwide and becoming increasingly attractive. The good exploitation of wind energy may enhance the power generation capabilities, maximize its capacity factor, and participate in generating electricity at good costs. The present paper comprises two parts; the first part utilizes fuzzy logic methodology to assess wind sites in Jordan and to decide which sites should be given the highest priority with respect to their benefits and costs, and to predict the annual generation for different turbines in the best sites. The criterion of evaluation using fuzzy logic is based on different parameters, i.e., wind resources, prevailing wind direction, above ground level (AGL), site capacity, soil conditions, site elevation, land cost, land roughness, temperature, cultural and environmental concerns, aviation/telecommunications conflicts, nearby resident's concerns, site environmental issues (corrosion, humidity), and distance to transmission line. In the second part, a MATLAB/Simulink model is developed to study the parameters that affect the power generation by wind turbines. The considered parameters are turbine swept area, air density, wind speed, and power coefficient as a function of pitch angle and blade tip speed. The results show that Al Harir site in Al Tafila city is found to be the best choice and should be given the highest priority. It is followed by Al-Fujeij in Al-Shawbak then Al-Kamsha in Jerash.

***Keywords**:* Wind energy, Fuzzy logic, Wind turbines, Site assessment.

1. INTRODUCTION

Today, new renewable resources provide only a small share of global energy production (Figure 1). However, the global market for wind power has been expanding faster than any other sources of renewable energy. The world wind power capacity has been duplicated around twelve times from just 4,800 MW in 1995 to reach over than 59,000 MW at the end of 2005 (Figure 2).

Hence wind energy technologies are still maturing; performance is becoming better and more reliable while at the same time costs continue to decline. Wind power is now established as an energy source in over 50 countries around the world. Those with the highest totals in 2005 were Germany (18,428 MW), Spain (10,027 MW), the USA (9,149 MW), India (4,430 MW) and Denmark (3,122 MW). A number of other countries, including Italy, UK, Netherlands, China, Japan and Portugal, have reached the 1,000 MW of wind power capacity (Figure 3) (Global Wind Energy Council, 2006). Denmark is planning for wind power to cover 50% of the electricity consumption by 2025 (American Wind Energy Association, 2004).

Jordan is heavily reliant on energy imports, placing a large annual burden on the national economy. Energy consumption is growing at 5.5 % annually and electricity demand growth is closer to 7.5 %. As part of its drive to reduce reliance on oil imports, Jordan has formulated plans to accelerate the expansion of wind energy reliance in electricity consumption.

The government has set a target of acquiring five per cent of total energy needs from renewable energy, including wind energy, by 2015 (MEMR, 2006). Many studies have been made to promote the wind energy throughout the world. Rosado et al (2008) used decision support technology to promote the new wind farms by selecting a suitable geographical locations in Spain, their research was devoted to overcome the problems posed by the different agents such as, investors, utilities, governmental agencies or social groups that could delay the planning process. Míguez et al (2006) studied the possibility of increasing the share of wind power generation by 51% of the total capacity size in Galicia (Spain) and showed its benefits from the economic and environmental point of view.

A promotional study has been prepared by Feller (2007) to help remove policy, regulatory, and financial barriers to the promotion of wind power in Jordan.

Another study has been proposed by Hrayshat (2007 a) to assess the wind in southern region of Jordan for water pumping applications using wind turbine. Badran (2003) also reviewed the wind turbine utilization for water-pumping applications to meet the energy requirements for remote villages, settlements, and farms in Jordan.

The interest and motivation for utilizing wind power have grown tremendously during the nineteen-eighties in many developed and developing countries (i.e. Jordan), as a result of frequent energy crises on one hand and persisting issues of environmental pollution on the other. These activities have inspired many researchers and scientific community in Jordan to investigate the wind potentials in Jordan.

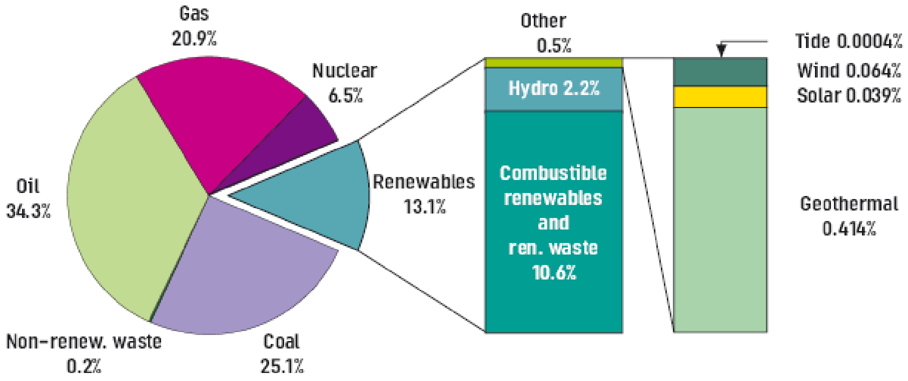


Figure 1 Fuel shares of world total primary energy supply (IEA, 2007)

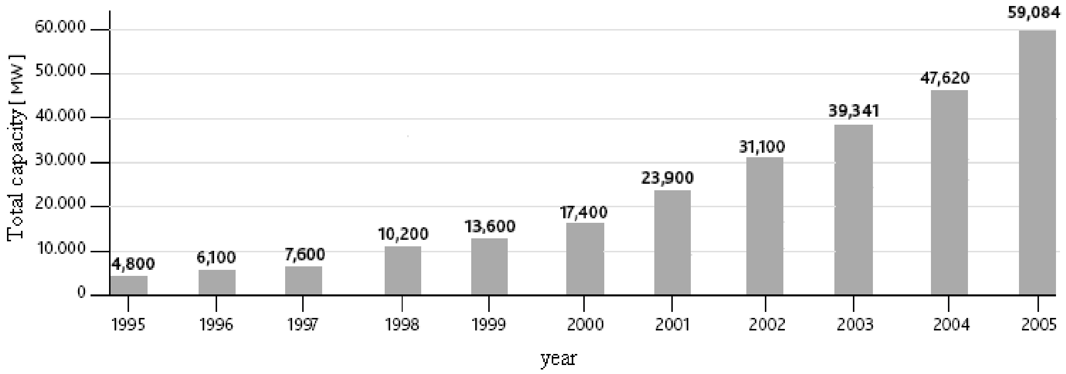


Figure 2 Global cumulative wind power capacity
Source: (Global Wind Energy Council, 2006)

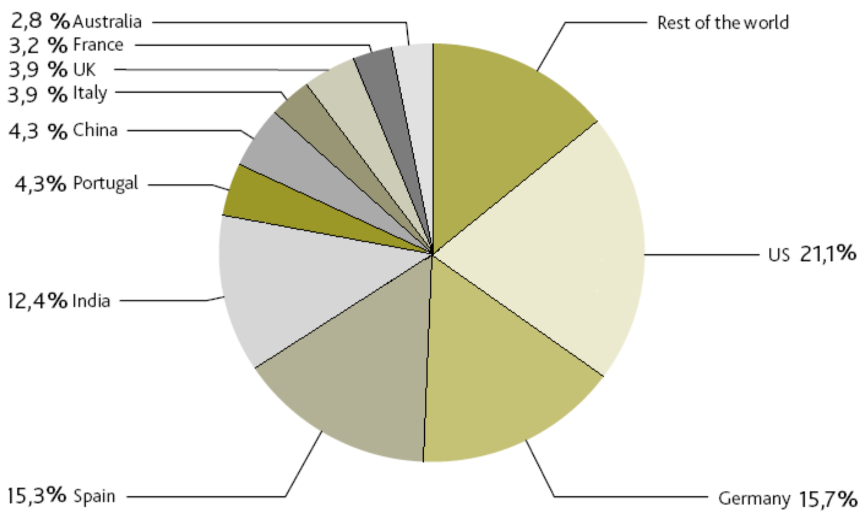


Figure 3 The greatest global wind capacity share
Source: (Global Wind Energy Council, 2006)

