Proc. Indian Acad. Sci., Vol. C2, Part 4, December, 1979, pp. 521–544. © Printed in India.

# Prospects for wind energy utilisation in Karnataka State

U SHRINIVASA*, R NARASIMHA and S P GOVINDA RAJU
Department of Aeronautical Engineering, Indian Institute of Science,
Bangalore 560 012
*Cell for the Application of Science and Technology to Rural Areas

MS received 4 March 1980

**Abstract.** An examination of the data available at 22 meteorological stations in Karnataka State shows that wind velocities in the State as a whole are neither spectacularly high nor negligibly low. The highest winds (annual mean of around 13 km/hr) are experienced in parts of the northern maidan region of the State (Gulbarga, Raichur and Bidar districts) and in Bangalore. The winds are strongly seasonal: typically, the five monsoon months May–September account for about 80% of the annual wind energy flux. Although the data available are inadequate to make precise estimates, they indicate that the total wind energy potential of the State is about an order of magnitude higher than the current electrical energy consumption.

The possible exploitation of wind energy for applications in rural areas therefore requires serious consideration, but it is argued that to be successful it is essential to formulate an integrated and carefully planned programme. The output of current windpumps needs to be increased; a doubling should be feasible by the design of suitable load-matching devices. The first cost has to be reduced by careful design, by the use of local materials and skills and by employing a labour-intensive technology. A consideration of the agricultural factors in the northern maidan region of the State shows that there is likely to be a strong need for mechanical assistance in supplemental and life-saving irrigation for the dry crops characteristic of the area. A technological target for a windmill that could find applications in this area would be one with a rotor diameter of about 10 m that can lift about 10,000 litres of water per hour in winds of 10 km/hr (2.8 m/s) hourly average speed and costs less than about Rs 10,000. Although no such windmills exist as of today, the authors believe that achievement of this target is feasible. An examination of various possible scenarios for the use of windmills in this area suggests that with a windpump costing about Rs 12,000, a three hectare farm growing two dry crops a year can expect an annual return of about 150% from an initial investment of about Rs 15,000. It is concluded that it should be highly worthwhile to undertake a coordinated programme for wind energy development that will include more detailed wind surveys in the northern maidan area (as well as some others, such as the Western Ghats), the development of suitable windmill designs and a study of their applications to agriculture as well as to other fields.

**Keywords.** Wind energy; Karnataka State; energy resources; economics of windpumps; load matching for windpumps.

## 1. Introduction

The growing energy crisis facing the world has led to a search for new sources of energy, and to a re-examination of some older ones: among the latter is the wind, which has been exploited for thousands of years, beginning with the use of sail to drive boats and ships and (later) of mills to grind corn or lift water. Sometime in the first half of this century it appeared as if the wind as a source of energy had 'finally' declined in importance. The recent revival of interest in its possibilities—due largely to the phenomenal increase in the cost of more conventional sources of energy, and to the realisation that global reserves of fossil fuel are limited—demands a brief look at the chequered history of efforts to exploit the wind.

From the fascinating account given by Derry & Williams (1960), we learn that windmills probably first appeared in West Asia around the 7th century A.D., and were used for irrigation particularly in Persia. They are thought to have reached Europe through Moorish Spain, but somewhere during this migration the axis of rotation changed by 90°—Asian windmills turned round a vertical axis, but European machines have invariably been of the horizontal axis type (till the inventions of Savonius and Darrieus in the 20th century). The famous windmills of Holland, which produced about 10 kW with a 10 m rotor in 30 km/hr (8·3 m/s) winds, helped drain much of the land reclaimed by the Dutch from the sea. Derry & Williams believe that windmills of this type were the prime movers that ushered the industrial revolution. With the advent of steam power windmills lost their importance in Europe, but reappeared in a slightly different version among the vast open spaces of the New World. In 1850, windmills are estimated to have produced about $10^9$ kWh ($3{\cdot}6 \times 10^{15}$J) in the USA (Clark 1977). The new version was the multi-bladed metal type, still familiar in many parts of the world; typically a 4 m rotor of this type delivers about a kilowatt in 30 km/hr (8·3 m/s) winds. By 1880, the 'twenty-five-dollar windmill' had finally become a reality (Bartlett 1974); and the mature industry that developed to manufacture these machines fell into rapid decline only after the 1930s in the US, when President Roosevelt set up a Rural Electrification Administration to provide subsidised electric power to the American farmer (Clark 1977). Even then, Dempster of USA still used to sell 10,000 windmills a year in the 1940s (Merriam 1972); and it is estimated that there were more than 0·6 million windmills operating in the world by the end of the last decade (Shefter 1972).

It has been suggested (Derry & Williams 1960) that the windmill came early to India from West Asia, but we know of no strong supporting evidence. In an India Meteorological Department (IMD) Scientific Note (IMD 1948), there is reference to a paper by Griffith, who in 1895 considered windmills as having no future in India. On the other hand, only a few years later (in 1903) Sir Alfred Chatterton was strongly advocating their use, after trials he conducted in Madras. A systematic attempt to introduce wind machines in India was made by the National Aeronautical Laboratory during the 1950s and 60s (Sen Gupta 1966).

In spite of all these efforts, however, the windmill has never gained a secure foothold in India. This raises two questions. Are there fundamental reasons why wind energy has remained untapped in India? Has the energy crisis now changed the picture substantially?

The answers* to these questions are to be sought in

(i) the nature and magnitude of the available resources;
(ii) the technologies available for their exploitation;
(iii) the economics of exploitation, particularly in relation to competing energy sources (which in India would not only be electricity, coal, oil, etc., but also muscle power, both human and animal).

---

*In handling such large issues sociological questions are undoubtedly relevant, but it is not our purpose to go into them here.

We consider each of these in turn, with particular reference to the possibilities for exploitation of wind energy in Karnataka State. Although the scope of the study is thereby (intentionally) limited, it is expected (for reasons that will become clear as we proceed) that our conclusions may be valid for many other parts of India as well.

The current revival of interest in wind energy may be partly attributed to certain well-known advantages. It is 'free' and renewable; where it is at all feasible to tap it, it is fairly widely distributed, so that power can be generated right where it is needed (of course if wind is used for large scale electric power generation distribution costs would have to be taken into account). The technology for extracting energy from the wind is largely already available, and may even be made accessible to rural areas. Furthermore, the wind is fairly reliable; for example, we calculate from meteorological data for Bangalore that the coefficient of variation of the mean annual wind speed is only 5·7%, whereas the coefficient of variation of rainfall is 23%. Finally, wind energy is pollution-free.

On the other hand, wind energy suffers from the serious disadvantage that its energy density is low (it is 60 $J/m^3$ at 10 m/s; petrol contains $30\times10^9$ $J/m^3$!). One consequence is that large structures are needed to extract reasonable amounts of energy, and the first cost of windmills tends to be high. Finally the wind, even if relatively reliable over a period of about a month, is intermittent over shorter periods.

Any success that may be achieved in utilising wind energy will have to overcome these disadvantages. Clearly, the problems are going to be: how to reduce first cost by ingenious design, how to increase power output for given first cost, and how to store energy efficiently and inexpensively to tide over 'lulls' in the winds. Our attention will be focussed on possible applications of windmills in rural areas, in particular for pumping water, which has often been noted as a key requirement (Reddy & Subramanian 1979).

## 2. Wind energy resources of the State

### 2.1 *Wind data*

The only source of data on winds in the State is the India Meteorological Department; these data comprise (Iyer 1973)

(i) continuous wind speed records at three observatories (two at Bangalore, the third at Mangalore Harbour);
(ii) daily mean speeds, hourly means at 0830 and 1730 hr, and the mean between these two hours, at 22 stations spread over the State;
(iii) additional hourly mean speeds at selected three-hour intervals starting at 0230 hr at five of the 22 stations (Bangalore, Bangalore Airport, Belgaum Airport (Samra), Gadag and Mangalore Airport (Bajpe)).

The stations at which data are available are shown on a map of the State in figure 1. The annual average speeds obtained from these records are listed in table 1.

