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Wind characteristics and wind power potential of the Indian summer monsoon

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सार –1969–73 तक की अवधि के घंटे-घंटे से लिए गए पवन के आंकड़ों का उपयोग करके सौराष्ट्र-कच्छ, गुजरात एवं प्रायद्ववीपीय भारत पर मानसून (जून-सितम्बर) के अभिलक्षणों को ज्ञात किया गया है। सौराष्ट्र-कच्छ, गुजरात और कोंकण से सटे तट, प्रायद्वीपीय भारत के दक्षिणी क्षेत्र एवं डक्कन पठार के कुछ स्टेशनों पर पवनें प्रवल रही। अन्तर्देशीय स्टेशनों पर पवन सुस्पष्ट दैनिक विचरणों को अनुभव किया गया है। शक्ति की गणनाओं से सौराष्ट्र-कच्छ और उसके साथ सटी तटीय पट्टी, प्रायद्वीप के दक्षिण भाग तथा डक्कन पठार के कुछ स्टेशनों पर पवन काफी मात्रा में शक्तिशाली रही। विशेषतया, कच्छ के उपर और उसके इर्दगिर्द पवन में उच्च शक्ति विभव रहा। आवश्यक नहीं है कि खराब मानसून वाले वर्ष में सौराष्ट्र-कच्छ एवं गुजरात पर पवन की शक्ति अच्छे मानसून वाले वर्ष की अपेक्षातया कम हो। मानसून की उपलब्ध पवन शक्ति को अच्छी तरह बनाई गई पवन चक्की से फसलों की आवश्यक सिंचाई, कुओं से पानी निकालने तथा देहाती क्षेत्रों में मक्का को मसलने के काम में लाया जा सकता है।

ABSTRACT. Utilising the hourly wind data for the period 1969-73, characteristics of the monsoon (June-September) wind over Saurashtra-Kutch, Gujarat and penisular India have been brought out. The wind regime over Saurashtra-Kutch, adjoining coasts of Gujarat and of Konkan, southern parts of the peninsular India and at some stations in Deccan plateau is strong. Marked diurnal variation in wind is experienced at inland stations. Power computations show that a good amount of power exists in the wind over Saurashtra-Kutch and the adjoining coastal belts in southern part of the peninsula and at a few stations in the Deccan plateau. In particular, over and around the Gulf of Kutch, the wind has a high power potential. Wind power over Saurashtra-Kutch and Gujarat in a bad monsoon year need not be less than that during a good monsoon year. The available monsoon wind power can be used through a suitably devised windmill for irrigation that may be required by the crops and for drawing water from wells and grinding corn in rural areas.

1. Introduction

Wind has been used for centuries as a source of power for sailing across the Oceans. In particular, the steady and the strong monsoon winds have been exploited by the sailors for crossing the Arabian Sea during their journeys from Africa to India. Before the steam engine was invented in the 18th century, energy of stream and wind were the only natural sources of mechanical power. With the advent of steam power, the use of sail ships was discontinued.

Windmills were being used in several countries for drawing water, grinding corn, etc, almost still the end of the last century. Thereafter, they gradually fell into disuse since they could not compete with the fossile fuels in the matter of cost of energy. Power produced by fossil fuels was very much cheaper and had the advantage that it could be continuously used to meet the requirements.

About 2 per cent of the solar radiation falling on the earth is converted into wind energy. It is estimated by Simon (1951) that if even a small fraction of this wind energy could be captured into usable form, it would be equivalent to that annually produced by burning 1500 million tons of coal, *i.e.*, about fifteen times the coal mined in India in 1978-79.

Some experiments on utilisation of wind power through a windmill were conducted in Madras during 1902 by Chatterton (1902), Professor of Engineering. He mounted an American Windmill (5m diameter) at Madras on 21 m tower, attached a pump to the mill and raised water to a height of 7.5m. According to him a steady breeze of 10 kmph would keep the windmill in continuous operation. By comparing the average wind at Madras with that at 28 stations evenly distributed over India, he came to the conclusion that there was a wide field in India for profitable utilisation of windmills for irrigation.

Iyer (1936) has given the mean monthly and annual mean hourly wind velocities at different observatories in India and neighbouring countries, percentage frequencies for different speed ranges and percentage frequency of days with different total durations of wind exceeding 10 kmph for selected observatories.

Sil (1952) has reported the findings on the experimental operation of a windmill (2.5m in diameter, 16 sails, exposed at 11m a.g.) by the Meteorological Office, Poona, from May 1940 to April 1944. The windmill, its tower for installation and the pump were obtained from Climax Windmill Co. of England. The windmill was connected to a pump which was employed for drawing water from a reservoir at the ground through a height of 5.8 m. A flowmeter was placed in the delivery pipe of the pump with the purpose of obtaining a continuous graphical record of the pump output against time. The flowmeter was made in the workshop at Poona. The idle time of the windmill during the year was 40 to 50 per cent, being 5-12 per cent only during the months June to August. From the anemograph records periods of fairly steady winds were selected and from the flowmeter records the values of output corresponding to these periods were obtained. With these data, the curve giving relationship between wind speed and power output was obtained. Power output at a speed of 10 miles per hour was obtained from this curve. Maximum theoretically derivable power from the 10 miles per hour wind was obtained by using the formula $\frac{8}{27}\ \rho A V^3$ $\left(\frac{16}{27} \times \frac{1}{2} \rho A V^3\right)$, where ρ is air density and A is the cross-section area and V is the wind velocity. The ratio of the two was obtained as 0.17. Since the maximum theoretically derivable energy from the wind is 59 per cent, the power output when expressed as a fraction of the wind power would be $0.17 \times 0.59 \approx 0.1$. Thus the windmill converts 10 per cent of the wind energy into work.

Bhatia (1952) computed the energy of winds in different months of the year at 20 selected and evenly distributed observatories over India and brought out that the windmill has great potentialities in Rajasthan and the coastal regions of India, particularly during the summer monsoon season.

Venkiteswaran (1952) has given the mean daily frequencies of hours with winds of speed 16 kmph and more for the different months on the basis of available anemograph data for 31 observatories. These bring out a high frequency of such winds during the monsoon months at stations in the western part of India.

Ramdas and Ramakrishnan (1956) have tabulated for 16 pilot balloon stations, mean number of hours per day with wind speed exceeding 8, 16 and 24 kmph at surface and at 0.1 and 0.2 km height, as well as the maximum gust speed in each of the months. In addition, they have given for New Delhi, Allahabad, Jodhpur and Pune the mean number of hours per day with wind exceeding specified speed limits. They have given a brief survey of the potentialities of the wind energy in India and have stressed the need for more anemographs recording at as high levels as may be practicable, at a network of stations.

Nilkantan (1956) has drawn attention to the two broad aspects of the problem of wind utilisation in India. The first one concerns with the development of wind power resources for lift irrigation, and for domestic and for small scale community purposes in areas of favourable wind velocities. This involves a careful examination of the wind records of the country and selection of areas with wind speeds sufficiently high for economic operation of the small and medium-sized windmills. The second aspect relates to the selection of the most favourable sites for location of high capacity wind generators. For this purpose, the surveys have to be confined to selection of specific points at hill-tops or other elevated places. The paper is concerned with the first aspect and stresses on the topographical features and geographical factors of peninsular India which have an important bearing on the distribution and characteristics of the surface wind.

Ramiah (1956) has reviewed the windmill trials in the different parts of India. From the experimental data on performance provided by these trials he has concluded that (*i*) favourable wind does not coincide with high demand for crop irrigation in Pune, Meerut, Coimbatore, Madras and Bangalore, (*ii*) wind power can be used better for lifting water to storage tanks at ground level, (*iii*) in no place and during no season a windmill can fully supplement natural rainfall to fulfil irrigation needs. According to him wind power can be utilised in India for lifting water for irrigation, for generating electric power on a small scale and for grinding corn. He has suggested that while selecting wind sites, we should keep in view (*a*) the availability and amount of wind power during a season *vis-a-vis* the demand for irrigation, (*b*) the amount of benefit in terms of crop production likely to result from irrigation through water lifted by windmill and (*c*) crops with high water requirements should not be irrigated by water lifted by windmills. He has mentioned that it would be beneficial to use wind power as complementary to bullock power in rural areas.

The development of a windmill suitable for pumping water for irrigation has been actively pursued in the National Aeronautical Laboratory, Bangalore, over the last two decades. Venkiteswaran (1962) has described water-pumping windmill WP-2 (4.8 m diameter) developed at this Laboratory. As mentioned by Tewari *et al.* (1979), the capacity of WP-2 windmill was limited, being smaller than even the bullock-powered water lifts and the estimated cost of this windmill is Rs. 10,000-15,000. During the period 1975-77, work was done on the development of vertical axis wind turbine (Shankar, 1979). Later, in 1977, the same Laboratory developed a horizontal axis sail windmill (10 m diameter) having lower cost and having higher capacity than the earlier windmill, and it is coupled with a pump which allows the windmill to function with speeds as low as 6 kmph (Tewari *et al.* 1979, Tewari 1978). The estimated cost of the materials and the parts of this NAL 10 m diameter windmill and pump is Rs. 7,000 excluding the cost of machining and fabrication charges. The rate of pumping water is 6,000 - 11,000 litres per hour over a head of 6.85 metres in wind speeds of 10 - 16 kmph and the maximum efficiency of 11 per cent is found in the wind speed range of 7 - 12 kmph.