The first wind speed measurement recorded in Jordan was in January 1923 at the Amman civil airport and was by the British Air Force. It lasted for one year and measured only the maximum wind gust according to the Lustrum forms filed by the Jordan Meteorological Department (JMD). The measurements were restarted in June 1948, taking into account all relevant climatic parameters. Wind measurements, however, were taken as an average of three readings in each day. Averages were taken over each indicated hour, and the three hourly points were averaged to obtain the mean wind speed for that day. Then, the JMD was relocated in 1952 as a branch of the Civil Aviation Authority. Later a law was issued declaring the JMD as an independent department in 1967. The JMD continued to measure wind speed using the above mentioned procedure. However, in 1977, they started taking four daily readings instead of three. Furthermore, the newly installed sensors were at a height of 10 m. This method of measurement is still followed today. Up to 1983, there were some meteorological stations in Jordan operated independently of the JMD by the Natural Resources Authority (NRA) and the Jordan Valley Authority (JVA). The Royal Social Society (RSS) installed accurate measuring instruments since the middle of eighties to determine the wind energy resources of different sites in Jordan. They have installed 14 data acquisition systems for measuring wind speed and direction in various geographical locations throughout the country (Ta'ani, 1986; RSS, 1994). In 1982, the Mechanical Engineering Department at the University of Jordan started theoretical studies on wind energy. These studies dealt with wind energy evaluation, economic feasibility of wind energy applications in Jordan and aerodynamic design of conventional and non-conventional wind energy converters. Wind energy augmentation principles and wind farms were also investigated (Habali et al, 2001; RSS, 1994; Badran, 2003). Many studies have been proposed to optimize wind turbine power generation. Shata and Hanitsch (2006) have evaluated different wind sites in Egypt using classical statistical analysis to estimate the best wind site. Koçak (2008) focused entirely on wind speed persistence during weather forecast, site selection for wind turbines and synthetic generation of the wind speed data. Herbert et al 2007 developed models for wind resources assessment, site selection and aerodynamic including wake effect to improve the wind turbine performance and to increase its productivity. Lackner et al (2008) utilized ground-based measurement devices instead of meteorological towers for wind resource assessment. They investigated the use of a monitoring strategy in more than one site to determine the best wind sites. The cumulative avoided CO_2 emission will be 3,375 million tones by 2020 if the global wind power capacity increased to 230,658 MW (Global Wind Energy Council, 2006; Saidur et al., 2007; Hasanuzzaman et al., 2008). Also Saddler et al (2007) showed that increasing the share of renewable power generation, including wind power, could result in 78% in CO_2 emission reduction in Australia.

There are many attempts made to improve the wind turbine itself; Irabu and Roy (2007) proposed a study to improve and adjust the output power of Savonius rotor under various wind power and suggested a method of preventing the rotor from strong wind disaster. Khalfallah and Koliub (2007) focused entirely on the turbine rotor and blades in order to improve the wind turbine power curves. Sutikno (2011) used two stages blades contra rotation to enhance the speed regulation of the wind turbine. The present study utilizes fuzzy logic to evaluate various sites in the bases of their benefits and costs to adopt the higher priority sites in terms of different criteria, i.e., wind resources, prevailing wind direction, above ground level (AGL), site capacity, soil conditions, site elevation, land cost, land roughness, temperature, cultural and environmental concerns, aviation/telecommunications conflicts, nearby resident's concerns, site environmental issues (corrosion, humidity), and distance to transmission line. Also it shows the factors that affect the wind power over wide ranges, which will lead the wind developers and researchers to focus on the highest priority parameters that should be considered for installation and manufacturing of the new generations of wind turbines. The parameters that affect the power generated by wind turbines can be classified into two categories, namely, the site in which the turbine will be installed, and the wind turbine itself as shown in Figure 4.

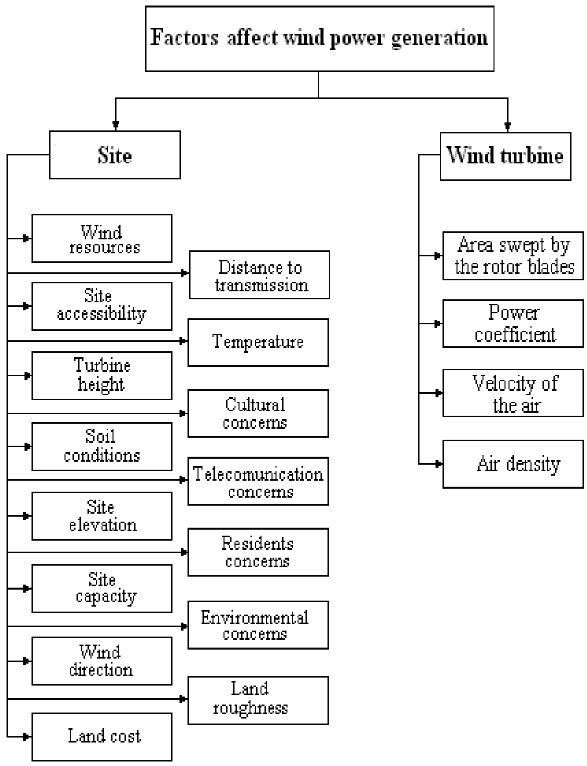


Figure 4 Classification of factors that affect wind power generation

2. SITE SELECTION

The most promising sites in Jordan have been considered in terms of their benefits and costs (barriers). The selected areas are located in the northern and southern regions of Jordan, they represent moderate-to-good wind resources (Ministry of Energy and Mineral Resources, 1996). According to the National Renewable Energy Laboratory (NREL) the wind resource classification of 6.4-7.5 m/s is classified beneath moderate-to-good wind resources (Young and Vilhauer, 2003)

The assessment criterion is classified into two main categories, namely, benefits and costs. Benefits represent the different parameters that enhance the site's credibility while costs characterize the factors that affect the suitability of the site and the installation cost.

The "benefit" parameters are wind resources, prevailing wind direction, turbine height (above ground level (AGL)), site capacity (compatibility with expansion plans), soil conditions, and site elevation, while the "cost" parameters are: land cost, land roughness for availability of rough terrain equipments, temperature, cultural and environmental concerns, aviation/telecommunications conflicts, nearby resident's concerns, site environmental issues (corrosion, humidity), and distance to transmission line (Young and Vilhauer, 2003; Wind Resource Assessment Handbook, 1997).