Unfortunately these stations are often in the centre of towns or cities, where the winds are strongly affected by the local terrain and the surroundings, and may not be

**Table 1.** Yearly mean wind speeds at the meteorological stations in Karnataka

| District | Station | Yearly mean speed km/hr (m/s) | Height of the anemometer (m) | Hours of observation* |
|---|---|---|---|---|
| Met. Sub-Division: *Coastal Mysore* | | | | |
| 1. N. Kanara | Honavar | 5·4 (1·5) | — | b |
| 2. | Karwar | 9.5 (2·6) | 6·9 | b |
| 3. S. Kanara | Bajpe(A) | 7·2 (2·0) | — | g |
| 4. | Mangalore | 8·4 (2·3) | 16·2 | b |
| 5. | Mangalore Harbour | — — | — | h |
| Met.Sub- Division: *Interior Mysore, North* | | | | |
| 6. Belgaum | Samra(A) | 9·7 (2·7) | — | e |
| 7. | Belgaum | 9·3 (2·6) | 12·6 | b |
| 8. Bidar | Bidar | 13·3 (3·7) | 10·8 | b |
| 9. Bijapur | Bijapur | 8·3 (2·3) | 9·6 | b |
| 10. Dharwar | Gadag | 11·4 (3·2) | 9·6 | f |
| 11. Gulbarga | Gulbarga | 13·2 (3·7) | 10·8 | b |
| 12. Raichur | Raichur | 13·0 (3·6) | 12·3 | b |
| Met. Sub-Division: *Interior Mysore, South* | | | | |
| 13. Bangalore | Bangalore(A) | 13·7 (3·8) | — | c, h |
| 14. | Bangalore | 11·5 (3·2) | 16·5 | d, h |
| 15. Bellary | Bellary | 8·4 (2·3) | 9·7 | b |
| 16. Chikmagalur | Balehonnur | 5·0 (1·4) | 5·1 | a |
| 17. Chitradurga | Chitradurga | 9·4 (2·5) | 7·8 | b |
| 18. Coorg | Mercara | 11·0 (3·0) | 5·4 | b |
| 19. Hassan | Hassan | 9·3 (2·6) | 10·2 | b |
| 20. Mysore | Mysore | 10·6 (2·9) | 21·9 | b |
| 21. Shimoga | Shimoga | 5·3 (1·5) | — | b |
| 22. | Agumbe | 4·7 (1·3) | — | a |

**Hours of observation***

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| a | | | 0830 | | | | | |
| b | | | 0830 | | | 1730 | | |
| c | | 0530 | 0830 | 1130 | | 1730 | | 2330 |
| d | 0230 | | 0830 | 1130 | 1430 | 1730 | 2030 | |
| e | | 0530 | 0830 | 1130 | 1430 | 1730 | 2030 | |
| f | | 0530 | 0830 | 1130 | 1430 | 1730 | 2030 | 2330 |
| g | 0230 | 0530 | 0830 | 1130 | 1430 | 1730 | 2030 | 2330 |
| h | Continuous recording using Dines Pitot Tube Anemograph. | | | | | | | |

A: Airport

**Hourly observations are based on 3-minute averages

sufficiently representative of the conditions away from urban areas. Furthermore, the height at which the wind is measured is not the same in all stations as data from IMD (1966) show. The data therefore cannot be used for a strict comparison of one station with another, and as Golding (1962) has pointed out, are only of limited value for wind power studies. More detailed wind surveys that provide continuous records at standard heights are therefore essential. This is in particular necessary for identifying possible sites where large scale wind power exploitation

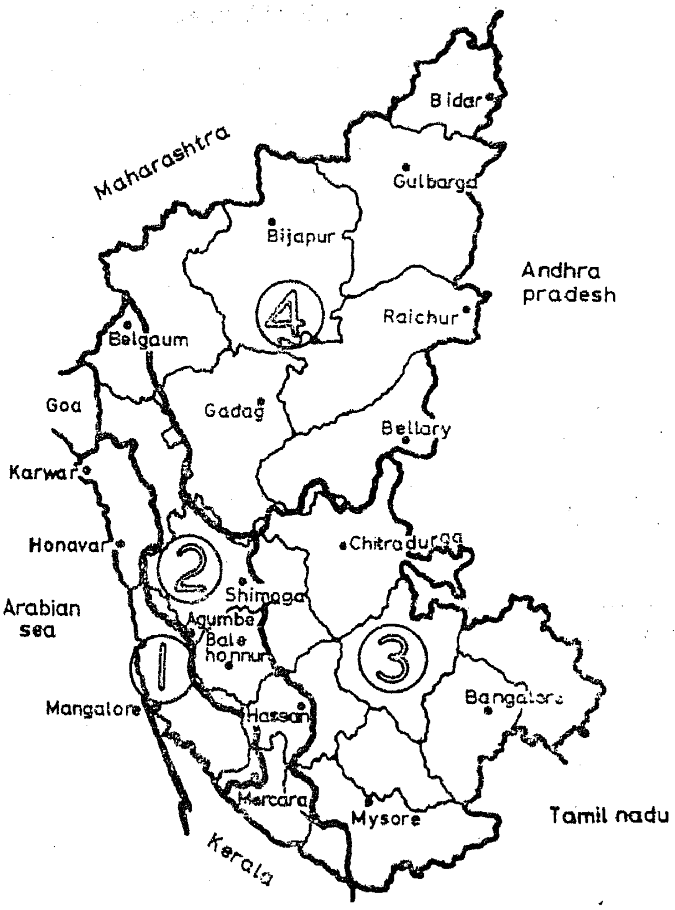

**Figure 1.** Meteorological stations and geographical regions of Karnataka: 1. Coastal plain, 2. Malnad region, 3. Southern maidan, 4. Northern maidan

may be attractive, as it is not unlikely that there will be sites in the hilly areas of the State at which wind speeds are far higher than those listed in table 1. (For example, recent observations at Raichur (1980, unpublished) have shown steady high winds of about 25 km/hr (6·9 m/s) for several hours during night even in February, which is generally a lean month (see § 2.2).)

Nevertheless, the data available do provide a good starting point for a preliminary assessment of the total wind energy potential in the State. That the wind velocities in the State cannot be considered very high or very low is evident from table 2, where data for some regions where windmills have at some time been in widespread use are shown.

## 2.2 *Seasonal and geographical patterns*

The State is normally divided into four geographically distinct regions (Learmonth & Bhat 1961): the coast, Malnad (=‘hill country’), and the northern and southern maidans (=plains); these regions are also shown in figure 1.

The monthly mean wind speeds at the stations listed in table 1 are plotted in figures 2a and 2b. The graphs for various stations seem to fall into three clusters as follows.

Mangalore, Honavar and Shimoga record generally very low wind speeds. Ac-

**Table 2.** Comparison of wind speeds of different regions

| Country (and location) | Annual mean wind speed km/hr (m/s) | Height of the anemometer (m) |
|---|---|---|
| 1. Netherlands | 19 to 32 (5·3 to 8·9) | Not known but is likely to be 10 m from the ground |
| 2. Denmark | 22 to 31 (6·1 to 8·6) | |
| 3. United Kingdom | 16 to 42 (4·4 to 11·7) | |
| 4. Southern Germany | 16 (4·4) | |
| 5. France | 13 to 25 (3·6 to 6·9) | |
| 6. India | | |
| 6.1 Sagar Islands (West Bengal) | 19 (5·3) | 15·6 |
| 6.2 Puri (Orissa) | 18 (5) | 8·7 |
| 6.3 Rajkot (Gujarat) | 18 (5) | 9·3 |
| 6.4 Bangalore Airport (Karnataka) | 14 (3·9) | — |
| 6.5 Bangalore (Karnataka) | 12 (3·3) | 16·5 |
| 6.6 Balehonnur (Karnataka) | 4 (1·1) | 5·1 |

Sources: Tewari and Srinath (1975) and Anon (1966).

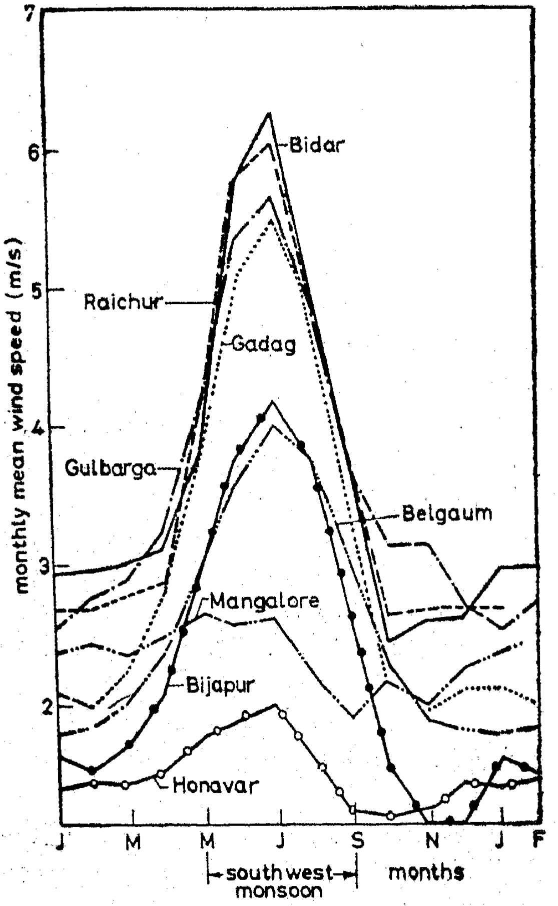

**Figure 2a.** Variation of monthly mean wind speed.

cording to IMD (1965), Karwar and Balehonnur also have similar winds. These stations are in the coastal and Malnad regions of Karnataka (figure 1).

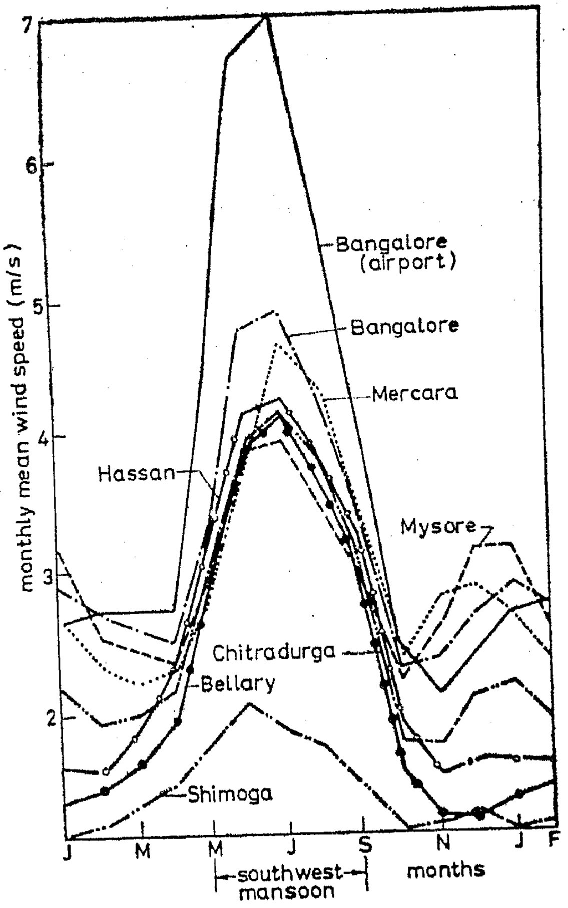

**Figure 2b.** Variation of monthly mean wind speed.

The second cluster consists of stations at Bidar, Gulbarga, Raichur, Gadag and Bangalore Airport. These record wind speeds of about 20 km/hr (5·6 m/s) during the south-west monsoon. Except Bangalore Airport, these stations are located on the northern maidan.