The Journal, *Agricultural Situation in India* (1979) mentions of a project undertaken by the National Aeronautical Laboratory, Bangalore on development and field trial of 10 m sail windmill to be used for pumping water in small farms. Ten such windmills will be fabricated and installed in selected spots in the country in collaboration with the Centre for Science in Villages, Wardha, which will assist in identifying suitable locations and will arrange to obtain the necessary feedback.

Govinda Raju and Narsimha (1979) have given the details of a low-cost water pumping windmill designed and fabricated at the Indian Institute of Science, Bangalore. It uses a sail type Savonius rotor rotating around a vertical axis and this windmill can be built mostly with materials and skills available in rural areas. The first prototype was constructed and installed at the Indian Institute of Science, Bangalore and the second prototype was constructed and installed at a village about 100 km from Bangalore, in 1977. On the basis of the performance of these two prototyes, they have shown that a reasonable amount of power could be extracted from the wind for pumping water for domestic use at a first cost substantially lower than that of other designs. The rate of pumping of this IISc windmill is 800 litres of water per hour at wind speed of 10 km per hour, and 1500 litres per hour at wind speed of 15 kmph at net head of water at 6m. The best efficiency of the system is about 12 per cent at wind speed of 10 kmph. The estimated cost of the system, *viz*, the windmill and the pump, (including material and labour) is Rs. 3000. It is, however, believed that this windmill, if built by the villagers, may cost around Rs. 2000 since both the material and labour would cost less.

Shrinivasa, Narasimha and Govinda Raju (1979) have examined the prospects for utilisation of wind energy in Karnataka State. Taking into account the wind data of 22 stations in the State, they consider it highly worthwhile to take up a coordinated programme covering detailed wind surveys in the northern maidan and the Western Ghats area of the State, development of suitable designs of windmills and exploring their application in agricultural and other fields.

On a careful examination of the average monthly mean hourly wind velocity for about 180 observatories of pre-partition India provided by Iyer (1936) it is observed that wind speeds over most parts of India are generally 4-10 kmph during the year except during the summer monsoon season when speeds in the range of 15 to 20 kmph are experienced in the western half of the peninsula, Saurashtra, Kutch and south Orissa coast. Since the wind power is proportional to the cube of the wind velocity, energy content of the monsoon wind is 5 – 10 times of that of the wind in other seasons. Though the energy content of the wind is low in other seasons, in the monsoon it is substantial in some parts of India. In view of this it is proposed to study the wind characteristics and the wind power potential over these parts of India during the summer monsoon season only.

2. Wind records

Wind records are maintained by the India Meteorological Department. At all the metorological observatories in India wind is measured by a cup anemometer at specific observation times. In addition, mean hourly wind for the day is calculated from the total run of the wind during the 24-hour period, and from this the mean hourly wind for each month is obtained. The normals based on data for 0800 IST for the 30-year period 1931-60 for all the observatories in India have been published by India Met. Dep. (1966) for each month and for the year. In addition, the India Meteorological Department maintains self-recording wind instruments (Dines' Pressure Tube Anemographs) at some of the observatories and tabulations of mean wind for each hour of each day are available at the Meteorological Office, Pune. The names of the stations with Dines' Pressure Tube Anemograph selected for this study are given in Table 1, along with their geographical coordinates, their altitudes, the heights above ground of their anemograph masts and the years for which data are available. The hourly wind data on punched cards were obtained from the Meteorological Office, Pune for the monsoon months, June to September, for the period 1969-1973.

3. Wind characteristics

3.1. *Duration of low wind speed regimes*

To estimate whether the wind regime at a particular location can be useful for the purpose

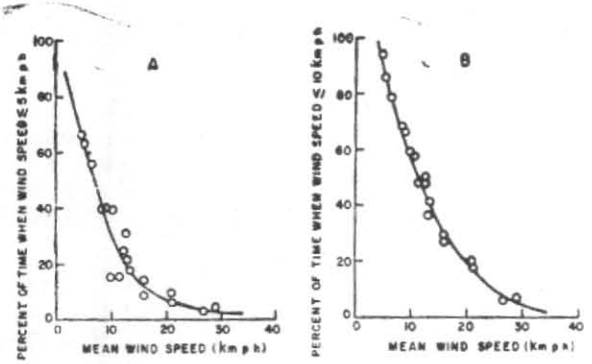

Fig. 1. Percentage of time when hourly wind speed during the monsoon is < 5 kmph (portion A) and ⩽ 10 kmph (portion B) in relation to the mean hourly wind speed during the monsoon season

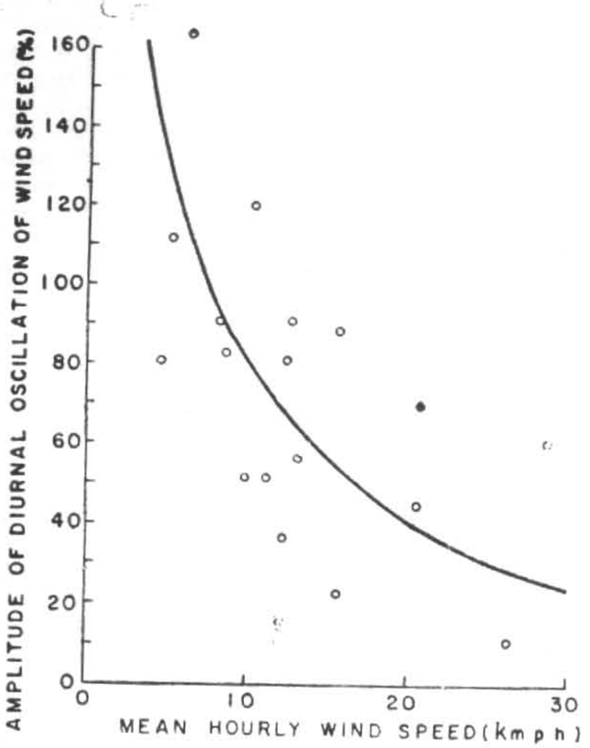

Fig. 2. Relation between the mean amplitude of diurnal oscillation of wind speed (expressed as percentage of mean hourly speed) and mean hourly wind speed during monsoon

of extraction of energy, it is necessary to find out for what percentage of the total time the wind is weak. When wind is weak, it would not be able to drive any energy-extracting machine. Two specific threshold values have been considered for examining the weak wind or low speed regimes. These are 5 and 10 kmph. Table 2 gives the percentage of the time when wind speed is ⩽5 kmph and ⩽10 kmph and the mean hourly wind speed during the monsoon season, at the different stations considered. It is seen from this table that Cochin, Jagdalpur, Mangalore, Nagpur, Raipur and Vishakhapatnam

TABLE 1

List of stations for which self-recording wind data have been used

S. No.	Station	Lat.	Long.	Altitude (m)	Height of anemograph above ground (m)	Years for which wind data are available
1	Ahmedabad	23°04′	72°38′	55	14.8	1969-72
2	Bangalore (Central Obsy)	12°57′	77°38′	897	19.2	1970-73
3	Bhopal	23°17′	77°21′	523	11.7	1969-73
4	Bombay (Colaba)	18°54′	72°49′	11	25.9	1969-73
5	Cochin (Naval Air Station)	09°58′	76°14′	3	15.3	1969-1971
6	Gopalpur	19°16′	84°53′	17	9.7	1969-73
7	Hyderabad (Begumpet)	17°27′	78°28′	545	18.5	1969-73
8	Jagdalpur	19°05′	82°02′	553	14.0	1969-73
9	Mangalore (Penambur)	12°55′	74°53′	102	16.5	1969-73
10	Marmagao	15°25′	73°47′	62	15.0	1969-73
11	New Kandla	23°00′	70°13′	14	33.3	1969-72
12	Nagpur	21°06′	79°03′	310	15.6	1969-73
13	Pune	18°32′	73°51′	559	39.6	1969-73
14	Raipur	21°14′	81°39′	298	15.0	1970-73
15	Tiruchirapalli	10°46′	78°43′	88	23.0	1969-73
16	Tuticorin	08°48′	78°09′	4	9.9	1969-73
17	Veraval	20°54′	70°22′	8	14.9	1969-70; 1972-73
18	Vishakhapatnam	17°43′	83°14′	3	12.2	1969-73

TABLE 2

Percentage of time when wind speed is less than specified levels

S. No.	Station	⩽5 kmph	⩽10 kmph	Mean hourly seasonal wind speed (kmph)
1	Ahmedabad	15.4	47.3	11.3
2	Bangalore	15.0	58.7	9.9
3	Bhopal	17.7	40.8	13.1
4	Bombay	8.7	27.1	15.7
5	Cochin	55.7	77.9	6.3
6	Gopalpur	30.8	50.0	12.5
7	Hyderabad	14.1	29.4	15.7
8	Jagdalpur	63.0	85.6	5.2
9	Mangalore	39.4	67.6	8.3
10	Marmagao	24.5	47.5	12.3
11	New Kandla	4.1	6.6	28.7
12	Nagpur	39.7	66.3	8.6
13	Pune	21.5	36.4	12.8
14	Raipur	65.7	94.2	4.6
15	Tiruchirapalli	9.6	20.1	20.6
16	Tuticorin	6.0	17.3	20.8
17	Veraval	2.3	5.8	26.4
18	Vishakhapatnam	39.1	57.7	10.4

are stations with low wind regime. At these stations, for 40 per cent or more of the time the wind is less than or equal to 5 kmph and for about 60% or more of the time the wind is less than or equal to 10 kmph. Wind regimes at Bombay, Hyderabad, New Kandla, Tiruchirapalli, Tuticorin and Veraval are seen to be promising energy sources; at these stations wind exceeding 10 kmph blows for about 75 per cent of the time or more.