2.1. Selected Sites

The sites that have been considered are located in Al-Fujeij near Al-Shawbak city, Al-Harir near Al-Tafila city, and Wadi Al-Aqaba near Aqaba city (southern region), and Al-Kamsha near Jerash city (Northern region). The collected data for these sites were taken from 1996 to 2005. The average temperature, humidity and prevailing wind direction were monthly averaged for the whole period (1996~2005) (Meteorological Department, 1996-2005), they will be discussed as follows:

Al-Fujeij site:

Al-Fujeij site lies to the north east of the city of Shawbak, in the area of Ma'an. The land is owned by the Ministry of Agriculture. The site is bounded by a petrol filling station and arable farm land. It is 1200-1250 m above the sea level (Figure 5 and Figures 6a and b) (Google Earth, 2008).

It has rocky desert soil nature (Figure 5 and Figure 6), and located 11 km away from transmission lines and substations (Figure 7a) (PB POWER, 2007).

The region has some environmental and cultural concerns sense it lies on flight line for migratory birds, and it is home to a number of archaeologically interesting sites and old cultural periods, namely, Roman (64 BC), Byzantine (333 BC), Nabatean (200 BC) (PB POWER, 2007).

Regional wind resource is considered the most important factor in site selection; the regional wind resources for the selected regions have been estimated from the wind resource map of Jordan as shown in figure 7b (Ministry of Energy and Mineral Resources, 1996). Al-Fujeij possesses good wind resources as shown in Figure 7b, the average wind speed is estimated (7.2- 7.5 m/s) at hub height 50 m (Ministry of Energy and Mineral Resources, 1996). The prevailing wind direction varies between (217^o and 283^o) as in Fig 8. The average temperature varies between (14–35^{o}C) (Figure 9). The mean relative humidity varies between (41% and 68%) as shown in Figure 10 (Meteorological Department, 1996-2005). It can be seen from Figs 8 to 10 that the wind direction for Al-Fujeij site is fluctuating during the summer months (June to August); this corresponds to higher temperature and lower average humidity.

Al-Harir site

Al-Harir is located near Tafilah city in the southern region of Jordan. As can be seen from Figs 6 a and b and Fig 11, the terrain is dry and it is 1300-1350 m above the sea level.

The region possess a good wind resources, it has around 7.2 m/s average speeds as shown in Figure 7 b (MEMR, 1998-2002). It is located about 3 km away from the closest substation (Figure 7a). The site has good prevailing wind direction which varies between 240^o and 260^o (Figure 8) that would decrease the turbines spacing and increase the turbines life due to the continuous wind direction tracking. This site has the lowest average temperature, it varies between 11 to 32^{o}C throughout the year (Figure 9), and lowest relative humidity between 30% and 55% (Figure 10), and that may reduce the environmental concerns like corrosion, which would lengthen the turbine's life.

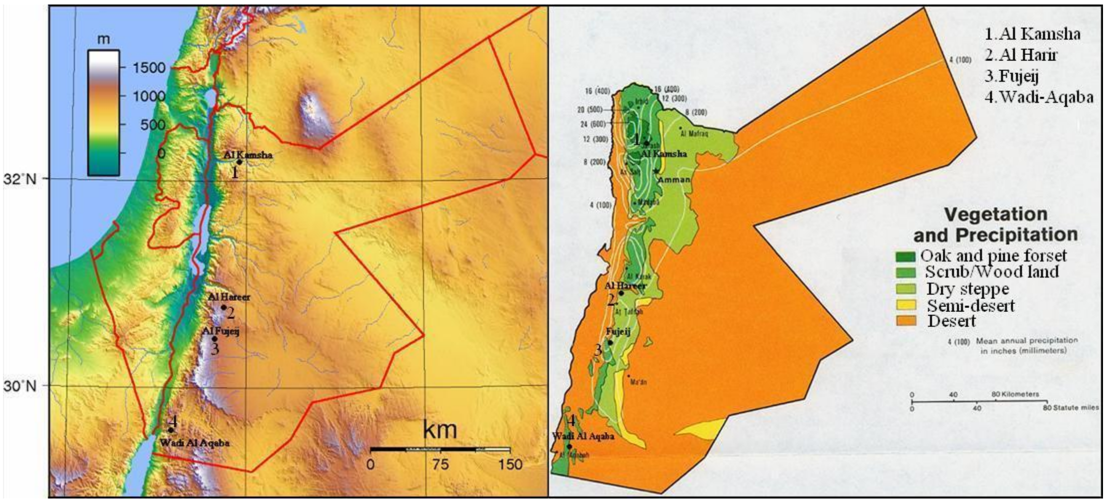
Al-Kamsha site

Al-Kamsha site is near Jerash city located in the northern region of the country. Its land nature is scrubby and woody (Figure 6 b and Figure 12). It is about 650-700 m above the sea level (Figure 6a). The site is bounded by military base, which can limit the expansion plans (MEMR, 2008). It has moderate-to-good wind resources 6.1-6.3 m/s (Figure 7b).

The prevailing wind direction in the site varies between 170^o and 280^o as shown in Figure 8. The average temperature varies between 14 and 33^{o}C while the mean relative humidity varies between 55% and 78% (Figs. 9 and 10) (Meteorological department, 1998-2005).

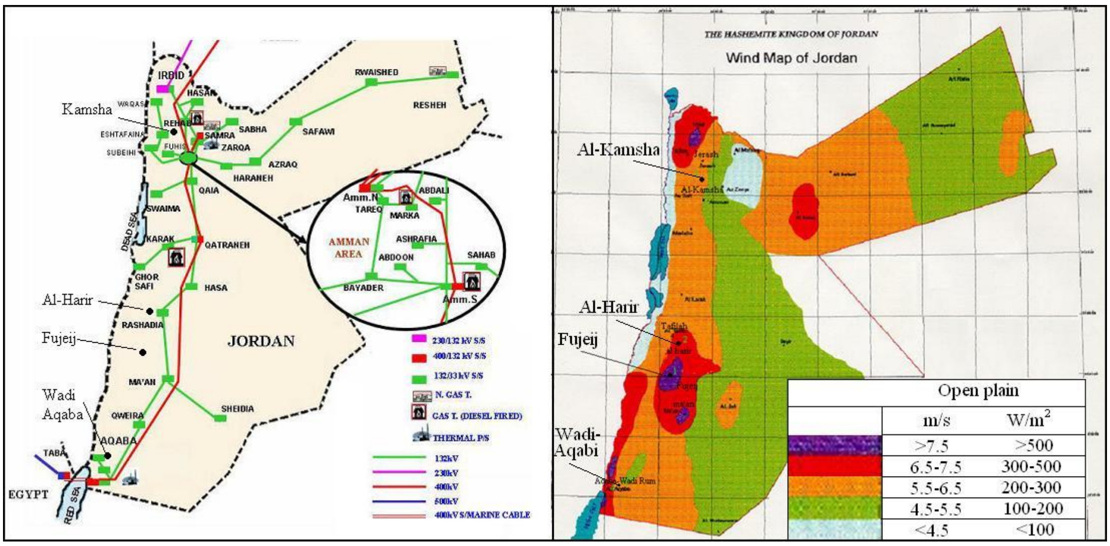
There are large number of old monuments located in Jerash and the land surrounding it belongs to the Roman province in 63 BC which may cause some cultural concerns that should be considered during the site selection (Ministry of Tourism & Antiquities, 2003).