The rest of the stations seem to experience winds of about 15 km/hr (4·2 m/s) during the south-west monsoon.

There seems to be very little wind (monthly mean of about 10 km/hr (2·8 m/s) or less) after September, though some stations (mostly those to the east) record a slight increase in the wind speeds during December, probably due to the north-east monsoon.

Thus, for windmill applications it would appear that the winds may be considered reasonably good during the south-west monsoon in the northern maidan and in Bangalore and nearby areas. They are likely to be mostly poor on the coastal plain and in the Malnad region. Elsewhere in the State wind speeds are not good, but may be useful under certain conditions.

It is necessary to stress here that the geographical patterns arrived at are based on the data from only 22 stations in the entire State. Therefore the existence of specially windy sites at least in some parts of the State cannot be ruled out, but separate surveys will be necessary to identify them. In any case, it will be assumed for the purpose of this paper that the annual mean wind speeds measured at the meteorological stations are valid for the entire district in which each station is located. For

Tumkur and Kolar* and also for the district of Bangalore itself, the wind speeds at Bangalore Airport will be used. For Mandya the wind speed at Mysore will be used.

### 2.3. *The energy content of the wind*

A wind stream of speed $V$ has an energy flux of $\frac{1}{2}\rho V^3$, which at normal temperture (30°C) amounts to about $0{\cdot}013V^3$ W/m$^2$ if $V$ is in km/hr (and $0{\cdot}6V^3$ W/m$^2$ if $V$ is in m/s). However, the total energy in a fluctuating wind is often considerably higher than the energy estimated by this formula if $V$ is taken as the mean wind speed; the reason is that the energy content at higher wind speeds is disproportionately more than at lower speeds. The energy in the mean wind has therefore to be multiplied by a so-called energy pattern factor (EPF) to obtain the total energy content. The value of this factor at different places listed in table 1 is not known in general; but for Bangalore and Belgaum, on the basis of *hourly* mean wind speeds, Golding (Ramakrishnan & Venkiteshwaran 1961) has obtained a value of 3·4 to be used with the *annual* means. (Golding actually quotes a value of 2 for the EPF,

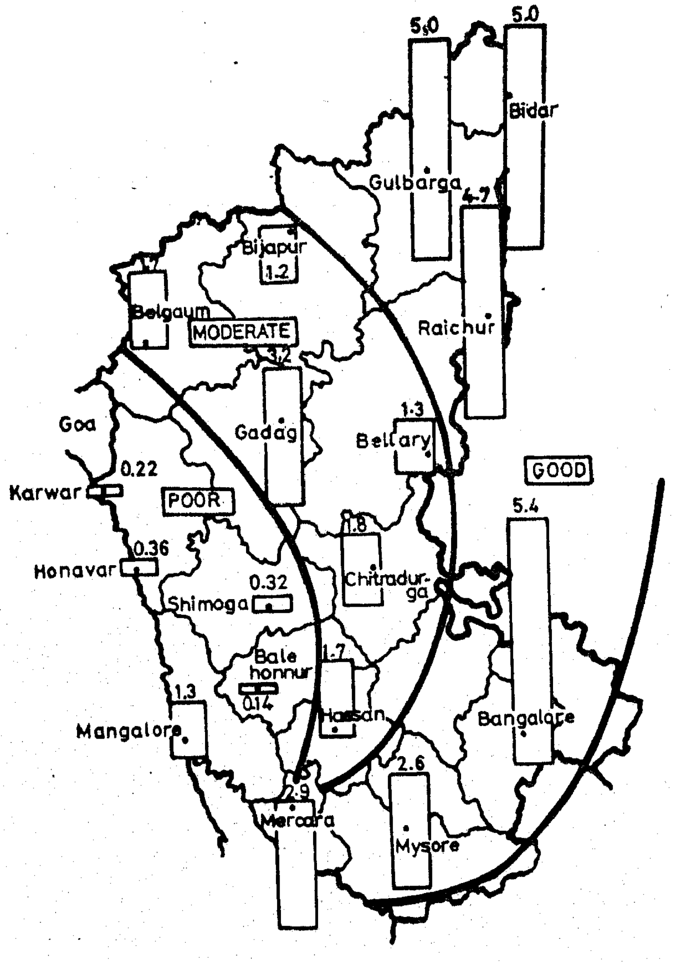

**Figure 3a.** Annual wind energy flux. Maximum monthly mean wind speed km/hr (m/s)—poor 0(0) to 10(2·8); moderate 10(2·8) to 15(4·2); good 15(4·2) and above.

---

*No data are available for Tumkur and Kolar; the present conjecture for these districts is based on geographical proximity to Bangalore and the general similarity in vegetation cover and rainfall patterns.

but this takes into account the Betz value of the limiting efficiency (~59%). The value quoted here is merely 2/0·59.) Using this value and the results from certain preliminary measurements at the Indian Institute of Science campus (Rajagopalan 1978), the *annual* energy pattern factor, including variations on the scale of seconds, is estimated by us to be roughly 5·5 (Shrinivasa *et al* 1978). (Note that this value of EPF is appreciably higher than in more temperate climates, where the atmosphere is less gusty than in a tropical country like India.) Assuming this factor to be valid at other stations also, an estimate of the total wind energy flux at each of the 22 stations in table 1 has also been made and is presented in figures 3a and 3b. It can be seen from figure 3b that at most of the stations nearly 80% of the annual wind energy flux is concentrated in the southwest monsoon period of May to September.

### 2.4. *Permissible windmill area*

If there are a large number of windmills in a given area there will be a reduction in the power generated by most of them due to wake interference. Rangi *et al* (1974) state that '. . . theoretical calculations of the retarding effect of the windmills on the earth's wind layer indicate that if their spacing is closer than 30 diameters, there is a fairly sharp reduction in the power available from each windmill . . .'. This spacing of 30 diameters when expressed as a ratio of total windmill area to the ground area turns out to be about 0·1% and was used by them to map the wind power potential of Canada.

Assuming a 10% loss in power due to interference as above, Newman (1977) also arrives at a figure of 0·1% for the area density.

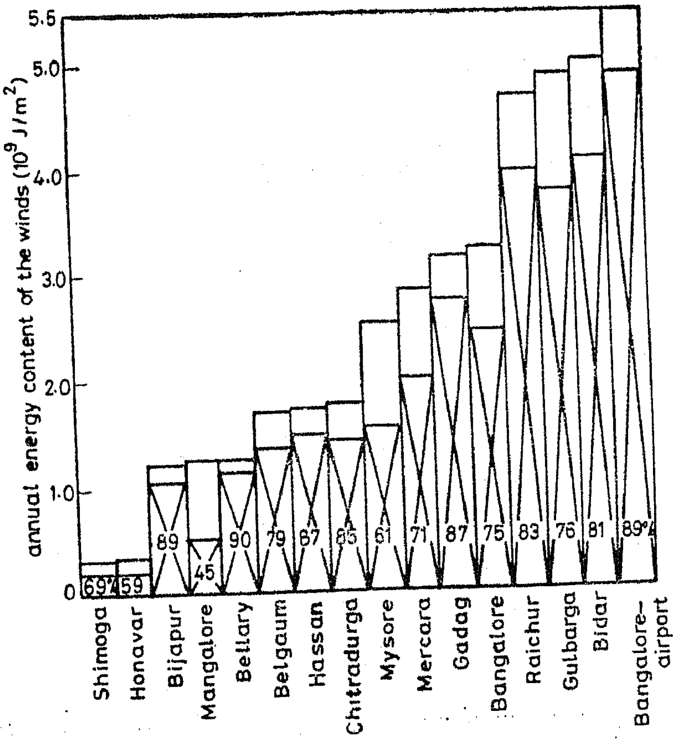

**Figure 3b.** Annual wind energy flux: the cross hatching indicates the portion available during the southwest monsoon (May to September).

Experiments using a wire gauze in a wind tunnel (Pelser 1975) suggest that an area density of 0·17% corresponds to a power loss of 10 to 15%.

From the studies of Musgrove (1976), Coty and Dubey (1976), Ljungstrom (1977), and Railly (1977), Ryle (1977) concludes that 'the vertical mixing of air allows one to site wind turbines so that their swept area corresponds to between 0·15 to 1·5% of the ground area'. He uses a value of 0·4% for the United Kingdom. This value will also be used in this report to get an estimate of the total power that could be generated in the State. It is hardly necessary to point out that since the prevailing wind speeds in most of Karnataka are low, windmill densities are never likely to reach values which would seriously affect any atmospheric phenomena or the weather.