Fig. 1 brings out the relationship between the mean wind speed and the percentage duration of the low wind regimes (speed $\leqslant 5$ and $\leqslant 10$ kmph). This relationship is helpful in the assessment of the duration of wind regimes with speed $\leqslant 5$ and $\leqslant 10$ kmph when hourly wind data are not available for a station but only the mean hourly wind during the monsoon season is available. It is observed from the figure that generally when mean wind speed during monsoon is about 10 kmph and less, more than 55% of the time the wind blows with a speed equal to or less than 10 kmph. Generally, at wind speeds of 10 kmph and less windmill is normally able to extract very little energy from the wind.

3.2. *Mean diurnal variation of the hourly wind*

The wind regime is rarely uniform over the 24 hours of the day. At most of the land stations, well-marked diurnal variation of the surface wind is observed. Table 3 gives the mean hourly wind speed at each hour of the day. The highest mean wind is generally observed around 2 p.m. in the afternoon, and the lowest around 3 a.m. in the early morning. The amplitude of the diurnal oscillation varies from station to station. Fig. 2 shows the variation of the amplitude of the diurnal oscillation with mean hourly wind speed. The mean amplitude during the monsoon is expressed as a percentage of the mean hourly wind during the season. A broad relationship is observed, amplitude falling with increase in mean hourly wind speed. For the stations with low wind regime, the amplitude varies from 70% to 150% of the mean wind, Cochin having the highest amplitude, whereas, for stations with strong wind regime, it varies from 10% to 60% of the mean wind, Veraval having the lowest amplitude. From the point of view of efficient extraction of energy from the wind by windmill a strong wind station with a lower amplitude is more suitable than another strong wind station with a higher amplitude of the diurnal wave in the hourly wind . For example, Veraval with an amplitude of about 10 per cent is more suitable than New Kandla, Tiruchirapalli and Tuticorin with amplitudes of about 35%, 50% and 50% respectively.

On account of lower frictional resistance on sea surface the wind out at sea 5-10 km from the coast, would be stronger than that over the coast and inland. The amplitude of the diurnal wave in the wind over the sea is relatively much smaller than that over inland areas.

It is seen from Table 3 that a mean hourly wind of speed 10 kmph or more prevails at all the 24 hours of the day over Bhopal, Bombay, Hyderabad, Marmagao, New Kandla, Tiruchirapalli, Tuticorin and Veraval.

3.3. *Wind velocity duration curves*

For an accurate estimation of the power contained in the wind it is essential to know the durations of winds exceeding specified values of speeds. From the hourly data from each of the stations, mean durations of winds exceeding the speeds 5,10,15,20,25,30,40,50,60,70,80 and 90 kmph have been obtained, and from these mean durations wind velocity duration curves have beeen constructed for all the selected anemograph stations. These curves have been shown in Fig. 3. It can be clearly seen from this figure that the hourly wind regimes at New Kandla, Veraval, Tiruchirapalli, Tuticorin, Hyderabad and Bombay are promising enough to be exploited as energy sources.

Table 4 gives the mean durations in hours of wind in the speed ranges, 0-5, 6-10, 11-15, 16-20, 21-25, 26-30, 31-40, 41-50, 51-60, 61-70, 71-80 and 81-90 kmph. These are useful in the computaion of the total wind energy at a station. Table 5 gives the percentage duration of wind exceeding $\overline{V}$, $2\overline{V}$ and $3\overline{V}$, where $\overline{V}$ is the mean hourly wind during the monsoon season. The wind at Bangalore, Bombay. Hyderabad, New Kandla, Pune, Tiruchirapalli and Tuticorin exceeds $\overline{V}$ for more than half the season.

Fig. 4 gives the plot of the mean hourly wind and the duration of the most frequent speed during the monsoon for the selected stations. It is seen that as the mean wind speed increases, the duration of the most frequent wind speed decreases. This broad relationship could be used for a general assessment of the duration of the most frequent wind speed from the mean wind speed during the monsoon season. Fig. 5 gives the relationship between the most frequent wind speed and the mean seasonal wind. Thus, from the mean seasonal wind speed we can obtain most frequent wind speed and its duration by using Fig. 5 and 4 respectively.

3.4. *Wind regime under poor monsoon conditions*

The year 1972 had a bad monsoon. About 60 per cent of the country's area had a monsoon rainfall deficiency of 20 per cent or more. The percentage departure of monsoon rainfall from normal was less than — 60% in Madhya Maharashtra — 40 to — 59% over Gujarat, Saurashtra-Kutch and Marathawada sub-divisions and — 20 to — 39 % over Konkan, Coastal Karnataka Telangana, Vidarbha and West MP. In Tamil Nadu, however, monsoon rainfall was 20 to 39% above normal.

TABLE 3

Mean wind speeds (kmph) for different hours of the day during the monsoon season

S. No.	Station	Hours (IST) 01	02	03	04	05	06	07	08	09	10	11	12
1	Ahmedabad	10.7	10.1	9.8	9.3	8.8	8.4	8.7	9.9	11.1	12.2	12.6	12.7
2	Bangalore	9.0	8.9	8.8	8.6	8.4	8.5	8.9	9.9	11.2	12.6	13.2	13.5
3	Bhopal	1.5	11.1	11.3	11.9	11.9	11.9	13.3	16.1	17.1	17.2	17.0	16.5
4	Bombay	15.3	15.4	15.4	15.4	15.5	15.6	15.5	15.5	15.8	15.4	16.0	16.6
5	Cochin	3.0	2.9	2.9	3.2	2.9	2.7	3.2	3.5	4.9	6.5	8.8	10.3
6	Gopalpur	9.5	9.1	8.5	7.9	8.4	8.4	9.3	10.4	11.8	13.5	15.4	16.0
7	Hyderabad	14.4	15.1	15.4	15.2	14.9	14.7	15.2	18.2	20.2	21.3	24.9	20.8
8	Jagdalpur	2.4	2.4	2.5	2.4	2.5	2.4	3.2	4.6	5.8	9.5	7.6	8.1
9	Mangalore	5.7	5.6	5.6	5.6	5.6	5.7	5.7	6.7	7.3	8.6	10.1	11.5
10	Marmagao	11.0	11.0	11.2	11.4	10.7	11.4	11.3	11.1	11.1	11.5	12.6	13.7
11	New Kandla	26.3	25.7	24.7	23.5	22.0	20.5	20.0	22.0	25.3	27.0	29.2	31.6
12	Nagpur	6.1	6.3	6.5	6.5	6.3	6.1	7.9	9.5	11.2	11.8	12.1	12.2
13	Pune	9.3	8.6	8.4	8.5	8.0	7.9	8.1	9.8	12.2	14.3	16.4	17.6
14	Raipur	3.1	3.0	3.1	2.9	2.8	3.0	3.7	4.7	5.5	6.1	6.4	6.5
15	Tiruchirapalli	17.5	17.6	18.0	17.7	17.6	17.1	17.5	21.6	25.3	26.5	26.3	25.8
16	Tuticorin	18.3	17.2	16.6	15.9	15.8	14.9	14.9	17.3	18.7	20.0	22.1	23.9
17	Veraval	26.6	26.7	26.8	26.6	26.1	26.1	25.7	25.6	25.7	26.0	26.1	27.1
18	Vishakhapatnam	5.7	5.8	5.9	6.0	5.8	6.2	7.0	9.7	12.2	13.4	14.2	15.6

TABLE 3 (*contd*)