Figure 5 Al-Fujeij satellite map view from 10 Km (Source: Google earth)



(a) (b)

Figure 6 Jordan maps (a) Topography (b) Vegetation and precipitation



(a) (b)

Figure 7 Jordan maps (a) Transmission lines and substations (Source: NEPCO), (b) Wind map resources (Ministry of Energy and Mineral Resources, 1998-2002)

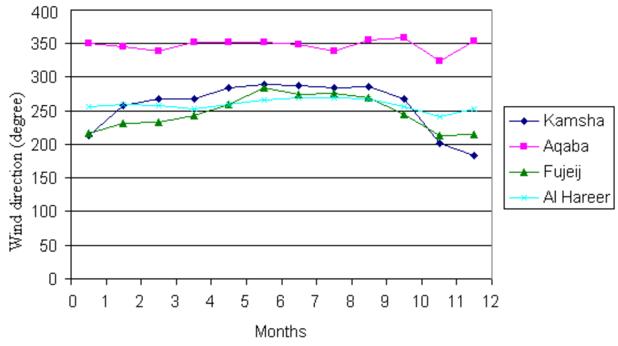


Figure 8 Prevailing wind direction for the selected cites

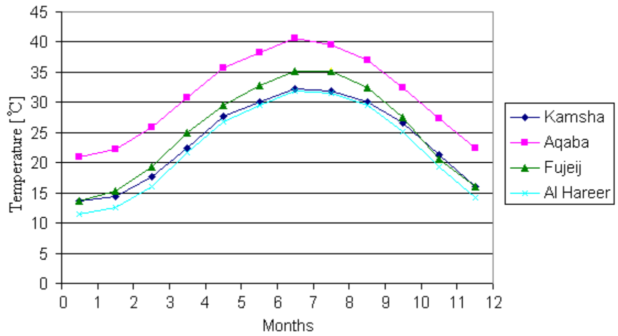


Figure 9 Average temperatures for the selected sites

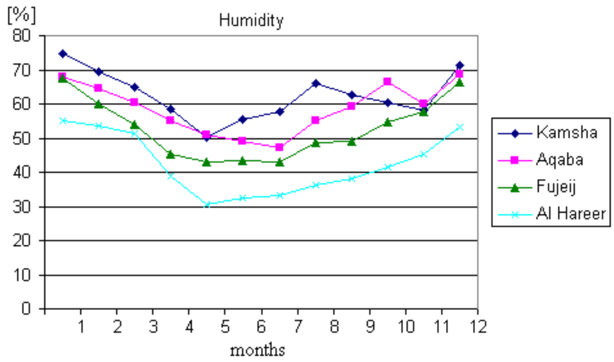


Figure 10 Annual average humidity for the selected sites

Wadi Al-Aqaba site

Wadi Al-Aqaba is located near Aqaba city in the southern region of Jordan. Aqaba is considered a home to number of archaeologically interesting sites and old culture since it was a center of the Edomites, and then of the Arab Nabataeans. It is strategically important to Jordan as it is the country's only sea port. The selected site is about 600-650 m above the see level and it has semi-desert nature (Figure 6b and Figure 13). It has moderate-to-good wind resources of about

Figure 11 Al-Harir satellite map view from 10 Km (Source: Google earth)

6.6 m/s average speed (Figure 7b) (Badran, 2006). Also It is has relatively high average temperature and high relative humidity (Figs 9 and 10).

The specific power (power per m^2) for a wind site can be determined from equation 1; (Danish Wind Industry Association, 2003):

$$\text{Specific power} = 1/2\ \rho\, v^3 \qquad (1)$$

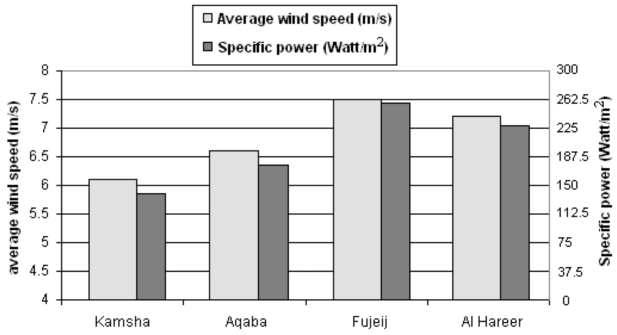
Where P is the power of the wind measured in W (Watt). ρ (rho) is the density of dry air = 1.225 measured in kg/m^3 (at average atmospheric pressure at sea level and 15° C). v is the velocity of the wind measured in m/s.

Figures 14 a and b compare between the different sites in Jordan in the basis of their average wind speed, specific power and elevation.

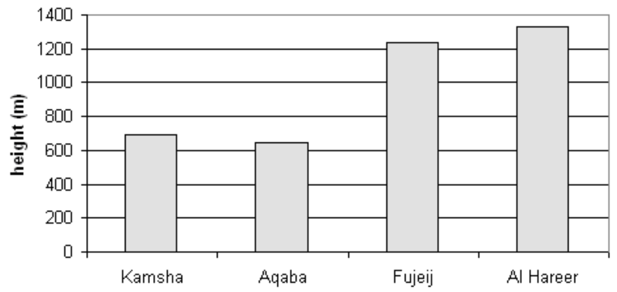
It is very important for the wind turbines industry to estimate the specific power and the variation of wind speeds in the sites for estimating the needed power output. Also turbine designers need the detailed information to optimize the design of their turbines to minimize the generating costs. The Weibull distribution (Figure 15) shows a probability density distribution of wind speed at different topographies in Jordan, as can be inferred from the figure 15, the wider distribution at higher velocities occurred in the hilly areas, followed by the desert regions.

Figure 12 Al-Kamsha satellite map view from 10 Km (Source: Google earth)

Figure13 Wadi Al-Aqaba satellite map view from 10 Km (Source: Google earth)



(a) Average wind speed and specific power



(b) Site elevation

Figure 14 Comparison of the four sites

2.2. FUZZY METHODOLOGY

Fuzzy logic has a wide range of utilizations in decision making since it condenses a large amount of parameters into smaller fuzzy sets. The current implementation uses the fuzzy steps as follows:

1- Determining the linguistic variables and the fuzzy sets.

The fuzzy logic decision selection (FLDS) of the sites options was applied according to benefits (Figure 16), namely, (B1= Wind resource based on Jordan wind map, B2= Prevailing wind direction, B3= Above ground level (AGL) (m), B4= Site capacity, B5= Site accessibility, B6= Soil conditions, B7= Site elevation) to make decision selections between different sites that cost less and have much benefits, many factors affect decision (i.e. costs) (Figure 17), they include (C1= Land cost, C2= Land roughness, C3= Temperature (°C), C4= Cultural and environmental concerns, C5= Aviation/Telecommunications conflicts, C6= Nearby resident's concerns, C7= Site environmental issues (corrosion, humidity), C8= Distance to transmission line (m)).

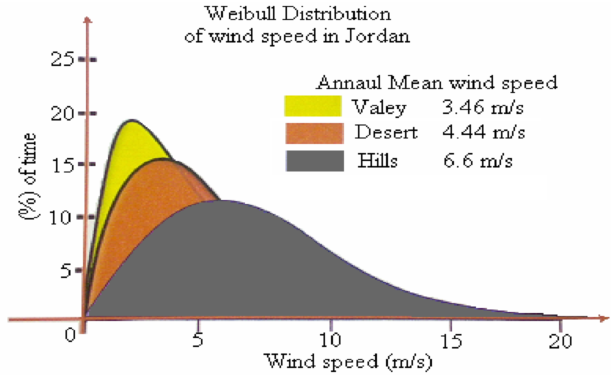


Figure 15 Weibull distribution of wind speed in Jordan

The Fuzzy input/ output combination is shown in the Figure 18.