Karnataka has a land area of $1{\cdot}92\times10^5$ km$^2$; of this, the 18·4% that is forested will be assumed to be unavailable for installation of windmills.

### 2.5. *Energy extraction*

2.5a. *Achievable windmill efficiency* The ratio of the power $P$ that a windmill rotor can extract to the power available in the wind is known as the power coefficient of the rotor,

$$C_P = P/\tfrac{1}{2}\rho A V^3,$$

where $A$ is the swept area of the rotor. It was shown by Betz that even an ideal actuator disc cannot have a $C_P$ greater than $16/27=0{\cdot}592$.

In fact, even this limit is never reached in practice. The power coefficient of any windmill depends on the tip speed ratio $\lambda=\pi nD/V$, where $D$ is the rotor diameter and $n$ the number of revolutions per second. The functional relationship between $C_P$ and $\lambda$ is characteristic of the rotor type. Simple rotors like the Savonius

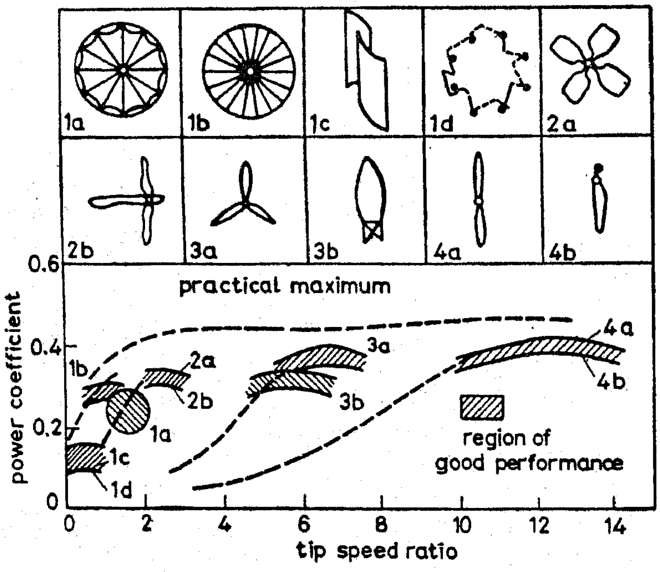

**Figure 4.** Various windmill rotors and their characteristics: **1a** Cretan sail type; **1b** American multivane; **1c** Savonius; **1d** Chinese sail type; **2a** cambered metal blade; **2b** Princeton sail wing; **3a** three-bladed propeller; **3b** Darrieus; **4a** two-bladed propeller; **4b** single bladed propeller. Source: ESCAP (?)

type produce $C_{P\ \max}$ of upto 0·3 (Turnquist & Appl 1975); higher values, upto about 0·45, are associated with rotors using sophisticated aerofoil shapes. Figure 4 shows sketches of different rotor types and their characteristics (Anon, undated); more details will be found in Shrinivasa *et al* (1979a).

2.5b. *Effect of cut-in and unfurling speeds* As stated already, wind speeds could show strong fluctuations; but the full range cannot be used for turning windmills. Typically, a windmill starts working at a wind speed called the cut-in speed below which hardly any work output is delivered. On the other hand, windmills are usually designed such that, for reasons of safety, they do not operate above a certain 'unfurling speed'. Hence only the energy content of the wind *between* these two speeds will be of interest for windmill applications. To estimate this, one would require the speed-duration curve for each region. However, continuous (or even hour-by-hour) records of wind speeds are kept at only three stations in Karnataka; the rest have at best daily averages.

As an example of the effect of these limiting speeds, consider the small wind electric generator KSV-800 rated at 0·85 kW, manufactured by Electro GMBH, Switzerland (DST 1973), which could be conveniently used in Bangalore. It has the following parameters:

cut-in speed = 4 km/hr (1·1 m/s),
rated speed = 32 km/hr (8·9 m/s),
unfurling speed (estimated*) = 35 km/hr (9·7 m/s).

Yearly loss in energy due to these limits in the operating speed would be 15%, as estimated from the wind data for Bangalore Airport.

2.5c. *Loss due to load mismatching* As figure 4 shows, $C_P$ generally falls off rapidly from its maximum value with any change in tip-speed ratio. To obtain the maximum possible net output from the windmill at any given wind speed, the torque absorbed by the load should match the torque developed by the rotor at $C_{P\ \max}$ and hence the power absorbed by the load should vary as $V^3$. Also for operation at $C_{P\ \max}$, the corresponding tip speed ratio remains constant, hence the rev/min of the load should vary as $V$. Therefore, the torque absorbed by the load should vary as $V^2$ or equivalently as the square of the rev/min. Failure to achieve this load torque variation can reduce the useful output from the windpump considerably, as is evident from the sample calculations presented in figure 5a. Some wind electric generators have provision to modify the torque demand when the winds are high (der Kinderen & van Meel 1973). However, small inexpensive windmills (like the American water pumping windmills, Savonius rotors or Cretan type windmills built with sails) generally carry only a simple load (like a pump or a grinding wheel) without any controls. Their overall efficiency† falls rapidly as the wind speed in-

---

*The precise value of the unfurling speed for the KSV-800 is not known, but the value quoted is typical for machines of this kind. If the unfurling speed were 40 km/hr (11.1 m/s), yearly loss in energy would go down to 7%.

†Overall efficiency=(useful work delivered by the utility system)/(energy available in the wind).

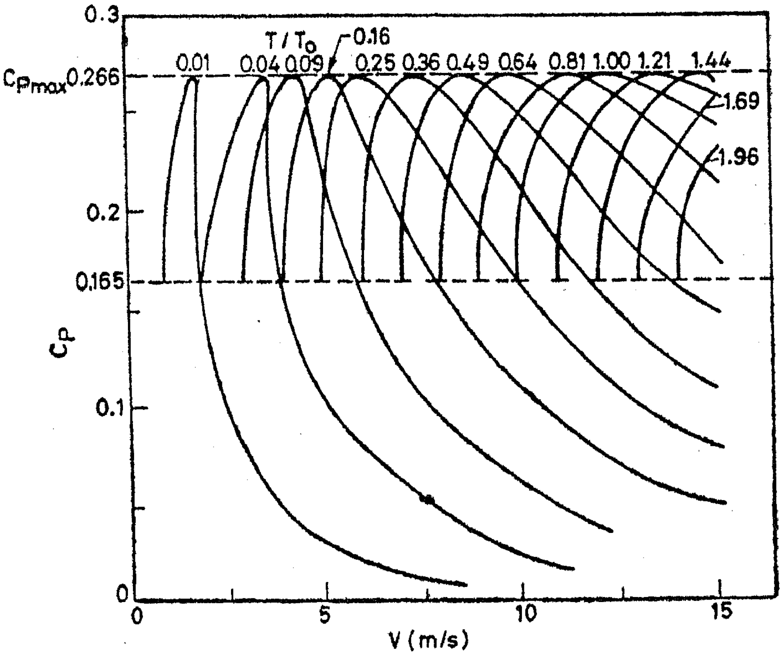

**Figure 5a.** Performance of an assumed rotor (whose characteristic is given in figure 5b): $T_t$ Torque applied on the rotor. $T_{0t}$=Torque required to start the rotor at 10 m/s wind; curves indicate constant torque lines. Dotted line corresponding to $C_P = 0{\cdot}266$ ($C_{P\max}$) indicates rotor output with load-matching.

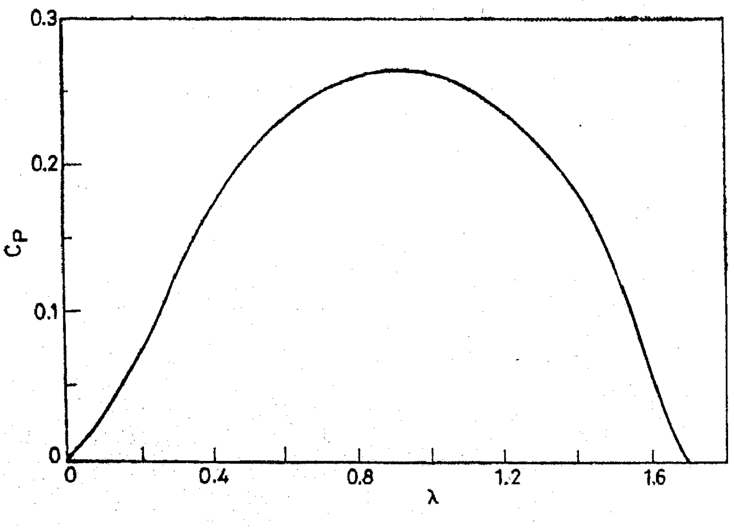

**Figure 5b.** Characteristics of an assumed rotor (Savonius type). Source: Newman (1974).

creases. However, it can be inferred from figure 5a that proper load matching will be able to increase the output of these windmills substantially.

The overall efficiency of a simple windmill when the winds are not steady is about 6–7% according to Golding (1962). The Indian Institute of Science windmill has 11% efficiency at the design speed but averages to less than 4% when varying wind speeds are encountered (Govinda Raju & Narasimha 1979a). We therefore believe that even simple windmills can in principle achieve overall operating efficiencies of about 15%, if provided with suitable load-matching devices (Shrinivasa *et al* 1979b).