Mean wind speeds (kmph) for different hours of the day during the monsoon season

S. No.	Station	Hours (IST) 13	14	15	16	17	18	19	20	21	22	23	24
1	Ahmedabad	12.8	12.9	13.0	13.1	13.5	13.1	13.7	14.2	13.7	12.6	11.5	11.2
2	Bangalore	13.4	13.1	13.0	12.8	11.7	10.8	9.5	9.0	8.9	8.8	8.9	8.9
3	Bhopal	16.4	16.0	16.5	15.6	15.3	14.0	12.1	10.2	9.8	9.9	10.1	10.2
4	Bombay	16.1	17.9	18.0	18.4	18.2	17.7	17.1	15.9	15.5	15.2	14.9	15.1
5	Cochin	11.6	12.4	12.9	9.9	10.8	9.2	7.0	5.4	4.7	3.3	3.2	2.6
6	Gopalpur	17.6	17.8	18.0	17.6	17.3	15.7	14.8	13.7	12.1	11.0	10.5	10.3
7	Hyderabad	20.1	19.6	18.8	18.2	16.6	14.3	11.9	11.3	11.0	11.7	12.6	13.7
8	Jagdalpur	8.1	8.2	8.0	7.5	6.6	5.4	4.1	3.2	2.6	2.4	2.5	2.6
9	Mangalore	12.9	12.9	13.0	13.1	12.1	10.6	8.7	8.2	7.5	6.4	6.1	5.8
10	Marmagao	14.6	15.0	14.9	14.8	15.2	15.2	14.3	13.2	12.2	11.8	11.1	10.9
11	New Kandla	33.7	35.4	36.6	37.1	37.4	37.3	35.4	33.1	30.9	29.2	27.8	27.3
12	Nagpur	12.7	12.9	13.0	12.2	11.4	9.7	7.8	6.7	6.2	6.0	6.0	5.9
13	Pune	18.0	18.8	19.1	19.5	18.7	17.4	15.0	12.7	11.5	10.4	9.7	9.6
14	Raipur	6.4	6.3	6.4	6.2	5.6	4.6	3.7	3.3	3.4	3.3	3.1	3.1
15	Tiruchirapalli	25.0	24.1	23.6	23.7	22.5	21.4	21.0	20.5	18.8	17.6	17.4	17.5
16	Tuticorin	26.1	27.6	29.1	29.5	28.8	27.0	24.5	22.3	21.0	20.0	19.1	18.9
17	Veraval	27.7	28.2	28.3	28.2	28.4	27.8	27.8	27.1	26.5	25.8	26.1	26.5
18	Vishakhapatnam	16.8	17.7	17.9	16.8	14.9	12.1	9.3	7.1	6.3	5.7	5.4	5.5

TABLE 4

Mean durations (in hours) for different ranges of surface wind speed during the monsoon season (June-September)

S. No.	Stations	Duration for wind velocity ranges (kmph)											
		0–5	>5 but ≤10	>10 but ≤15	>15 but ≤20	>20 but ≤25	>25 but ≤30	>30 but ≤40	>40 but ≤50	>50 but ≤60	>60 but ≤70	>70 but ≤80	>80 but ≤90
1	Ahmedabad	450.1	933.7	766.8	565.5	117.7	77.5	14.7	1.6	0.6	0		
2	Bangalore	439.7	1278.0	684.4	426.9	74.2	21.3	1.5	0				
3	Bhopal	516.8	676.6	539.0	673.0	273.1	195.4	48.6	5.0	0	0.2	0	
4	Bombay	255.8	537.6	544.8	845.0	376.0	264.2	90.8	9.4	3.6	0.6	0	
5	Cochin	1630.0	650.5	340.5	238.5	37.5	26.0	4.5	0.5	0			
6	Gopalpur	919.6	554.1	357.7	444.1	229.0	271.6	128.5	13.2	3.6	3.6	2.4	0.6
7	Hyderabad	411.9	448.5	497.7	690.4	432.5	307.9	128.3	10.4	0.4	0		
8	Jagdalpur	1845.0	661.8	341.2	71.8	6.8	1.4	0					
9	Mangalore	1154.2	825.7	448.7	364.5	90.7	34.6	7.9	1.5	0			
10	Marmagao	716.0	673.6	495.6	540.4	220.8	174.8	95.0	10.8	1.0	0		
11	New Kandla	119.5	75.0	156.4	319.0	424.9	479.7	869.4	393.9	84.5	4.7	0.2	0
12	Nagpur	1161.6	779.3	466.5	339.0	114.5	52.0	13.7	1.4	0			
13	Pune	628.2	438.0	712.6	671.8	316.4	120.6	34.6	5.8	0			
14	Raipur	1925.0	831.8	154.5	15.0	1.2	0.5	0					
15	Tiruchira-palli	279.8	309.8	404.2	441.8	474.4	405.0	488.0	115.4	9.4	0.2	0	
16	Tuticorin	174.3	330.8	415.1	506.2	495.9	445.6	468.7	87.0	4.2	0.2	0	
17	Veraval	68.5	101.9	228.7	446.9	576.4	555.0	645.7	230.9	45.0	24.8	4.2	0
18	Vishakhapat-nam	1145.0	544.0	363.8	456.8	211.2	151.4	48.6	6.8	0.4	0		

TABLE 5

Mean percentage of the time during which hourly wind exceeded $\bar{V}$, $2\bar{V}$ and $3\bar{V}$, where $\bar{V}$ is mean hourly wind during monsoon season

Station	Percentage of time hourly wind greater than														
	June			July			August			September			Season		
	$\bar{V}$	$2\bar{V}$	$3\bar{V}$	$\bar{V}$	$2\bar{V}$	$3\bar{V}$	$\bar{V}$	$2\bar{V}$	$3\bar{V}$	$\bar{V}$	$2\bar{V}$	$3\bar{V}$	$\bar{V}$	$2\bar{V}$	$3\bar{V}$
Ahmedabad	62.7	11.1	1.1	57.0	5.5	0.1	40.3	2.0	0	35.5	2.1	0.2	48.9	5.1	0.3
Bangalore	57.6	9.6	0.3	76.1	11.6	0.1	61.5	1.7	0	36.1	2.7	0.1	58.0	26.1	0.1
Bhopal	43.4	3.6	0.3	58.9	8.2	0.7	54.1	5.8	0.5	40.8	2.3	0	49.4	5.0	0.4
Bombay	55.3	5.8	0.3	70.7	3.4	0.2	60.7	1.9	0	32.5	3.3	0.6	55.0	3.6	0.2
Cochin	34.6	12.8	3.3	33.2	13.6	3.8	39.2	19.1	5.6	43.8	21.5	5.0	37.7	16.8	4.4
Gopalpur	53.1	21.4	2.0	44.8	14.6	1.6	38.2	9.4	0.5	39.8	12.8	3.3	43.9	14.5	1.8
Hyderabad	56.9	4.6	0.1	72.4	7.4	0.1	58.6	5.8	0.1	26.1	0.2	0	53.7	4.6	0.1
Jagdalpur	40.0	16.0	3.5	48.4	20.5	2.3	33.6	12.3	2.5	25.8	8.9	1.6	37.0	14.5	2.5
Managalore	43.6	17.1	3.1	50.7	17.1	2.9	39.7	7.5	0.7	30.8	5.6	0.3	41.3	11.9	1.7
Marmagao	44.4	8.0	0.6	56.8	35.3	4.0	45.7	5.8	0.3	23.2	1.5	0.1	45.0	12.8	1.2
New Kandla	63.6	3.6	0	70.7	0.3	0	50.2	0.1	0	28.9	0	0	53.5	1.0	0
Nagpur	51.7	16.3	3.3	50.3	18.7	3.9	41.7	10.9	1.7	31.8	4.9	0.3	43.9	12.7	2.3
Pune	61.1	9.8	1.0	62.9	7.3	0.2	58.5	4.2	0	35.4	0.7	0	54.6	5.5	0.3
Raipur	42.3	10.4	2.1	52.3	13.7	1.7	41.4	11.5	2.2	33.2	8.6	1.4	42.3	11.1	1.8
Tiruchirapalli	57.5	4.0	0	64.2	5.2	0	51.8	3.1	0	30.1	1.3	0	51.0	3.4	0
Tuticorin	53.9	2.6	0	61.5	3.7	0	55.8	2.3	0	40.4	2.5	0	53.0	2.8	0
Veraval	46.6	4.0	0	70.8	4.0	0	47.0	0	0	13.5	0.1	0	44.0	2.0	0
Vishakhapatnam	47.8	16.6	1.8	52.3	20.0	3.4	39.2	11.5	0.8	29.8	9.0	1.6	42.3	14.3	1.9