The fuzzy logic methodology is applied taking into account each site parameters as shown in Tables 1. and 2. Data in Tables 1 and 2 are estimated based on the data provided in section (2.1).

The inputs in tables 1 and 2 are considered to be the fuzzy variables, each variable can vary over a fixed range, and the inputs' and output's sets are either three fuzzy sets type or five fuzzy sets type as shown in Figure 19. The linguistic variables used in the fuzzy methodology are: Very low (VL), Low (L), Normal (N), High (H), Very high (VH), Poor, Marginal, Satisfactory, Good, Excellent, Upgradeable, Solid rock, Fractured rock, Rock/soil, Soil/rock, All soil, Moderate None, Extensive, Minor, Average, Very close, Close, Not far, Far, Very far. Each fuzzy set is addressed as listed in table 3.

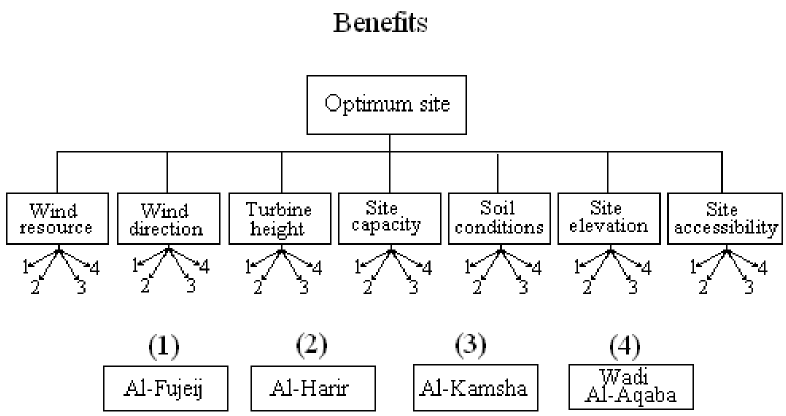


Figure 16 Benefits fuzzy structures

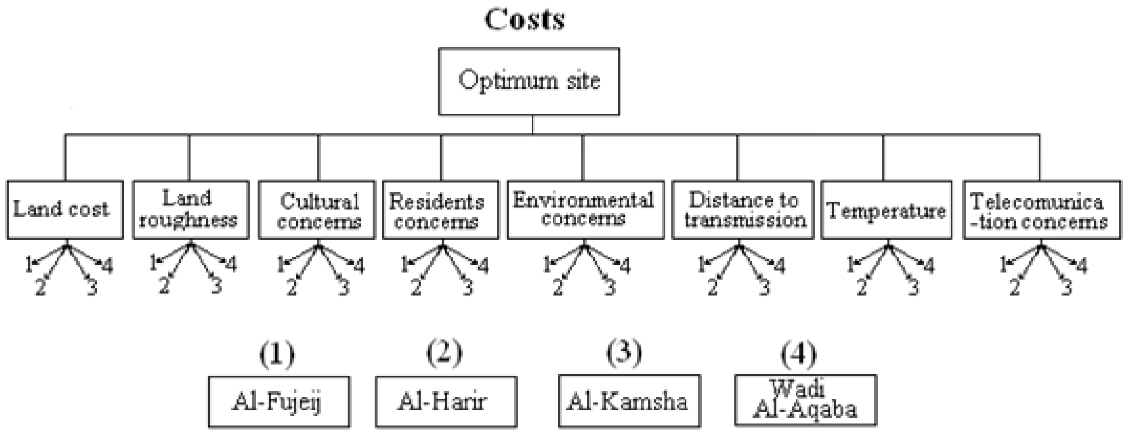


Figure 17 Costs fuzzy structures

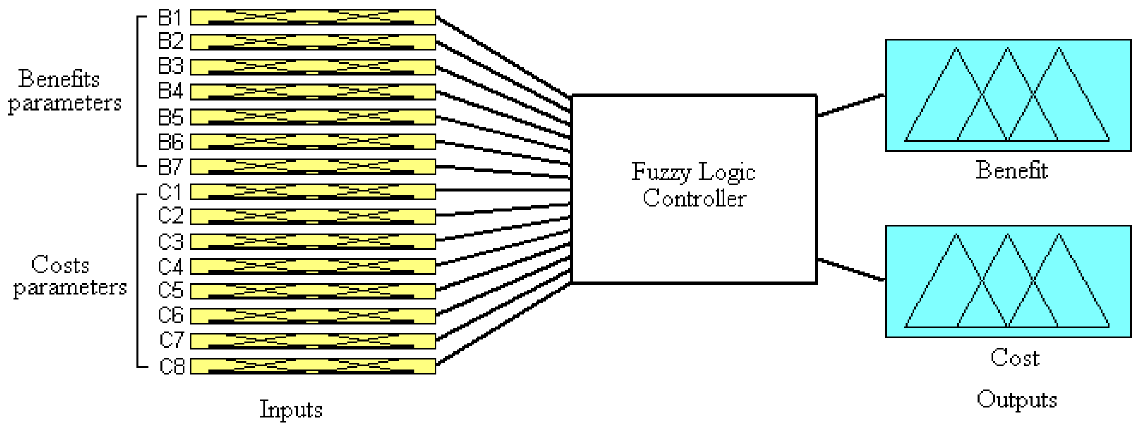


Figure 18 Fuzzy inputs/outputs combination

Table 1 Overall fuzzy weights for the selected sites based on benefits

	B1	B2	B3	B4	B5	B6	B7 **	Relative weight	Normalized relative weight*
Parameter's weight	1	0.4	0.4	0.4	0.4	0.4	0.4	-	-
Al Harir	0.9	1	50	1	0.8	0.5	1331	0.814	1.000
Fujeij	1	0.7	50	0.8	0.9	0.3	1236	0.737	0.905
Wadi Aqaba	0.8	0.8	50	0.9	1	0.4	649	0.725	0.891
Kamsha	0.7	0.45	50	0.25	0.8	0.9	697	0.651	0.800

* Normalized relative weight = relative weight/maximum relative weight
** B: Benefit

Table 2 Overall fuzzy weights for the selected sites based on costs

	C1	C2	C3	C4	C5	C6	C7	C8	Relative weight	Normalized relative weight*
Parameter's weight	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	-	-
Al Harir	0.8	0.1	22.4	0.3	0.1	0.1	0.3	3	0.292	0.605
Fujeij	0.2	0.1	25	0.65	0.1	0.4	0.5	11	0.394	0.816
Wadi Aqaba	0.4	0.5	31	0.65	0.1	0.5	0.75	3	0.483	1.000
Kamsha	0.2	0.3	23	0.8	0.1	0.6	0.8	3	0.42	0.87