However, inexpensive load-matching devices are yet to be built. Therefore, for estimating the potential of the State we will use a value of 10% as the economically feasible overall efficiency of extraction of energy from the wind.

2.5d. *Other losses* These include energies in high frequency wind fluctuations and hydraulic losses. The former are estimated to be of the order of 8% of the output of the rotor (Shrinivasa & Sastry 1978); the latter are assumed to be about 20% of the pump output.

2.5e. *Summary* Based on the above estimates, the energy flow in a typical 'simple' windpump (without load-matching) is illustrated in figure 6. It is seen that the final useful output is only about 4% of the energy content of the wind; even this figure is not always achieved!

It is clear from the figures quoted above that simple load-matching devices, if found feasible, could dramatically increase the output of windmills.

### 2.6 *Total extractable energy*

This is estimated on the basis of the following assumptions which have already been discussed in the earlier sections:

(i) Annual energy pattern factor = 5.5.
(ii) The overall efficiency of extraction of energy from the wind=10% (with suitable load-matching devices).

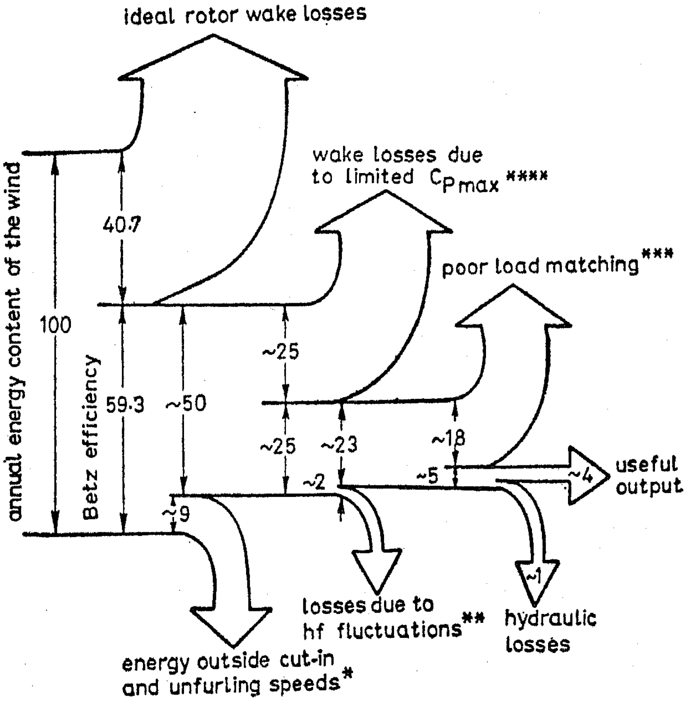

**Figure 6.** Energy flow in a typical simple windpump (the numbers in the figure are only rough indicators). *Energy outside 1·1 m/s and 9·7 m/s at Bangalore airport. **Losses estimated for a hypothetical wind pump. ***Losses estimated for a windpump rated at 4·2 m/s. ****Corresponds to an American multiblade type rotor.

(iii) The wind velocities measured at the meteorological stations are valid in the entire district in which each station is located. Where a district has no station at all, the mean wind speed is the same as in a neighbouring district in the same geographical region.

(iv) The windmill area that can be used for extraction of energy from the wind is 0·4% of the total unforested land area.

The energy estimates so derived are shown in table 3 where they are also compared with the low tension electrical energy consumption in the respective areas. It is seen that the total extractable wind energy in the State is about $40\times10^{9}$ kWh ($=1{\cdot}4\times10^{17}$ J) per year; this may be compared with the total electrical energy consumption in the State, of only about $3{\cdot}4\times10^{9}$ kWh ($0{\cdot}12\times10^{17}$ J) in 1972-73. Thus, even with the relatively low wind velocities prevailing in the State, the possibility of exploiting wind energy deserves serious consideration.

## 3. Technological problems

Two important factors that affect the economic viability of any product that is meant for use in rural areas are its first cost, and the ease and cost of maintenance. These factors have been discussed in relation to windmills by Govinda Raju & Narasimha

**Table 3.** Estimates of wind energy potential

| District | Annually extractable energy | | Low tension electrical energy consumed | |
|---|---|---|---|---|
| | $10^{9}$ kWh | ($10^{15}$ J) | $10^{6}$ kWh | ($10^{12}$ J) |
| 1. Bangalore | 3·4 | (12·0) | 290 | (1000) |
| 2. Belgaum | 2.2 | (7·9) | 47 | (170) |
| 3. Bellary | 1·1 | (4·0) | 31 | (110) |
| 4. Bidar | 2·9 | (10·0) | 27 | (97) |
| 5. Bijapur | 2·2 | (7·9) | 61 | (220) |
| 6. Chikmagalur | 0·2 | (0·7) | 16 | (58) |
| 7. Chitradurga | 1·3 | (4·7) | 51 | (180) |
| 8. Coorg | 0·8 | (2·9) | 8 | (29) |
| 9. Dharwar | 1·6 | (5·8) | 86 | (310) |
| 10. Gulbarga | 8·6 | (31·0) | 29 | (100) |
| 11. Hassan | 1·2 | (4·3) | 26 | (94) |
| 12. Kolar | 3·6 | (13·0) | 84 | (300) |
| 13. Mandya | 1·4 | (5·0) | 18 | (65) |
| 14. Mysore | 2·4 | (8·6) | 94 | (340) |
| 15. N. Kanara | 0·06 | (0·2) | 14 | (50) |
| 16. Raichur | 7·0 | (2·5) | 26 | (94) |
| 17. Shimoga | 0·2 | (0·7) | 39 | (140) |
| 18. S. Kanara | 0·5 | (1·8) | 42 | (150) |
| 19. Tumkur | 4·8 | (17·3) | 73 | (260) |
| Total | 40 | (140) | | |

Total electricity consumption in 1972-73: $3{\cdot}4\times10^{9}$ kWh ($12\times10^{15}$ J) (Source: Sen Gupta 1977)

1979b); they have pointed out and illustrated how a 'soft' design, involving local materials, skills and labour, can keep costs down by utilising technologies available in or accessible to rural areas.

Apart from these general considerations, there are certain specific technological problems that demand attention, and these are discussed below.

### 3.1. *Non-availability of suitable pumps*

It has been argued in § 2.5c that, when the wind speeds fluctuate, the torque absorbed by the pump should vary as the square of the rotor angular speed to enable the rotor to extract energy from the wind at maximum efficiency. However, a pump with this characteristic that delivers water at a reasonably high efficiency does not seem to exist as of today. The two major pump-types available suffer from the following difficulties.

(i) In the absence of frictional losses, a positive displacement pump has the undesirable characteristic that it absorbs a nearly constant torque at all speeds. However, as the stroke rate increases the torque absorbed also increases rapidly due to mounting hydraulic losses, and this helps the rotor to operate closer to the design $C_p$. Nevertheless the windpump output still remains poor (as is shown by the sample calculation presented in figure 7), because the portion of the torque used to overcome hydraulic losses does not contribute to the pump output, but only increases the inefficiency of pumping.

(ii) Centrifugal pumps have nearly quadratic torque absorption characteristics with respect to their angular speed. However, their pumping efficiencies decrease rapidly as one operates them away from the design rpm (figure 8). Hence these pump-types are also unsuitable.

Therefore one cannot help concluding that the non-availability of pumps suitable for coupling with windmills is a major hurdle in improving the output of windpumps. The problem is particularly severe where wind speeds are not high, as one cannot afford to spill any energy.

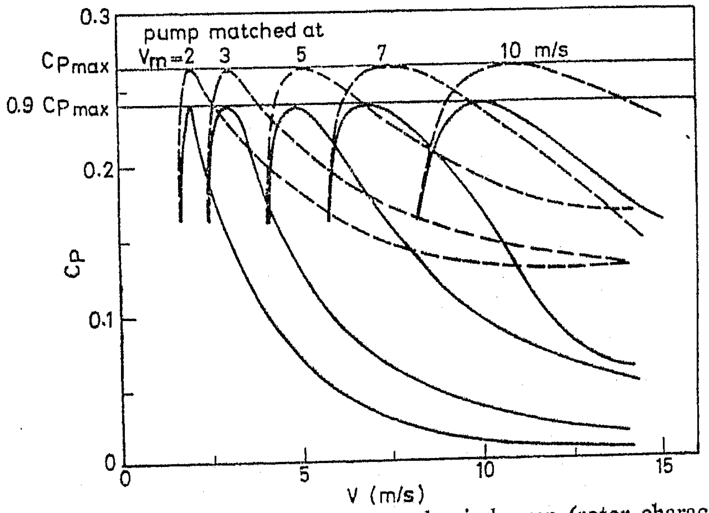

**Figure 7.** Performance of an assumed windpump (rotor characteristic is given in figure 5b. Pumps are of a positive displacement type with constant discharge per revolution of the rotor. Each pump is matched to the rotor for it to operate at $C_{P\max}$ at the velocity indicated on the figure. Hydraulic losses are assumed to be 10% at the match point.); dotted lines indicate rotor output and the full lines pump output.