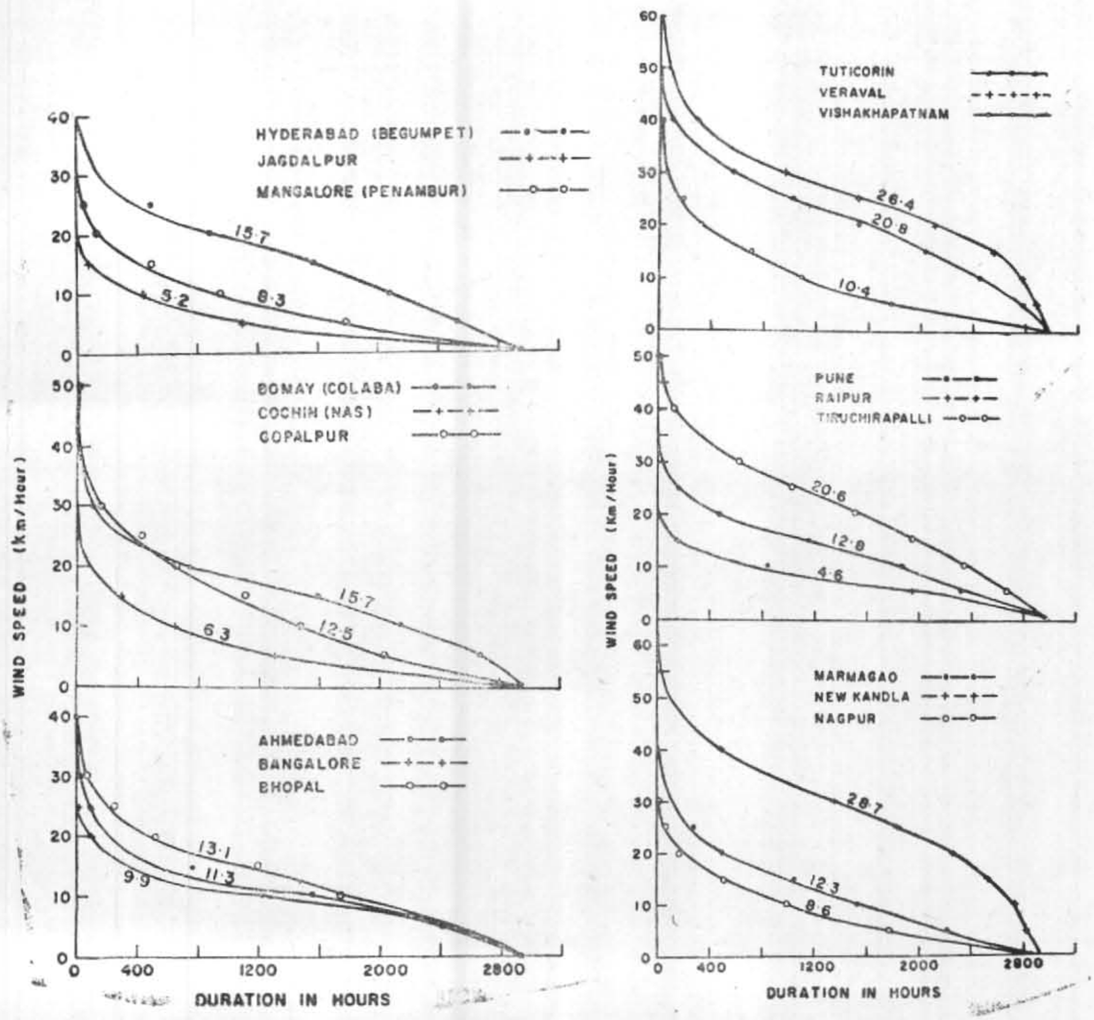

Fig. 3. Wind velocity duration curves. Mean hourly wind speed during monsoon season indicated on curves in kmph

Monsoon was good during the year 1973. Rainfall over practically the whole country was either normal or in excess. In Gujarat and west MP sub-divisions, rainfall was about 40% above normal.

To find out whether the wind regime is weaker in an year of poor performance of the monsoon, we can compare the mean hourly wind averaged over the monsoon season of 1972 with that of 1973 for the observatories from the meteorological sub-divisions which had monsoon rainfall departure of —20% and less during 1972. For these stations, the mean hourly monsoon wind for the good and the bad years is shown in Fig. 6. For two of the stations, Nalliya and New Kandla, wind data for 1973 were not available. For these two stations, the data for good year are for 1970. During 1970, the monsoon rainfall over the whole country was normal or excess and over Saurashtra-Kutch it was about 50% above normal. It is seen from Fig. 6 that only Bhopal, Bombay, Marmagao and Pune show stronger mean monsoon wind during good monsoon. For most of the remaining stations the wind, in general, is slightly stronger during bad monsoon year than during good monsoon year. We can thus see that over Saurashtra-Kutch and Gujarat sub-divisions the monsoon wind need not be weaker during bad monsoon year than during good monsoon year.

4. Variation of wind speed with height

According to Harris (1977), the power law which has traditionally been used by structural engineers proves a good fit to data over the range of heights of 10-200 m above the ground, whereas, the logarithmic law gives the best results over the height range of 0-40m above ground.

Justus and Mikhail (1976) have examined the variation of wind with height. They find that

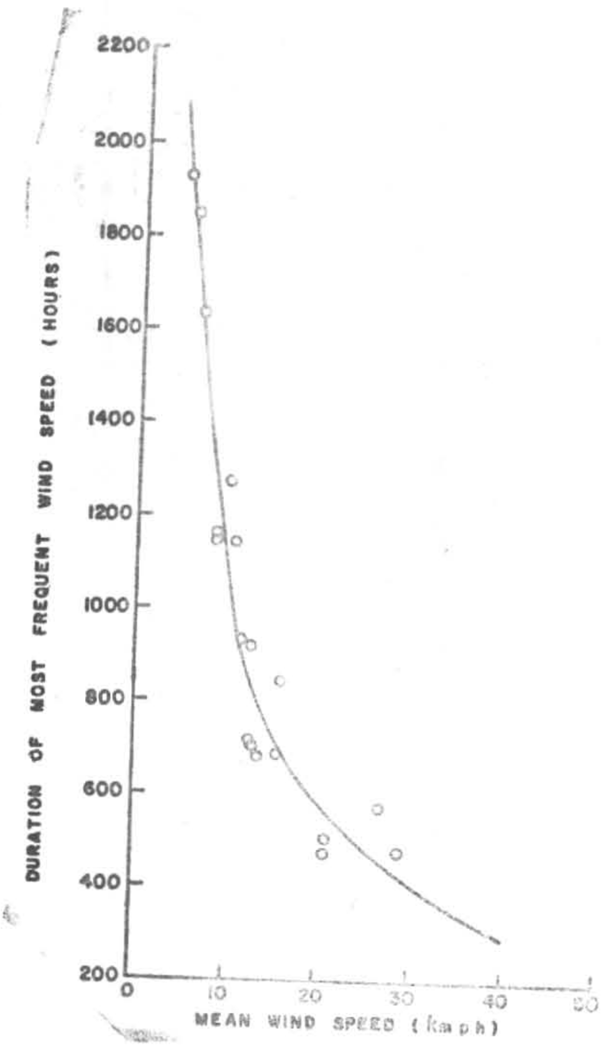

Fig. 4. Relation between the mean hourly wind speed and the duration of most frequent wind speed during the monsoon season

upto 100 m, the observed wind speed is adequately described by the power law,

$$\bar{V}_2 / \bar{V}_1 = (Z_2 / Z_1)^n \qquad (1)$$

where, $n = (0.37 - 0.0881 \ln \bar{V}_1) / [1 - 0.0881 \ln (Z_1 / 10)]$ (1)

$\bar{V}_2$ and $\bar{V}_1$ are mean wind speeds in metres per second at heights Z_2 and Z_1 metres. $\bar{V}_1$ is the mean wind recorded at a station by the instrument at height Z_1. 'ln' denotes natural logarithm.

The agreement of the computed and the observed wind speeds breaks down above 100 m.

We have seen from an analysis of the hourly wind data of stations in Table 1, that Saurashtra & Kutch, west coast of India north of 15°N, and southern part of the peninsula are areas having good amount of wind energy. In view of this, other meteorological observatories from these areas for which only monthly mean hourly wind data were available were also considered and the mean winds for these observatories for the monsoon months of 1969-73 were collected. From these mean monthly wind data, mean monsoon wind speed was obtained for the period, for each of these stations. Utilising the mean monsoon winds of these stations as well as those of the stations in Table 1, the corresponding heights of the wind instruments at the stations and the formula given by Eqn. (1) the mean winds over these stations at 50 m and 100 m above the ground were computed. These computed mean wind speeds at the two heights, *viz,* 50m and 100 m and the value of the exponent n in Eqn. (1) are given in Table 6. The stronger winds at 50 m and 100 m provide a much higher power.

Winds over Saurashtra-Kutch, Gujarat and neighbouring coast are generally strong (exceeding 20 kmph) due to the steep pressure gradient to the south of the seasonal low over Pakistan during the monsoon. Elsewhere, they are strong apparently due to some local terrain peculiarities.

5. Wind power

5.1. *Computation of the wind power*

Wind power is computed by using the relation :

$$P = \tfrac{1}{2} \rho A V^3 \qquad (2)$$

where P is wind power, ρ is air density, A is the area through which wind passes normally and V is the wind velocity. Mooley (1951) has computed the mean surface air density at Indian stations for summer (mean of July and August) and winter (mean of December, January and February). From the density values obtained by him it is seen that the mean surface air density over India during July and August is within 3% of 1100 gm/m³. Using the value of 1100 gm/m³ of surface air density and taking $A = 100$ sq m, we get for the average wind power, the relation,

$$\bar{P} = 0.00117 \, \bar{V}^3 \qquad (3)$$

where V is in kmph, P is in kilowatts and bar denotes the average value.

Utilising Eqn. (3) and the wind durations for different speed ranges given in Table 4, power duration curves were drawn for the stations, Bombay, Hyderabad, Gopalpur, New Kandla, Tiruchirapalli, Tuticorin and Veraval which had a rather strong wind regime. These are shown in Fig.7.

The power duration curves are very useful in assessing the wind power at a station. Over Saurashtra and Kutch, and southern part of India, the energy content of the monsoon wind is quite high.