* Normalized relative weight = relative weight/maximum relative weight
**C: Cost

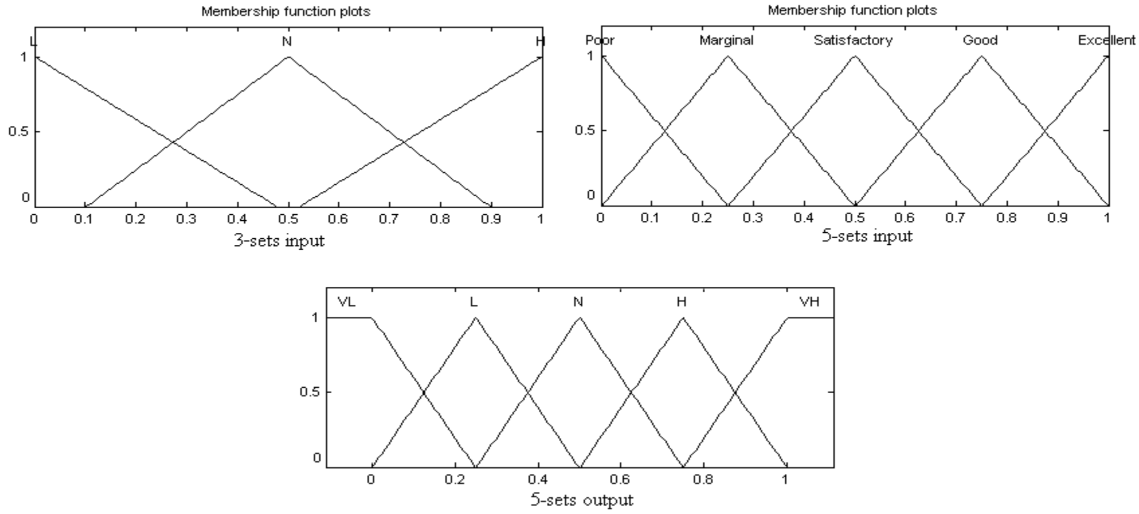


Figure 19 Input/Output fuzzy sets

Table 3 Fuzzy sets

		Variable type	Fuzzy sets						
Main parameters	Symbol		1	2	3	4	5	Range	Unit
Wind resource	B1	Input	VL	L	N	H	VH	0-1	-
Wind direction	B2	Input	Poor	Marginal	Satisfactory	Good	Excellent	0-1	-
AGL	B3	Input	VL	L	N	H	VH	10-70	m
Site capacity	B4	Input	Poor	Marginal	Satisfactory	Good	Excellent	0-1	-
Site accessibility	B5	Input	Poor	Marginal	Upgradeable	Good	Excellent	0-1	-
Soil conditions	B6	Input	Solid rock	Fractured rock	Rock/soil	Soil/rock	All soil	0-1	-
Site elevation	B7	Input	VL	L	Moderate	H	VH	0-1500	m
Land cost	C1	Input	L	N	H			0-1	-
Land roughness	C2	Input	VL	L	N	H	VH	0-1	-
Temperature	C3	Input	L	N	H	-	-	15-35	^{o}C
Cultural concerns	C4	Input	None	Moderate	Extensive	-	-	0-1	-
Tele-communication concerns	C5	Input	None	Moderate	Extensive	-	-	0-1	-
Residents concerns	C6	Input	Low	Moderate	Extensive	-	-	0-1	-
Environmental concerns	C7	Input	None	Minor	Average	Moderate	Extensive	0-1	-
Distance to transmission	C8	Input	Very close	Close	Not far	Far	Very far	0-20	km
	B	Output	VL	L	N	H	VH	0-1	-
	C	Output	VL	L	N	H	VH	0-1	-

2- Constructing fuzzy rules.

Sixty five rules were used in the current fuzzy method implementation to predict the most preferable options or option out of the four sites; they are represented in statements form as shown in Figure 20. Fuzzy logic enabled us to dense large amount of data, collected to compare between different sites, into a smaller set of variable rules (see Tables 1 and 2), to make a decision in the basis of their merits and barriers to produce higher power output at low cost as well as to capture as maximum wind power as possible.

The benefit to cost ratio is shown in Table 4.

1. If (B1 is VL) then (B is VL) (1)
2. If (B1 is L) then (B is L) (1)
3. If (B1 is N) then (B is N) (1)
4. If (B1 is H) then (B is H) (1)
5. If (B1 is VH) then (B is VH) (1)
:
30. If (C3 is N) then (C is N) (0.4)
31. If (C3 is H) then (C is VH) (0.4)
32. If (C4 is Extensive) then (C is VH) (0.4)
33. If (C4 is Moderate) then (C is N) (0.4)
34. If (C4 is None) then (C is VL) (0.4)
:
60. If (C8 is very__far) then (C is VH) (0.4)
61. If (B7 is VL) then (B is VL) (0.4)
62. If (B7 is L) then (B is L) (0.4)
63. If (B7 is Moderate) then (B is N) (0.4)
64. If (B7 is H) then (B is H) (0.4)
65. If (B7 is VH) then (B is VH) (0.4)

Figure 20 Fuzzy rules

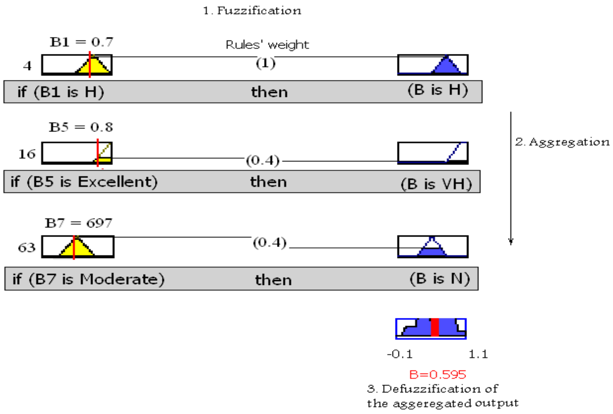


Figure 21 Fuzzy implementation sequence

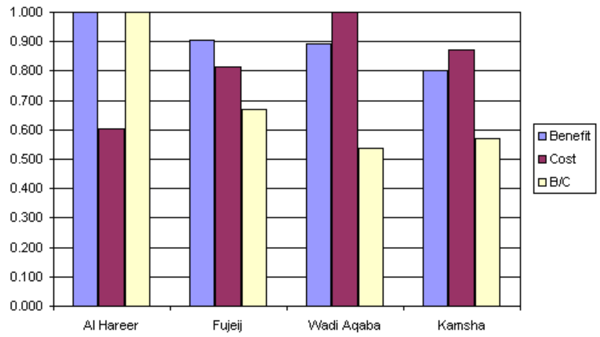


Figure 22 Comparison between normalized benefits costs and benefits to cost ratios

3- Performing fuzzy inference into the system.

Finally, the mapping process takes place to provide the final decision as shown in Figure 21. Fuzzification turns numeric values into linguistic descriptions (VL, L, N, H, and VH). This process is accomplished by evaluating the membership functions (MFs) with respect to the input value in order to establish the degree of activation of each output membership function.

At the end of this process, list of activations are obtained and can be carried forward to the next stage (aggregation sub-process). In the aggregation sub-process, the effects of each rule on the possible output conditions are accumulated. Defuzzification carries out the estimation of the outcomes of the inference processes. Each output variable is analyzed separately as shown in Figure 21.

2.3. RESULTS AND DISCUSSION

As can be seen from Table 4 and Figure 22, Al-Harir site showed the highest benefit to cost ratio. Therefore, it should be given the highest priority in terms of installing wind turbines to achieve high power production capacity for supplying nearby grid lines and for the electrification of small arid communities. The second and the third are, Al-Fujeij and Al-Kamsha, respectively.