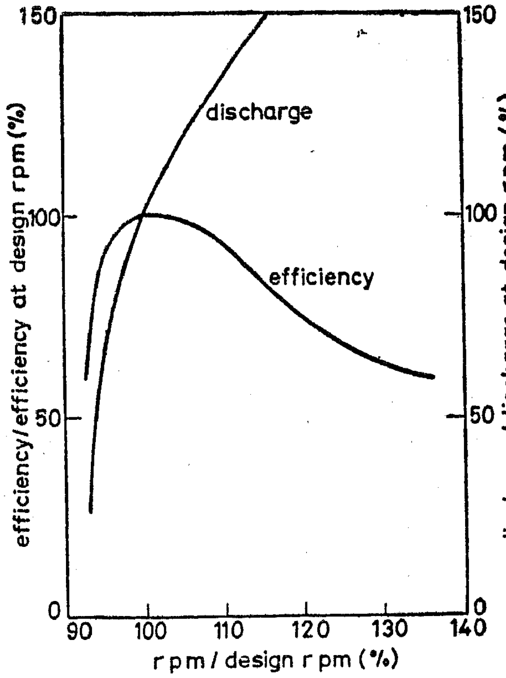

**Figure 8.** Variation of the overall efficiency of a typical centrifugal pump with its rpm. (Source: Lazarkiewicz & Troskolanski 1965).

Some developmental work is in progress at the Indian Institute of Science (Rajagopalan & Govinda Raju 1979) to design and fabricate a positive displacement pump whose stroke can be programmed to vary suitably with the rotor angular speed. A windmill with a similar pump has also been attempted at Auroville, Tamil Nadu (see Jaap *et al* NAL in 1979).

### 3.2 *High cost of wind pump towers*

According to Merriam (1972), the cost of an all-steel tower is 50% more than the cost of the rotor and gearing for traditional multivane water pumpers. Standard four-post towers of 21 to 47 ft (6·7 to 14·3 m) height, supplied by Aermotor, USA for rotors of 6 to 16 ft (1·8 to 4·9 m) diameter, cost from US $ 535 to 3175, whereas the rotors themselves cost between US $ 465 and US $ 4235 (NAS 1976). Thus it appears that the tower accounts for a major share of the total cost of the wind pump itself (anywhere between 40 to 80%). The situation is further aggravated in Karnataka because of the high variability of the winds: even though the annual mean wind speed may be rather low, one does occasionally get very high winds. For example, according to Tewari *et al* (1979), during a three-year period gust speeds in Bangalore exceeded 20 m/s nine times and 25 m/s once, while the annual mean speed was less than 4 m/s. Hence, towers for a given windpump output are often required to withstand disproportionately larger loads than what they normally experience.

It is therefore important to look for inexpensive tower designs. Among the technological options available to reduce the load on the tower during high winds are:

(i) feathering of the blades,
(ii) turning the rotor away from the wind,

(iii) partially furling the sails,
(iv) introducing certain elements on the rotor which will unfurl the sails at predetermined windspeeds in such a way that the rotor drag is reduced.

However, it appears that enough experience is not yet available to enable designers to confidently select towers which can be designed for only relatively low wind speeds.

### 3.3 *Lack of multiple utility load systems*

It has been observed by Merriam (1972) that multipurpose utility load is the best way to put a windmill to maximum use. As nearly 80% of the annual energy content in the winds in Karnataka is available during the southwest monsoon (figure 3b) when the need for pumping may not always be severe, it stands to reason that alternative uses for the rotor output must be identified to derive larger benefits from the investment on windpumps.

## 4. Economics of windpumps

Table 4 gives the approximate costs and the quantity of water lifted by pumps driven by diesel, electricity and wind. Tewari (1978a) has compared these alternatives on the basis of discounted cash flow (i.e. the amount of cash one should have now to take care of the capital and running costs over the life of the system). However even a favourable comparison on the basis of discounted cash flow is not sufficient to justify adoption of one of the alternatives; it is necessary to consider the return from the land. We therefore briefly examine various scenarios relevant to the windie rregions of the State.

The following facts have to be considered before the economic viability of windmills can be assessed.

(i) The districts in the northern maidan where winds are appreciable happen to be in the semi-arid tropics (with a rainfall of 500 to 1000 mm per year).

(ii) Parts of the region enjoy supply of irrigation water from canals, reservoirs or tanks; here pumping requirements are not severe, and may well be adequately met with bullock- or even man-power.

**Table 4.** Capacity and cost of some typical electric, diesel and wind pumps

| Description | Cost Rs | Discharge | Source |
|---|---|---|---|
| 3·5 hp (2·2 kW) electric motor with pump, plumbing and pump house | 3,000 | 24,000 litres/hr | Tewari (1978b) |
| 3·5 hp (2·6 kW) diesel engine with pump, plumbing and pump house | 4,500 | 24,000 litres/hr | Tewari (1978b) |
| Sherman's Madurai windmill | 5,480 | 6000 litres/hr in 16 km/hr wind | Sherman (1975) in Tewari (1978b) |
| NAL sail type | 10,000 | 6000 litres/hr in 10 km/hr wind | Anon 1979 |
| Smith's Sholapur windmill | 14,000 | 6,500 litres/hr in 16·7 km/hr wind | Smith 1977 (private communication) |
| IISc windpump | 3,000 | 1000 litres/hr in 12 km/hr wind | Govinda Raju & Narasimha (1979) |

(iii) In the rest of the region, the chief crops grown are generally rainfed; either kharif (during the monsoon season), or rabi (using the moisture absorbed by the soil during the rains), or sometimes both, depending on the intensity and distribution of the monsoon rainfall in the particular year.

(iv) The monsoon season here is often plagued by mid-monsoon droughts, which could sometimes last over 40 days (as was the case in 1979). Ramana Rao & Havanagi (1979) have observed, on the basis of rainfall analysis, that areas like Gulbarga district are subject to moisture stress severe enough to spoil the crops in two out of five years. There is therefore a strong need for supplemental and life-saving irrigation, to protect the crops from such stress at least during the critical periods of their growth.

(v) Probably because of this same need, there are a large number of wells in the area. However the water yields from these wells are relatively low, because of unfavourable geological factors. The weathered rock that may contain water is a layer of only 10 m depth; except in some special locations where the hard granite below has fissures or joints, no advantage is obtained by digging deeper than 10 m. The yield of a majority of the wells (due to ground water percolation) is of the order of 1800 litres/hr, which is too meagre for pumping for irrigation. Therefore large-scale well irrigation may not be generally feasible in this region.

A large portion of the crops sown in these areas does not even get supplemental irrigation. However, the total agricultural output of the area is considerable, and the possibility of irrigation is therefore important from the point of view of annual food production.

(vi) Because of the uncertainties of the return from rainfed agriculture, the farmer is unable to risk his meagre capital to buy better seeds and fertilisers. As a consequence the yield per unit area in this region is very low. Experiments conducted over a period of three years at ICRISAT (Ryan *et al* 1979) have indicated that the yield from the land can be increased by about 3 to 5 times in such areas by using better seeds, better fertilisers and improved land and crop management practices. To tide over likely mid-monsoon droughts they recommend (for water sheds of at least 10–15 ha) that surface run-off be collected in a pond and used for life-saving and supplemental irrigation. However, the water needs to be applied only once or twice during the crop-growing period, and therefore could probably be satisfactorily lifted with bullock- or man-power.

To see where windpumps may be suitable, we must distinguish between pumping from surface sources like ponds, tanks, canals and reservoirs, and pumping from wells for supplemental irrigation.

In the former case the quantity of water pumped is generally large. The crop duty for even dry crops is of the order of about 500 to 600 mm per crop. The pumps normally operated handle about 25,000 litres/hr from depths of upto 15 m if necessary, as in the case of a 3 hp electric motor. Presently existing windmills in India can pump barely about 6,000 litres/hr in the non-monsoon winds of about 10 km/hr hourly average.

Where water has to be lifted only against small heads (of 1 or 2 m), traditionally either man- or bullock-powered pumps have been found adequate (see table 5), giving a discharge of about 10,000 litres/hr or more.

It must be noted here that, apart from the total water requirement for a crop (table 6), the *rate* of discharge is also an important factor, at least for crops other

**Table 5.** Outputs of traditional water lifts

| Device | Source of power | Optimum lift (m) | Average discharge $10^3$ litres/hr |
|---|---|---|---|
| 1. Counter poise lift | Single man | 1·2 to 4 | 8 to 11 |
| 2. Swing basket | Two men | 0·9 to 1·2 | 14 to 19 |
| 3. Archemedian screw | Single man | 0·5 to 1·2 | 14 to 19 |
| 4. *Don* | Single man | 0·5 to 1 | 9 to 13 |
| 5. Water wheel | A pair of bullocks | 1 to 1·2 | 40 to 60 |
| 6. Persian wheel | A pair of bullocks | 5 to 10 | 14 to 18 |
| 7. Chain pump | A pair of bullocks | 3 to 6 | 15 to 20 |
| 8. Self emptying rope and bucket lift | A pair of bullocks | 4 to 6 | 10 to 15 |
| 9. Rope and bucket lift | Two pairs of bullocks | 10 to 30 | 6 to 10 |

Source: Dakshinamurti *et al* (1973)

**Table 6.** Water requirements of field crops (other than rice*) at 70% field irrigation efficiency (in hot and semi arid tropics)

| Seasons | Water requirement (mm) |
|---|---|
| Kharif (July–October) | 600 to 700 |
| Rabi (November–March) | 600 to 700 |
| Hot weather (March–June) | 900 to 1000 |

*Water requirement of rice is 12 mm/day on clayed soils and 18 mm/day on loamy soils. Source (Dakshinamurti *et al* 1973)

than paddy. This is because at low rates of discharge the percolation is too large to distribute water through field canals. Other means of distribution like sprinkler or drip irrigation require large capital investments and therefore are not in widespread use in India. From table 5 it can be seen that even the traditional water lifting devices give a yield of about 10,000 litres/hr. Therefore we assume for this report that either the windmills must provide this discharge rate or must be accompanied by small tanks of about 10 $m^2$ area and of 20,000 litres capacity, found adequate in the US to regulate the flow of water to the fields.