TABLE 6

Mean hourly wind speed during the monsoon season at different Indian stations at 50 m and 100 m above the ground estimated from the speed-height relationship

S. No.	Station	Value of n	Speed at 50m (kmph)	Speed at 100m (kmph)	S. No.	Station	Value of n	Speed at 50 m (kmph)	Speed at 100 m (kmph)
1	Ahmedabad (AHM)	.279	15.9	19.3	20	Mandvi(MDV)	.195	36.1	41.3
2	Bangalore	.298	13.2	16.2	21	Mangalore	.310	11.7	14.5
3	Bhavnagar (BHV)	.226	26.5	31.0	22	Marmagao	.271	17.1	20.6
4	Bhopal	.260	19.1	22.9	23	Nagpur	.305	12.3	15.2
5	Bhuj (BHJ)	.222	27.6	32.3	24	Nalliya (NLA)	.228	26.1	30.6
6	Bombay (BMB)	.262	18.7	22.4	25	New Kandla (KDL)	.209	31.2	36.1
7	Broach (BRC)	.223	27.3	31.5	26	Okha (OKH)	.200	34.1	39.2
8	Belgaum Aerodrome (Sambre)	.221	27.9	32.5	27	Palayamcottai	.259	19.3	23.0
9	Cochin	.333	9.3	11.8	28	Palghat	.277	16.1	19.5
10	Coimbatore (Pilamedu)	.202	33.7	38.7	29	Pamban	.229	25.9	30.3
11	Dahanu (DHN)	.222	27.6	32.2	30	Porbandar (PRB)	.217	28.8	33.5
12	Dwarka (DWK)	.201	33.8	38.9	31	Pune	.294	13.7	16.8
13	Gadag	.233	24.7	29.0	32	Raipur	.364	7.1	9.1
14	Gopalpur	.260	19.1	22.9	33	Rajkot (RJK)	.202	33.4	38.5
15	Hyderabad	.254	20.2	24.1	34	Surat (SRT)	.281	15.5	18.8
16	Jagdalpur	.348	8.1	10.3	35	Tiruchirapalli	.233	24.7	29.0
17	Kanyakumari	.226	26.5	31.0	36	Tuticorin	.215	29.5	34.2
18	Madurai (Aerodrome)	.238	23.6	27.8	37	Veraval (VVL)	.201	33.7	38.7
19	Mahuva (MHV)	.265	18.2	21.8	38	Vishakhapatnam	.281	15.5	19.8

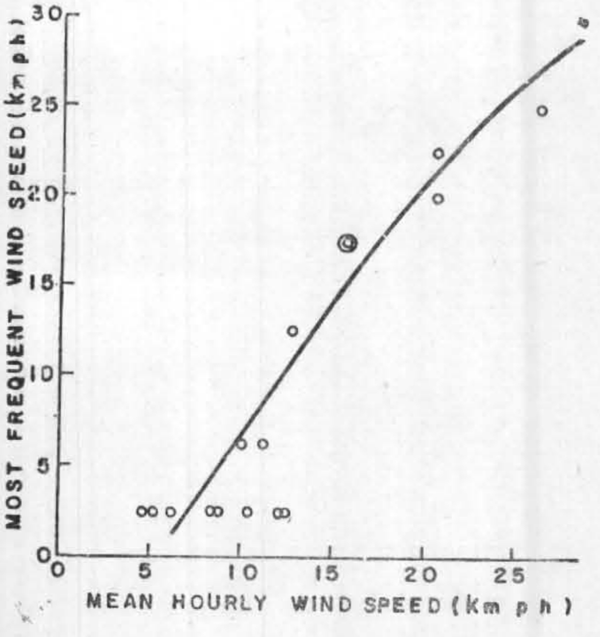

Fig. 5. Relation between the mean hourly wind speed and the most frequent wind speed during the monsoon season

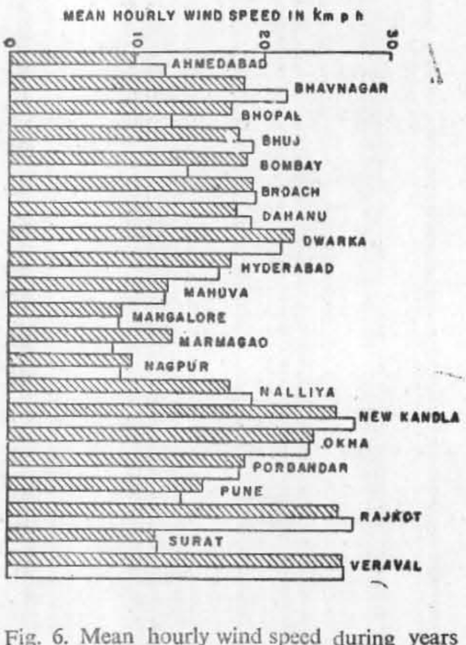

Fig. 6. Mean hourly wind speed during years of good and bad monsoon (Hatched and plain histograms respectively)

TABLE 7

Estimate of the power of the wind at 50 m above ground at different Indian stations during the monsoon season

S. No.	Station	Power (kw per 100 sqm)
1	Ahmedabad	10.8
2	Bangalore	6.0
3	Bhavnagar	37.5
4	Bhopal	16.5
5	Bhuj	41.0
6	Bombay	15.2
7	Broach	40.0
8	Belgaum Aerodrome (Sambre)	42.0
9	Cochin	3.0
10	Coimbatore (Pilamedu)	62.6
11	Dahanu	41.0
12	Dwarka	63.0
13	Gadag	32.0
14	Gopalpur	16.5
15	Hyderabad	19.5
16	Jagdalpur	8.0
17	Kanyakumari	37.5
18	Madurai (Aerodrome)	38.0
19	Mahuva	16.7
20	Mandvi	73.0
21	Mangalore	5.0
22	Marmagao	12.0
23	Nagpur	5.4
24	Nalliya	35.9
25	New Kandla	53.6
26	Okha	64.0
27	Palayamcottai	17.0
28	Palghat	10.1
29	Pamban	35.0
30	Porbander	45.4
31	Pune	7.0
32	Raipur	1.5
33	Rajkot	61.6
34	Surat	9.5
35	Tiruchirapalli	31.5
36	Tuticorin	48.0
37	Veraval	63.0
38	Vishakhapatnam	9.5

5.2. *Estimation of wind power at 50 m above ground*

The mean power of the wind during the monsoon season was obtained by computing the area under power duration curves of Fig. 7, and dividing the area by the number of hours in the monsoon season. The mean power was calculated for each of the stations listed in Table 1, and this was plotted against the mean hourly wind speed during the monsoon. A smooth curve was drawn through these points to obtain the relation between the mean power and the mean hourly wind during the monsoon season. This relationship is shown in Fig.8.

Applying this relationship to the estimated mean wind at the hight of 50 m given in Table. 6, the mean wind power at all these stations at 50 m above ground has been obtained. The same is given in Table 7. It is clear from this table that wind energy potential is high over Kutch, Saurashtra and adjoining coasts of Gujarat and of Maharashtra, south Tamilnadu and northern part of north interior Mysore. Fig. 9 shows the geographical distribution of the monsoon wind power over Saurashtra-Kutch and adjoining parts of Gujarat and of Maharashtra at a height of 50 m above ground. The station abbreviations used in Fig. 9 are given in Table 6 along with the names of the corresponding stations. Apart from the good wind energy potential over Saurashtra and Kutch, the Gulf of Kutch and the surrounding coast, in particular, has a very high wind energy potential. In addition, there may be some very good wind sites over and near the hilly area of Saurashtra and these need to be explored. The average power over Saurashtra and Kutch is about 50 kw per 100 sq meter of rotor area. Thus the average a wind energy over this area during the monsoon season is about 1.46×10^5 kwh. Over south Tamilnadu it averages about 1.20×10^5 kwh during the monsoon season. While making a survey of wind power over an area we need to know how many windmills can be set up over the area so that one windmill does not interfere with another. Basically, we need to know what should be the ratio of windmill area to land area. There are various recommendations for this ratio. One of the values used while prospecting for wind energy is 0.4 per cent, *i.e.*, 40 windmills (each of 100 sqm) per sq km. The area of Saurashtra and Kutch is about 1.1×10^5 sq km. Hence the number of windmills of 100 sq m (rotor diameter about 11.3m) which can be set up over Saurashtra and Kutch is $1.1\times10^5\times40$, *i.e.*, 4.4×10^6. If we consider an efficiency of 0.1 of the windmill then the total energy that can be extracted out of the wind over this meteorological sub-division during every monsoon season would be $0.1\times4.4\times10^6\times1.46\times10^5$, *i.e.*, 6.42×10^{10} kwh which is equivalent to the calorific value of 10^7 tons of coal.