Table 5 shows the list of different turbines that may be erected for producing electricity (i.e. annual generation and estimated levelized cost), at the best chosen site (Al-Harir). The economical considerations are the most important aspect in selecting the proper technology to be used in any project and location. If appropriate location is chosen, wind energy will be economically viable option for the production of electricity. A major consideration in the assessment of different wind turbines viability in Jordan, is the analysis of the cost of energy or electricity produced by the system (Table 5). Power plants are compared on the basis of their Levelised Electricity Cost (LEC), which depends on the capital cost of the plant, annuity factor, and annual operation and maintenance costs to the annual production of electricity (Equation 2), the wind turbine life should be assumed (30 years). Equation 2 is used for calculating the LEC:

$$\text{Levelized Electricity Cost (LEC)} = \frac{a \times CC + O\&M}{P_{el}} \qquad (2)$$

Where:
CC: capital cost [$], the raw equipment of wind turbine is estimated with $750/rated kW which represents about 80% of the total capital cost. Other costs represent foundation, grid connection lines, electrical installations, communication, land roads, consulting services, (Edelstein et al, 2003) (NWCC, 1998) (Smith, 2001) (Fingersh et al, 2006).

a: annuity factor, assumed to be 19%.
O&M: annual operating and maintenance expenditure [$], evaluated with 0.015$/kW
P_{el}: yearly electricity production [kWh]

The results from the recent study have shown that wind electricity generation cost ranges between 7.35 to 7.8 cents/kWh depending on benefits and costs factors discussed earlier (Tables 1-2 and 4-5).

Table 4 Benefit to cost ratio

Site	Normalized benefits relative weight (Table 1)	Normalized costs relative weight (Table 2)	B/C	Normalized B/C
Al Harir	1.000	0.605	1.653	1.000
Fujeij	0.905	0.816	1.109	0.671
Wadi Aqaba	0.891	1.000	0.891	0.539
Kamsha	0.800	0.87	0.92	0.57

The final results obtained are shown in Figure 22.

Table 5 Annual generations for Al-Harir site for different turbines model

Existing turbines	Hub height [m]	Average wind speed [m/s]	Rotor diameter [m]	Swept area [m^2]	Required specific power [W/m^2]	Site specific power [W/m^2]	Max power [MW]	Capacity factor	*Annual generation [MWh]	Estimated levelized cost [Cent/kWh]
Nordex	50	7.2	54	2290.2	440	440	1	0.32	2803.200	6.36
Enercon	50	7.2	66	3421.19	440	440	1.5	0.27	3547.800	7.53
Nordex	60	7.41	60	2827.4	460	475	1.3	0.3	3416.400	6.78
Kvaemer	100	8	80.5	5089.57	590	600	3	0.26	6832.800	7.82

*Annual production = Max power * Capacity factor * 8760

3. PARAMETERS THAT AFFECT WIND TURBINE GENERATION

In the previous sections, the factors that affect the selection of the wind site have been discussed. The current section discusses the factors that affect the wind turbine generation in the site.

Wind machines were used long time ago, the very first electricity generating windmill operated in the UK was a battery charging machine installed in 1887 by James Blyth in Scotland. The first utility grid-connected wind turbine operated in the UK was built by the John Brown Company in 1954 in the Orkney Islands.

Wind turbines are designed to exploit the wind energy that exists at a location. Virtually all modern wind turbines convert wind energy to electricity for energy distribution. The modern wind turbine is a system that comprises three integral components with distinct disciplines of engineering science. The rotor component, which is approximately 20% of the wind turbine cost, includes the blades for converting wind energy to an intermediate low speed rotational energy. The generator component, which is approximately 34% of the wind turbine cost, includes the electrical generator, the control electronics, and most likely a gearbox component for converting the low speed rotational energy to electricity. The structural support component, which is approximately 15% of the wind turbine cost, includes the tower for optimally situating the rotor component to the wind energy source (Fingersh et al, 2006).

Wind turbines are classified, in the basis of their axis in which the turbine rotates, into horizontal axis and vertical axis wind turbines. Because of the ability of the horizontal axis turbines to collect the maximum amount of wind energy for the time of day and season and to adjust their blades to avoid high wind storms; they are considered more common than vertical-axis turbines (Danish Wind Industry Association, 2003).

Turbines that used in wind farms for commercial production of electric power nowadays are usually three-bladed and pointed into the wind by computer-controlled motors. This type is produced by the most common wind turbines manufacturers. The top ten worldwide wind turbines manufacturers are shown in table 6. (Efiong and Crispin, 2007).

A wind turbine captures energy from moving air and converts it into electricity. The captured energy is affected by factors such as air density, turbine swept area, air velocity and power coefficient as in the following equation (Mukund, 1999):

$$P = 0.5.\rho.C_p.V^3.A \qquad (3)$$

Where, P is the mechanical power from the moving air, Watt; ρ air density, kg/m; A area swept by the rotor blades, m; V velocity of the air, m/s; C_p power coefficient.

A MATLAB/Simulink model (Figure 23) is developed to show how these factors affect the generated power from wind turbine.

Table 6 Top ten wind turbines manufacturers in 2006

	Accumulated MW 2005	Supplied MW 2006	Share 2006 %	Accumulated MW 2006	Share accumulated %
Vestas	20,766	4,239	28%	25,006	34%
Gamesa	7,912	2,346	16%	10,259	14%
GE Wind	7,370	2,326	15%	9,696	13%
Enercon	8,685	2,316	15%	11,001	15%
Suzlon	1,485	1,157	8%	2,641	4%
Siemens	4,502	1,103	7%	5,605	8%
Nordex	2,704	505	3%	3,209	4%
Repower	1,522	480	3%	2,002	3%
Acciona	372	426	3%	798	1%
Goldwind	211	416	3%	627	1%
Others	6,578	689	5%	7,267	10%