From experience in India, rotors of upto about 10 m diameter can be conveniently built even using local materials in the villages (see various reports in NAL 1979). To be useful, one must require that they pump a reasonable quantity of water from these windpumps even in non-monsoon winds. The data discussed in § 2.2 indicate that wind speeds with a monthly average of about 10 km/hr (2·8 m/s) are prevalent in the windier parts of Karnataka during the non-monsoon months. Tewari (1978a) observes that in Bangalore, hourly average wind speeds of about 10 km/hr (2·8 m/s) are usually found on the average for about 10 hr a day throughout the year. Using an hourly EPF = 2, the windpump under consideration can deliver about 2 kWh ($7{\cdot}2 \times 10^6$ J) per day in Bangalore assuming an overall efficiency of about 10% (with load-matching) and a pump mechanical efficiency of about 80%. This output is equivalent to about 8 hr from a pair of bullocks, and looks attractive.

However, without load-matching the output will fall to about a third, which cannot justify the investment on windpumps, particularly where the wind speeds are not very good. Windpumps without load-matching will therefore not be considered here.

An output of 2 kWh is equivalent to 70,000 litres of water lifted over a height of 10 m under the assumed efficiency of pumping. However at the lower pumping heads it may not be possible to maintain the assumed efficiencies. As an example we present the computed performance of the IISc windmill in figures 9a and 9b. Here as the wind energy flux increases 8 times ($V$ changes from 20 km/hr to 40 km/hr) the pump output just about doubles. Even when the hydraulic loss coefficient (hydraulic loss/reference dynamic head) is reduced from 40 to 2·8, the output is only doubled (figure 9b). Therefore when one considers large discharges it will also become necessary to account for this increased hydraulic loss.

Hence it appears that outputs far in excess of 10,000 litres/hr are unlikely to be obtained during the non-monsoon months from a 10 m diameter rotor windmill which does not use a specially designed pump. (The largest output from wind pumps manufactured by Aermotor, a US windpump manufacturer, is about 13,000 litres/hr (NAS 1976).) Therefore we assume here that the output from simple windpumps would at best be about 20,000 litres/hr.

Based on the foregoing discussion, a variety of illustrative scenarios, both favourable and adverse, have been presented in table 7. The assumptions underlying these scenarios are the following.

(i) Crops like sorghum, bajra, maize and wheat require about 500 mm of water (after taking into account a field irrigation efficiency of 70%), and paddy requires 1,500 mm per crop (see table 7).

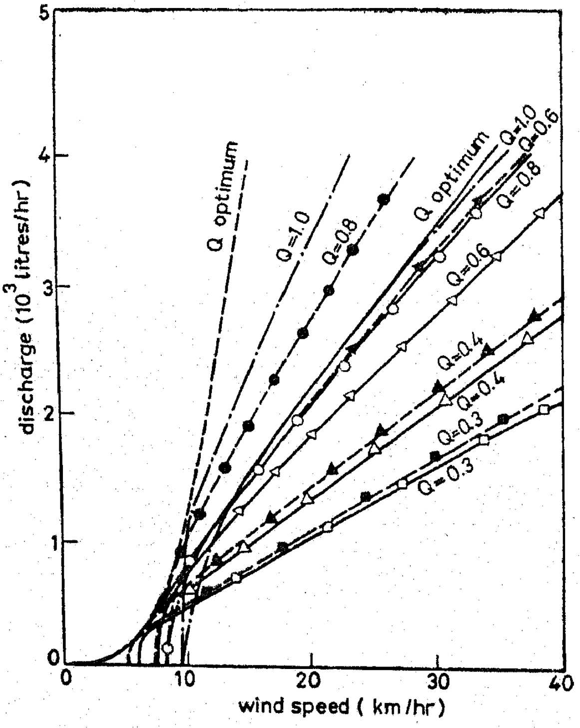

**Figure 9a.** Performance of IISc wind pump. Net head is 5m. $Q$ is the pump displacement in litres/stroke. Full lines indicate performance with hydraulic loss and the dotted lines without any loss ($k$=hydraulic loss/reference dynamic head=46). (Source: Rajagopalan & Govinda Raju 1979.)

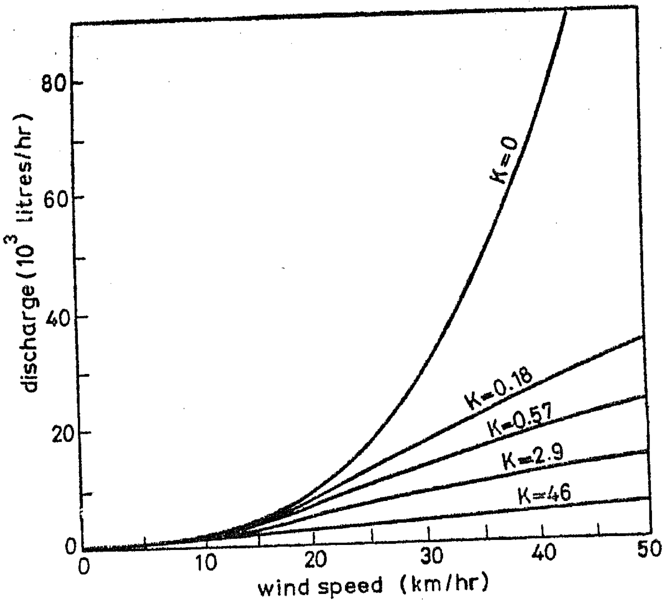

**Figure 9b.** Performance of IISc windpump with load matching. Different size pipes and suitable pumps are to be used to achieve the hydraulic loss coefficients indicated on the figure. In each case the pump stroke is programmed so that the rotor can operate at $C_{P\,\max}$. (Source: Rajagopalan & Govinda Raju 1979.)

**Table 7.** Economics of windpumps

| Sl. No. | Land area ha | Crop | No. of crops | Yield/ha kg (for each crop) | Wind pump cost (Rs.) | Tank cost | Depreciation % | Repair and maintenance % | Annual return % |
|---|---|---|---|---|---|---|---|---|---|
| Well water | | | | | | | | | |
| 1. | 0·5 | Rice | 2 | 5,000 | 12,000 | No tank | 10 | 5 | 18 |
| 2. | 0·5 | Rice | 2 | 2,500 | 12,000 | No tank | 10 | 5 | -ve |
| 3. | 0·5 | Rice | 3 | 5,000 | 12,000 | No tank | 10 | 5 | 33 |
| 4. | 0·5 | Rice | 2 | 5,000 | 5,000 | No tank | 20 | 10 | 45 |
| 5. | 0·5 | Rice | 3 | 5000 | 5,000 | No tank | 20 | 10 | 81 |
| 6. | 0·5 | Rice | 3 | 2500 | 5,000 | No tank | 20 | 10 | 14 |
| 7. | 0·5 | Rice | 2 | 2500 | 5,000 | No tank | 20 | 10 | 0 |
| 8. | 0·5 | Rice | 3 | 5000 | 12,000 | No tank | 3·3 | 0 | 44·8 |
| 9. | 1·5 | Dry crop | 2 | 5000 | 5,000 | 1,500 | 20 | 10 | 130 |
| 10. | 1·5 | Dry crop | 2 | 2500 | 5,000 | 1,500 | 20 | 10 | 35 |
| 11. | 1·5 | Dry crop | 2 | 2500 | 12,000 | 1,500 | 10 | 5 | 17 |
| 12. | 1·5 | Dry crop | 2 | 5000 | 12,000 | 1,500 | 20 | 10 | 68 |
| Water from a large source | | | | | | | | | |
| 13. | 3 | Dry crop | 2 | 5000 | 5,000 | No tank | 20 | 10 | 280 |
| 14. | 3 | Dry crop | 2 | 5000 | 12,000 | No tank | 10 | 5 | 150 |
| 15. | 3 | Dry crop | 2 | 2500 | 12,000 | No tank | 10 | 5 | 50 |
| 16. | 3 | Dry crop | 2 | 2500 | 5,000 | No tank | 20 | 10 | 94 |

(ii) The possible yield for each crop, under favourable conditions, is about 5,000 kg/ha (Dastane *et al* 1970). However the average yield of paddy in India according to Dakshinamurthy *et al* (1973) is only 1,000 kg/ha. The projected average paddy yield for Karnataka in the year 2000 AD is 2,400 kg/ha (Iyer 1975). We shall consider here a yield of 2,500 kg/ha as the lower bound under favourable conditions.

(iii) The crops can be sold at a uniform price of Re. 1/kg.

(iv) The variable cost of each crop (including expenditure on fertilisers, seeds etc., but not on labour) is Rs 1,000 per hectare.

(v) A well can yield 60,000 litres of water per day uniformly throughout the year. The larger source of water (e.g. a tank) considered here can yield 200,000 litres/day.

(vi) Two windpumps, both with a rotor diameter of 10 m, will be considered. One of these, with a life of 10 years, is assumed to cost Rs 12,000 (10% depreciation per year), and the other (5-year life) Rs 5,000 (20% depreciation per year). The maintenance and repair charges are taken to be 5% and 10% per year of their respective first costs.