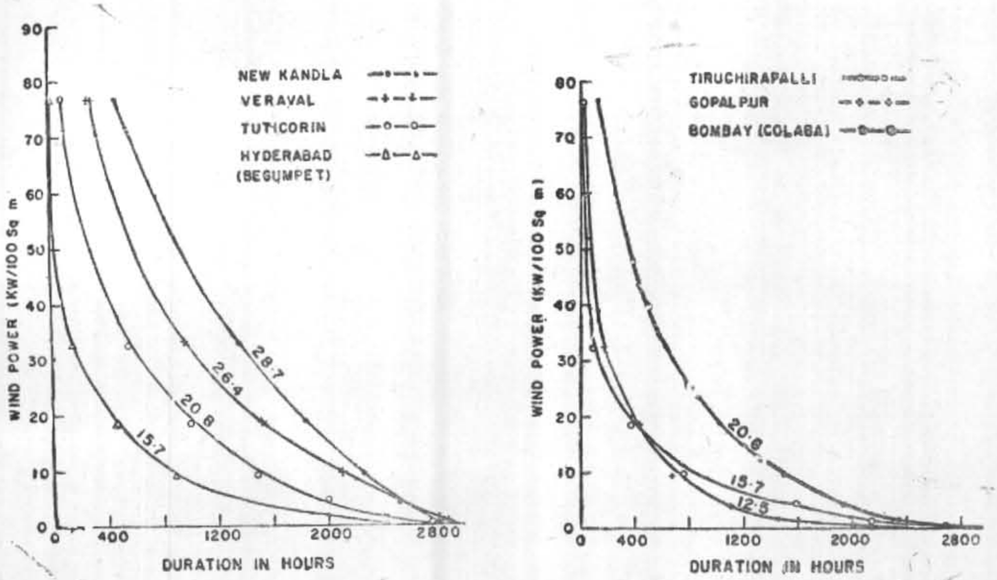

Fig. 7. Wind power duration curves. Mean hourly wind speed during monsoon season indicated on the curves in kmph

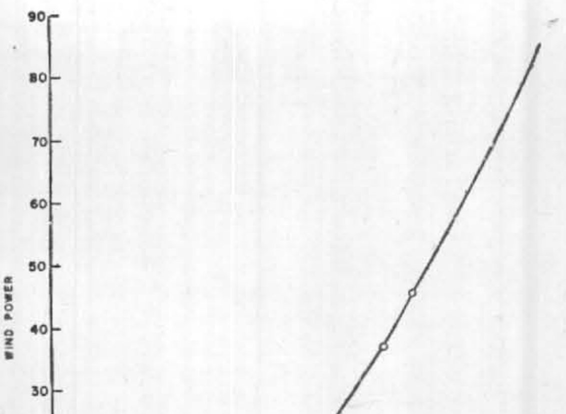

Fig. 8. Relation between mean hourly wind during the monsoon season and the wind power (kw per 100 sq m area through which wind passes normally) during the monsoon season

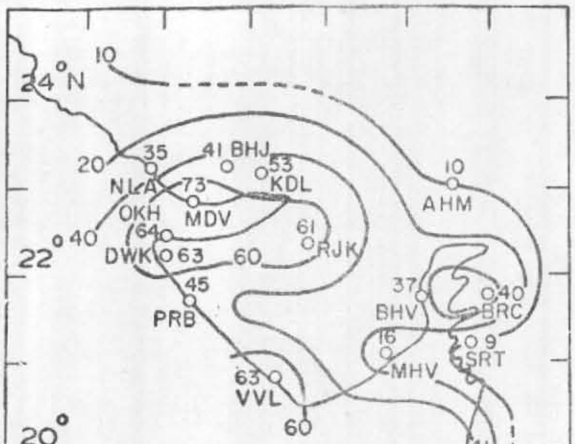

Fig. 9. Distribution of mean wind power during monsoon season (over Saurashtra-Kutch and neighbourhood)

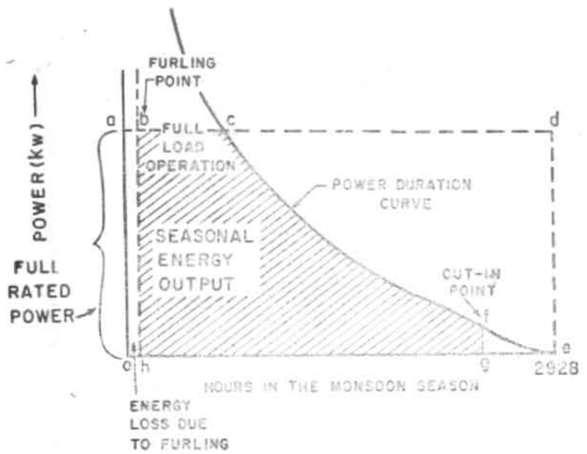

Fig. 10. Estimation of seasonal energy output

TABLE 8

Monsoon wind power (kw per 100 sq m of swept area) in a year of good monsoon and in a year of bad monsoon

S. No.	Station	Power in a good monsoon year	Power in a bad monsoon year
1	Ahmedabad	2.89*	4.51
2	Bhopal	11.97	5.72
3	Bombay	15.72	6.54
4	Hyderabad	13.95	11.47
5	Mangalore	3.25	2.72
6	Marmagao	7.22	2.15
7	Nagpur	3.85	2.86
8	New Kandla	34.85*	39.69
9	Pune	12.12	6.42
10	Veraval	37.71	33.80

Note : The values with astorisk are for the good monsoon year 1970.

TABLE 9

Seasonal Plant Load Factor (SPLF)

(cut-in speed : 10 kmph; furling speed : 60 kmph)

Station	Rate wind speeds (kmph)							
	17.5	20.0	22.5	25.0	27.5	30.0	32.5	35.0
Bombay	0.60	0.51	0.41	0.35	0.29	0.24	0.19	0.16
Hyderabad	0.61	0.53	0.46	0.39	0.32	0.26	0.21	0.18
New Kandla	0.90	0.86	0.82	0.78	0.73	0.68	0.63	0.58
Tiruchirapalli	0.73	0.67	0.61	0.55	0.49	0.43	0.38	0.34
Tuticorin	0.75	0.68	0.62	0.56	0.50	0.44	0.38	0.33
Veraval	0.89	0.84	0.78	0.72	0.66	0.59	0.53	0.48

6. Extraction of power from the wind

6.1. *Power coefficient*

C_p , the power coefficient of a windmill is defined as the ratio of the power P_c that a windmill rotor can extract to the power of the wind, that is $C_p = P_c / (1/2\ \rho\ AV^3)$. By applying the simple momentum theory to the windmill, Betz (1920) arrived at the result that the theoretical upper limit to the power extracted from the wind by a windmill is 59.3% of the power in the wind. Thus C_p cannot exceed 0.593. Later, there were some suggestions to the effect that this upper limit was higher than 59.3%. Rosenbrock (1951), who examined the reasons given for accepting higher upper limit came to the conclusion that the upper limit of 59.3% was justified and that the reasons advanced for the higher upper limit, would lead to a decrease rather than an increase in the value of the upper limit. In view of this controversial position in the matter, further research on this point is necessary. It is believed that 59.3% could be taken as the theoretical upper limit to the extraction of wind energy by a machine till research in the matter established a higher or lower upper limit.

Overall efficiency of a system is defined as the ratio of useful work delivered by the system to the energy of the wind. According to Shrinivasa *et al.* (1979), simple windmills can in prinicple achieve operating efficiency of about 15% if provided with suitable load-matching devices.

6.2. *Specific output*

It is not possible to use the whole range of wind speed for turning a windmill. Each windmill is designed for operation at a certain rated wind speed, a certain cut-in speed, and a certain furling speed. Rated wind speed is the lowest wind speed at which full output is realised; for higher wind speed the output is limited to this full rated value by some controlling mechanism in some propeller type wind electric generators. The cut-in speed is the speed below which the wind is unable to drive the windmill. The furling speed is the speed above which the windmill is not allowed to operate for reasons of safety. Thus only the energy of the wind between the cut-in speed and the furling speed is of concern to the windmills.

Fig. 10 shows a typical power-duration curve. The output is controlled at the full load value for all speeds above the rated wind speed V_R, till we reach the furling speed, V_f. This is possible only in some wind electric generators. This, however, does not apply to wind-pumps. Line *Cb* in Fig. 7 shows the period of operation at full output. Below V_R, the output continues to fall till the cut-in speed is reached when the output is zero. This implies that the energy curve will start at *c* and reach *g*, always remaining

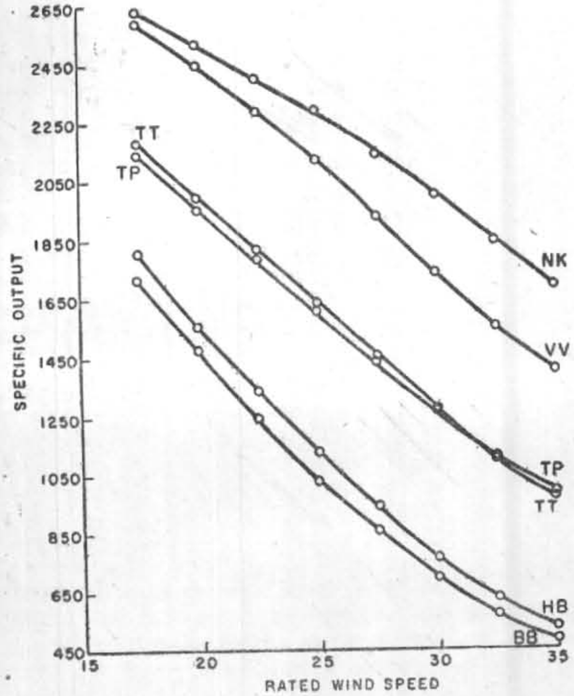

Fig. 11. Specific output (kwh per monsoon season per **kw**) of aero-generator for different rated wind speeds (kmph)
BB-Bombay; HB-Hyderabad; TT-Tuticorin, TP-Tiruchirapalli; NK-New Kandla; VV-Veraval