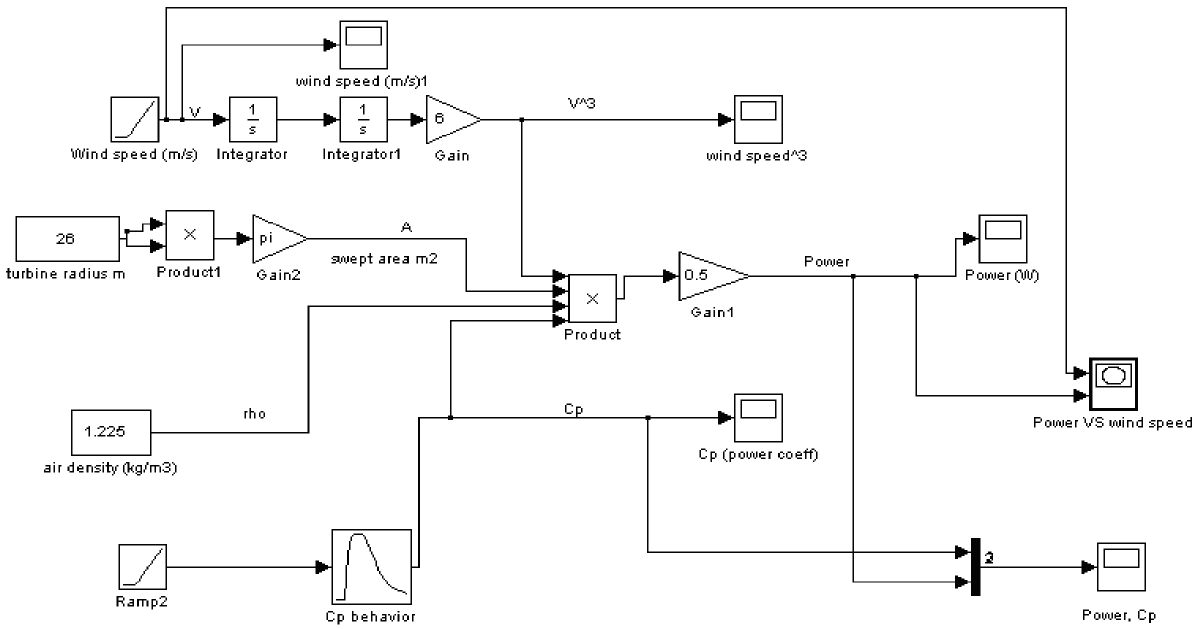


Figure 23 MATLAB/Simulink model

The Simulink model is valid for wide ranges of wind turbines. It is tested on VESTAS V52 wind turbine for validation purposes. The VESTAS V52 wind turbines have been erected in many countries more than any other turbines in VESTAS portfolio, approximately 2,100 turbines installed all over the world due to their highly efficient operation and flexible configuration. The V52 specifications are shown in table 7. (VESTAS wind systems, 2000).

Table 7 Specifications of VESTAS V52 wind turbine

Rotor diameter	52m
Area swept	2,124 m^2
Number of blades	3
Power regulation	Pitch/OptiSpeed
Air brake	Full blade pitch
Cut-in wind speed	4 m/s
Nominal wind speed	16 m/s
Cut-out wind speed	25 m/s
Nominal output	850 kW

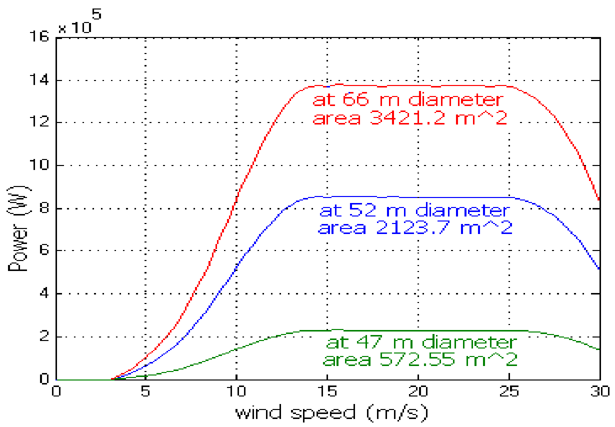


Figure 24 Effect of swept area on the generated power

The results showed that the mechanical power increases when the turbine's swept area increase as shown in Figure 24. The temperature and the air density impact on the generated power are shown in Fig 25. It can be seen from figure 25, that the ambient temperature in the site has a direct effect on the wind power, as the temperature increases the power decreases, this is due to a decrease in the density of air, which affect the air flow movements.

The power variation with the wind speed and power coefficient is shown in Figure 26. Turbine power increases as the wind speed increases, putting more momentum on blades by air up to certain range then the power decreases, due to the turbulence effect of air around blades at high wind speeds, which creates stall on blades. The power coefficient follow same trend as total power but high values occur at lower wind speeds.

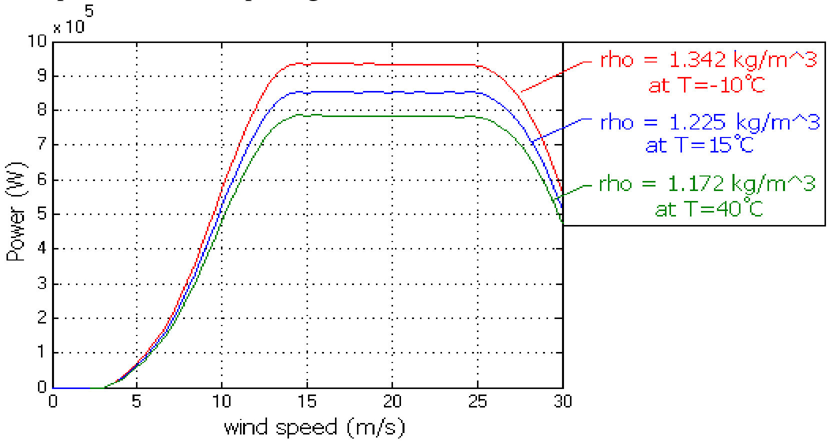


Figure 25 Effect of air density-temperature on the generated power

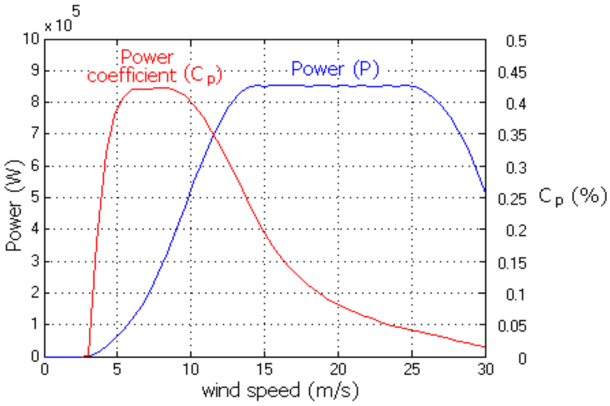


Figure 26 Generated power as a function of the power coefficient

3.1. RESULTS AND DISCUSSION

Wind turbines should be optimized, by taking swept area into consideration, in terms of the local area conditions to capture power as maximum as possible. As can be seen from Figure 24, the output power of a wind turbine is directly related to the wind speed as well as to the swept area of blades. The larger the diameter of its blades, the more power can be extracted from the wind. The power produced by the wind turbine increases from zero at the threshold wind speed (cut in speed) (usually around 5m/s but varies with site) to the maximum at the rated wind speed. Above the rated wind speed, (15 to 25 m/s) the wind turbine continues to produce the same rated power but at lower efficiency until shut down is initiated if the wind speed becomes dangerously high, i.e. above 25 to 30m/s (gale force). The exact specifications for energy capture by the turbine depend on the distribution of wind speed over the year at the individual site. Air density has a significant effect on wind turbine performance (Figure 25). The power available in the wind is directly proportional to air density. As air density increases the available power also increases. Air density is a function of air pressure and temperature. It increases when air pressure increases and the temperature decreases. Both temperature and pressure decrease with increasing elevation. Consequently changes in elevation produce a profound effect on the generated power as a result of the air density change.

4. CONCLUSION

It can be concluded that the advantages of the fuzzy logic methodology for evaluating different sites in Jordan presented in this study enabled us to condense large amount of data into smaller set of variable rules. Based on the results of fuzzy logic methodology, Al-Harir site has the greatest wind potential and the best wind power generation output, and it should be given the highest priorities in terms of installing the maximum number of wind turbines. Different wind turbine types have been proposed to meet the target demand and to find out the best turbine suited to the highly preferred site for future erection of wind farms. In conclusion, many factors have to be considered during manufacturing or installation of wind turbines, i.e., (turbine swept area, air density, wind speed, and power coefficient as a function of pitch angle and blade tip speed).

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