(vii) When the average discharge from the windpump is less than 10,000 litres/hr, a tank of 20,000 litres capacity just above ground level is considered necessary. Such a tank is assumed to cost about Rs 1,500, and require 10% of this cost for annual maintenance.

One can draw several useful conclusions from the results displayed in table 6. Obtaining a reasonable return on a half-hectare rice field is clearly very difficult: 3 crops per year each with a high yield of 5,000 kg/ha, and a wind pump costing only Rs 5,000, are required to give a return of more than 50% on the investment. On the other hand, with two dry crops per year on a 3 ha farm, either a relatively high yield of 5,000 kg/ha, or a windmill that costs less than Rs 5,000, promises an appreciable return.

It is clear from these figures that only an integrated programme that includes the development of suitable windmills on the one hand, and of appropriate water- and crop-management practices on the other, promises any success. Certainly such a programme is worth pursuing, in view of the increasing costs of both water and energy for irrigation.

## 5. Conclusions

We have shown that the total wind energy potential of Karnataka State is about an order of magnitude higher than current electrical energy consumption in the State. Although the wind velocities are too low or variable over large parts of the State to enable economic exploitation, the data available, with all their limitations, indicate that there are certain districts in the northern maidan of the State (namely Gulbarga, Raichur, Bidar) where wind velocities are moderately good and where a serious experiment to exploit wind energy would be definitely worthwhile. However, for such an experiment to be successful it is important that the nature of possible applications should be constantly kept in mind. For example, if the application is irrigation, it is necessary that the programme should be integrated carefully with the needs of the crops grown in the particular region and the water resources there; and should indeed include within its scope possible improvements in land and water management practices.

A technological target for windmills that might find application in rural areas would be the design and construction of a windmill of about 10 m rotor diameter costing not more than about Rs 10,000, with suitable load-matching device and pump that will provide an output of about 10,000 litres/hr in 10 km/hr hourly average winds. No windmill with these characteristics is available as of today, but it is our belief that the target set out above is technically feasible. A first cost of even Rs 10,000 may appear to be on the high side when compared to such alternatives as electrically or diesel-driven pumps, but this comparison is superficial and misleading as it takes no account of the hidden subsidy that supports these more familiar sources of energy (Reddy & Krishna Prasad 1977). The use of such windmills should be particularly attractive in the semi-arid tropics to provide supplementary irrigation for such dry crops as maize, jowar etc., especially where water is available at relatively low depths of the order of 10 m; in Karnataka State, it seems clear that in the districts of Raichur, Gulbarga and Bidar and possibly also Bangalore and the Western Ghats, more detailed wind surveys should be immediately carried out, accompanied or followed by a programme of erection of windmills of different designs to meet rural applications.

The work reported here was sponsored by the Karnataka State Council for Science and Technology; we are grateful to KSCST for its support, and to Prof. A K N Reddy for his encouragement.

## References

Anon (undated) ESCAP Report of wind energy sectorial group, Annexure II E/ESCAP/NR/3/L.2

Bartlett R A 1974 *The new country* (Oxford: University Press)

Clark W 1977 *Energy for survival* (Bombay: Allied Publishers)

Coty U & Dubey M 1976 2nd Annual Energy Symposium, Los Angeles Council for Engineers and Scientists, Los Angeles

DST 1973 Report of NCST expert committee on wind power, Part II (New Delhi: Department of Science and Technology)

Dakshinamurti C, Michael A M & Mohan 1973 *Water resources of India and their utilisation in agriculture* (New Delhi: Indian Agricultural Research Institute)

Dastane N G, Singh M, Hukkeri S B & Vamadevan V K 1970 *Review of work done on water requirements of crops in India* (Poona: Navabharat Prakashan)

der Kinderen W & van Meel J 1973 Field performance of wind power machines: systems analysis and measuring methods. Application to a small wind generator, Ir. thesis, Department of Physics, Eindhoven University of Technology, Eindhoven

Derry T K & Williams T I 1960 *A short history of technology* (Oxford: University Press)

Golding E W 1962 Technical Note TN-WP 7-62, National Aeronautical Laboratory, Bangalore

Govinda Raju S P & Narasimha R 1979a A low-cost water pumping windmill using a sail type Savonius rotor, Report 79 FM 2, Dept. of Aero. Eng., Indian Institute of Science, Bangalore

Govinda Raju S P & Narasimha R 1979b *Proc. Indian Acad. Sci.* **C2** 67

IMD 1948 Wind data for windmills, India Met. Dept. Scientific Notes, Vol. VI, No. 63

IMD 1965 India Weather Review Annual Summary, Part A, India Met. Dept.

IMD 1966 *Climatological tables of observatories in India* (1931-1960), India Met. Dept.

Iyer H 1973 in Anon 1973 on Wind Power, Department of Science and Technology, Government of India

Iyer A S 1975 Food crops of Karnataka State (in Kannada) University of Agricultural Sciences, Bangalore

Lazarkiewicz S & Troskolanski A T 1965 *Impeller pumps* (London: Pergamon Press)

Learmonth A T A & Bhat L S (ed) 1961 *Mysore State—An atlas of resources*. Vol. 1, Indian Statistical Institute, Calcutta

Ljugstrom O 1977 *Proceedings of the International Symposium on Wind Energy Systems, Cambridge* UK (BHRA Fluid Engineering, Cranfield)

Merriam M F 1972 Is there a place for the windmill in the less developed countries? Working papers of the East West Technology and Development Institute, Honolulu, Hawaii

Musgrove P 1976 *New Sci.* **72** 596

NAS 1976 *Energy for rural development* (Washington DC: Natl. Acad. Sci.)

NAL 1979 *Wind energy developments in India*, Proceedings of the Wind Energy Workshop held at National Aeronautical Laboratory, Bangalore

Newman B G 1974 Measurements on a Savonius rotor with variable gap, Sherbrooke Univ. Symposium on wind energy

Newman B G 1977 *Energy Conver.* **16** 169

Pelser J 1975 Wind energy research in the Netherlands, ERDA/NSF Workshop on wind energy conversion systems, Washington

Railly J W 1977 *New Sci.* **73** 231

Rajagopalan G 1978 *Energy potential of the wind*, ME Dissertation, Dept. of Aero. Eng., Indian Institute of Science, Bangalore

Rajagopalan G & Govinda Raju S P 1979 Prospects of improving windpump performance by load matching, Report 79 FM 9, Dept. of Aero. Eng., Indian Institute of Science, Bangalore

Ramakrishnan K P & Venkiteshwaran S P 1961 Wind power resources of India with particular reference to wind distribution, Technical Note No. TN-WP-61, National Aeronautical Laboratory, Bangalore

Ramana Rao B V & Havanagi C V 1979 Meteorology in the service of agriculture—Report submitted to the Karnataka State Council for Science and Technology, Bangalore

Rangi R S, South P & Templin R J 1974 Wind power and the vertical axis wind turbines developed at the National Research Council, DME/NAE Bulletin (2) NRC Canada

Reddy A K N & Krishna Prasad K 1977 *Econ. Pol. Weekly* **12** 465

Reddy A K N & Subramanian D K 1979 *Proc. Indian Acad. Sci.* **C2** 395

Ryan J G, Savin B & Pereira M 1979 Assessment of prospective soil, water and crop management technologies for the semi-arid tropics of peninsular India, Workshop on socio-economic constraints to development of semi-arid tropical agriculture, ICRISAT, Hyderabad

Ryle M 1977 *Nature* (*London*) **267** 111

Sen Gupta D P 1977 Energy planning for Karnataka State: Phase-I. Towards a more general distribution of electrical energy, Report submitted to the Karnataka State Council for Science and Technology, Bangalore

Sen Gupta R N 1966 *J. Instn. Engrs.* Part GE 1 47 90

Shefter Ya I 1972 *Wind-powered machines* (Moscow: Mashinostroyeniye; NASA TTF-15, 149)

Shrinivasa U & Sastry D 1978 Effect of wind speed variation on the performance of windmills, Presented at the 23rd Congress of Indian Soc. of Theor. and Appl. Mech., Warangal

Shrinivasa U, Narasimha R & Govinda Raju S P 1978 Wind energy potential of Karnataka, Report 78 FM 12, Dept. of Aero. Eng., Indian Institute of Science, Bangalore

Shrinivasa U, Narasimha R and Govinda Raju S P 1979a Characteristics of windmills available for rural use, Report 79 FM 8, Dept. of Aero. Eng., Indian Institute of Science, Bangalore

Shrinivasa U, Narasimha R and Govinda Raju S P 1979b Performance of windmills, Report 79 FM 4, Dept. of Aero. Eng., Indian Institute of Science, Bangalore

Tewari S K & Srinath L S 1975 A systems approach towards utilisation of wind energy—A preliminary study, National Aeronautical Laboratory, Bangalore

Tewari S K 1978a *Science* **202** 481

Tewari S K 1978b Economics of wind energy use for irrigation in India, TN-52, National Aeronautical Laboratory, Bangalore

Tewari S K, Ningaiah, Subramanyam D V V and Samraj A C 1979 *Proc. Indian Acad. Sci.* **C2** 107

Turnquist R O & Appl F C 1975 Design and testing of a prototype Savonius Wind Turbine, Kansas State University Technical Report