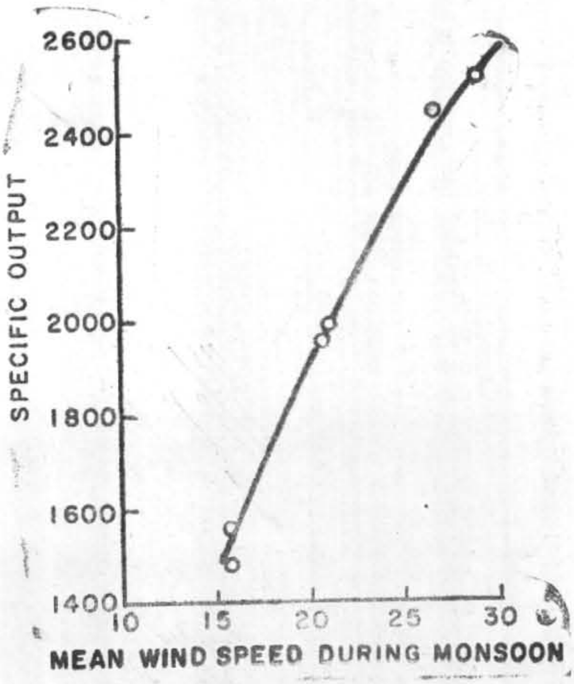

Fig. 12. Relation between specific output (kwph per monsoon season per kw) and mean wind speed (kwph) during monsoon season
Rated speed : 20 kmph ; cut-off speed : **10 kmph**; furling speed : 60 kmph

within the shaded area. Hence SPLF will be an upper bound to the fraction of the wind energy that is available for exploitation. The shaded area *bcfgh* in Fig. 10 represents the seasonal energy output. The area of the rectangle *adeo* would have been the seasonal energy output if the wind had been blowing continuously at speed V_R, for the whole season. The two areas are on the same scale. The seasonal plant load factor, SPLF, is given by

SPLF = Area *b c f g h* / Area *a d e o*

The specific output = 2928 × SPLF

2928 is the number of hours in the monsoon season. SPLF has been computed for different rated wind speeds for the six sites, Bombay, Hyderabad, New Kandla, Tiruchirapalli, Tuticorin and Veraval, which have the mean monsoon hourly wind speed greater than 15 kmph. The cut-in and furling wind speeds have been taken as 10 kmph and 60 kmph respectively. The values of SPLF have been given in Table 9.

The specific power output for these six stations for different rated wind speeds has been shown in Fig. 11. The units are (killowatt hours per season per killowatt (kwh per season per kw).

Specific output for V_R=20 kmph, for V_c =10 kmph and for V_f=60 kmph, is plotted against mean hourly wind speed during monsoon at the six stations, Bombay, Hyderabad, New Kandla, Tiruchirapalli, Tuticorin and Veraval. The smooth curve passing through these points gives the relationship between the specific output and the mean hourly wind speed during the monsoon. This relationship is shown in Fig. 12. Assuming that the wind duration curves could be expressed as one parameter family of curves and utilising the relation in Fig. 12, sepcific output (for V_R = 20 kmph, V_c = 10 kmph, furling speed = 60 kmph and area swept by rotor = 100 m²) has been estimated at 50 m above ground for all the stations for which the mean monsoon wind was more than 15 kmph. This estimated specific output of power is given in Table 10.

For a fixed specific output of 1700 kwh per monsoon season per kw, rotor cross-section of 100 m², V_c, the cut-in speed = 10 kmph, rated wind speeds were obtained for Bombay, Hyderabad, New Kandla, Tiruchirapalli, Tuticorin and Veraval, by using the relationship brought out in Fig. 11. From these rated wind speeds (V_R), the

TABLE 10

Estimated specific power output (kwh per monsoon season per kw) at 50 m above ground

(V_R =20 kmph, V_c =10 kmph; area swept by rotor=100m²)

S. No.	Station	Specific power output
1	Ahmedabad	1525
2	Bhavnagar	2425
3	Bhopal	1850
4	Bhuj	2475
5	Bombay (Colaba)	1810
6	Broach	2460
7	Belgaum Aerodrome (Sambre)	2465
8	Coimbatore (Pilamedu)	2710
9	Dahanu	2480
10	Dwarka	2710
11	Gadag	2310
12	Gopalpur	1850
13	Hyderabad (Begumpet)	1955
14	Kanyakumari	2425
15	Madurai (Aerodrome)	2235
16	Mahuva	1750
17	Mandvi	2775
18	Marmagao	1640
19	Nalliya	2400
20	New Kandla	2625
21	Okha	2720
22	Palayamcottai	1865
23	Palghat	1535
24	Pamban	2385
25	Porbander	2535
26	Rajkot	2660
27	Surat	1460
28	Tiruchirapalli	2310
29	Tuticorin	2560
30	Veraval	2710
31	Vishakhapatnam	1460

TABLE 11

Relation between capacity, rated wind speed and mean monsoon wind speed

(Rotor cross-section 100m², overall power coefficient 0.1, specific output 1700 kwh per monsoon season per kw, cut-in speed=10 kmph, furling speed=60 kmph)

S. No.	Station	Rated capacity (kw)	Rated speed (kmph)	Mean monsoon wind (kmph)
1	Bombay	0.627	17.5	15.7
2	Hyderabad	0.741	18.5	15.7
3	New Kandla	5.013	35.0	28.7
4	Tiruchirapalli	1.519	23.5	20.6
5	Tuticorin	1.617	24.0	20.8
6	Veraval	3.487	31.0	26.4

rated power capacities were calculated by using the formula, $C_p \times (.000117V^3_R)$ for an overall power coefficient (C_p) of 0.1. Table 11 brings out the relation between rated capacity, rated wind speed and mean hourly monsoon wind speed. As the mean wind speed increases, the rated speed and the capacity increase.

7. Risk of storms striking different sectors of the Indian coast

The cyclonic storms pose a risk to wind power installations, particularly located on or near the coast. In these storms a sustained wind in excess of 60 kmph occurs. In severe storms, the speed may reach 90-100 kmph. The wind machines can suffer partial to complete destruction if hit by a cyclonic storm. The associated wind speed, however, rapidly decreases on the storm crossing the coast. If the wind machines are located about 50-100 km inland they are less likely to be damaged. Table 12 gives the probabilities of cyclonic storms striking the different sectors of the Indian coast on the basis of the data for the period 1877-1978.

Iyer (1936) has given a map showing the maximum pressures resulting from gales and strong winds associated with cyclonic storms which prevail for appreciable periods of hours at a time. These maximum pressures are based on the relation, $P = .003V^2_{max}$, between pressure and velocity, V_{max} being the maximum wind speed experienced.

Ramdas and Ramakrishnan (1956) have tabulated for each month the maximum gust speed at 16 stations in India.

The windmill designer is interested to know the maximum windspeed which the rotor and the tower have to withstand. The cost of windmill depends on the maximum speed to which the windmill is likely to be exposed. The probabilities given in Table 12, and the data given by Iyer (1936) and Ramdas and Ramakrishnan (1956) would be useful to the windmill designers.

9. Conclusions

The following conclusions can be drawn from this study:

(*i*) Monsoon wind regime over Saurashtra-Kutch and southern parts of the Peninsula is strong and has a good power potential.

(*ii*) For over 75% of the time, winds exceeding 10 kmph blow over Saurashtra-Kutch, southern parts of the Peninsula, coasts of Konkan and of Gujarat and at some places in Deccan during the monsoon.

(*iii*) The inland stations are characterised by marked diurnal variation of the wind.

(*iv*) Over Saurashtra-Kutch and Gujarat sub-divisions wind during a bad monsoon need not be weaker than that during a good monsoon. Consequently, wind power during bad monsoon need not be less than that during good monsoon,

TABLE 12

Probabilities of cyclonic storms striking different sections of the Indian coast based on data for the period 1877-1978

Coast	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
West coast north 20° N	0.0	0.0	0.0	0.02 (0.02)	0.01 (0.01)	0.03 (0.02)	0.02 (0.0)	0.0	0.01 (0.01)	0.05 (0.01)	0.02 (0.01)	0.0	0.15 (0.08)
West coast between 13° & 20° N	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.01 (0.01)	0.03 (0.01)	0.0	0.04 (0.02)
Kerala coast	0.0	0.0	0.0	0.0	0.02 (0.02)	0.0	0.0	0.0	0.0	0.0	0.01 (0.01)	0.0	0.03 (0.03)
Tamilnadu coast	0.03	0.0	0.02 (0.02)	0.01 (0.0)	0.07 (0.04)	0.0	0.0	0.0	0.0	0.06 (0.01)	0.26 (0.17)	0.12 (0.07)	0.56 (0.30)
Andhra Coast (13.5–19.0°N)	0.01 (0.01)	0.0	0.0	0.01 (0.0)	0.04 (0.01)	0.03 (0.0)	0.0	0.01 (0.0)	0.04 (0.02)	0.24 (0.07)	0.18 (0.10)	0.02 (0.0)	0.57 (0.21)
Orissa Coast (19.0–21.5°N)	0.0	0.0	0.0	0.0	0.04 (0.04)	0.15 (0.01)	0.21 (0.03)	0.20 (0.01)	0.20 (0.06)	0.12 (0.05)	0.07 (0.05)	0.0	0.98 (0.24)
Gangetic West Bengal coast	0.0	0.0	0.0	0.0	0.04 (0.03)	0.12 (0.03)	0.16 (0.04)	0.08 (0.02)	0.13 (0.05)	0.10 (0.05)	0.04 (0.02)	0.0	0.66 (0.24)

Note : The probabilities for severe cyclonic storms are given in parentheses.

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