Possible Means of Large-scale Use of Wind as a Source of Energy

by

JOHN O'M. BOCKRIS, Ph.D., D.Sc. (London), F.R.I.C.

Professor of Chemistry and Director, Institute of Solar and Electrochemical Energy Conversion, School of Physical Sciences, Flinders University of South Australia, Bedford Park, Adelaide, South Australia 5042, Australia.

INTRODUCTION

The development of new energy sources is mainly associated with the gasification of coal and with breeder reactors, though solar and fusion sources are distant possibilities. Coal's supposed long-term availability depends upon calculations which originate in coal's use in electricity production. Electricity comprises about 15% of energy-use in technologically advanced countries. Were coal to be used to replace oil and natural gas, the supplies in the United States would become exhausted between A.D. 2000 and A.D. 2030 (Elliott & Turner, 1972; Linden, 1974). Coal's removal from the ground at a rate sufficient to replace a substantial fraction of oil by, say, A.D. 2000, is impossible with established technology (Arthur, 1973). Breeder reactors are associated not only with pollutive and other grave problems (Petkau, 1972; Sternglass, 1973; Edsall, 1974, 1975), but are still not yet technically practical (price- and pollution-wise). Coal and atomic energy sources will not be able in time to fill the gap of failing oil and natural gas supplies. Imports would not only be costly, but largely impractical, involving, it has been calculated, a 250,000-tons tanker per hour for the U.S. by 1985 (Hottel, 1973).

Wind is not commonly considered an energy-source for the general solution of the energy shortfall, because it is sporadic and the energy obtainable from it in most areas on land is uninteresting in magnitude. The situation changes, however, when the following conditions are simultaneously present:

(1) There is a mean annual wind greater than 25 k.p.h. (*ca* 16 m.p.h.).

(2) There are wind generators very much bigger than the earlier ones—e.g. 100 metres in radius*.

(3) There is a sufficient water-supply. Electrolytic hydrogen would smooth out the power supply by acting as a storage medium, and enable fuel to be transferred economically to sites of high-energy use up to 6,000 km distant from a wind-belt (Bockris, 1971).

To obtain numerical estimates, it is necessary to elucidate the calculation of wind energy from the mean annual wind, which is the only wind datum that is at all widely available.

WIND-ENERGY CALCULATIONS

Calculations of the energy conversion that is possible from wind data are rare. They exist in the books by Putman (1948) and Golding (1955), in the extensive Australian work by Mullett (1956), most of which is in a report that has not earlier been available, and in a reprint from a meeting presentation by Heronemus (1972).

The formula† for the maximum power which can be transduced from a wind of instantaneous velocity, v, is:

$$P = \frac{16}{27}\left[\frac{1}{2}\right]\rho v^3 \qquad (1)$$

per unit area swept out by the arms of the generator, where ρ is the density of the area. The formula is ideal because of mechanical efficiency losses. The relevant efficiency factor is a matter of experiment, a conservative figure being 0.75.

Wind generators have upper and lower limits for the v at which they can function. They have to be feathered when the wind reaches a higher limit, e.g. 60 k.p.h. (*ca* 38 m.p.h.). At less than, e.g., 15 k.p.h. (*ca* 9 m.p.h.), they do not function because of drag effects. Hence, when we calculate the mean of the cubes of the sporadic winds over the year for substitution in (1), we have to neglect wind velocities greater than v_{max} and less than v_{min}. The effect of the critical lower value is small, because the v^3 law of equation (1) makes the higher winds dominate the situation.

Accordingly in calculations of the energy that is collectable from a wind generator over a year (i.e.,

* No wind generators of anything like this size yet exist. However, by resting the weight of the wind generator upon gears on the ground and using an axle only as a guide—not as a bearer of weight—the large size suggested here should be practicable.

† Readers who dislike or do not fully comprehend such technical formulae etc. can derive almost full benefit from this important paper while 'skipping' them.—Ed.

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through the complete cycle of the winds for the region), one needs to have the amount:

$$\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} v^3_t dt = v^3_{mean} \qquad (2)$$

rather than the mean annual wind, cubed:

$$\frac{1}{t_2 - t_1} \left[\int_{t_0}^{t_2} vdt\right]^3 = \left[v_{mean}\right]^3 \qquad (3)$$

The mean of the cubes of the velocities is greater than the cube of the mean velocity. The ratio of these means depends upon location. The parameters for the cut-offs of top and bottom velocities depend upon the rotor characteristics, the ratio being rotor-dependent (Table I).

Anemometers record at hourly intervals. This is inadequate, because wind energy may be available in gusts of high velocity and these are of such short duration that most of them are missed as the anemometer only records for a brief time at hourly intervals. Thus, the mean of the cubes of the velocities, based on hourly readings, substituted in (1), will give a result that is lower than the actual one obtained in practice.

TABLE I

The Cube of the Means and the Means of the Cube for Wind Velocities from Three Sets of Data.

Origin of Data	v_{mean} *excluding data above 40 mph* and below 10† mph*	$(v_{mean})^3$	$(v^3)_{mean}$	$\frac{(v^3)_{mean}}{(v_{mean})^3}$
Golding (1955)	26 k.p.h.	17,576	50,606	
	(16.5 mph)	(4,467)	(12,355)	(2.8)
Mullett (1956)	16.6 k.p.h.	4,574	14,997	
	(10.4 mph)	(1,158)	(3,666)	(3.2)
Heronemus (1972)	28 k.p.h.	21,952	49,276	
	(17.3 mph)	(5,178)	(12,045)	(2.3)

* *Ca* 63 k.p.h. † *Ca* 16 k.p.h.

When no information about the ratio of $\frac{V^3_{mean}}{(V_{mean})^3}$ is available (as is nearly always the case), and the mean annual wind, cubed, is used in equation (1), the power calculated will be lower than that available from an actual aerogenerator, at the same location, operating a device which collects and smooths out its sporadically produced energy. It is therefore desirable to obtain an indication, from the data in the literature, of what this ratio of the seldom-available v^3_{mean} to the easily available $(v_{mean})^3$ may be, so that a rough estimate may be made of the wind energy available for a given rotor in a given location.

Calculations have been made from Golding (1955), Mullett (1956), and Heronemus (1972) (Table I). The mean of the values is 2.7, but a factor of 2.5 will be used in view of the small number of cases employed.

EVALUATION OF AN EMPIRICAL WIND-PATTERN FACTOR

The combination of the factor of 2.5 backed by the data of Table I, with the conservative factor of 0.75, gives us equation (4):

$$P_{prac} = 1.7\ \rho v^3 R^3 \qquad (4)$$

Equation (4) can be used to compute power from a wind generator, having arms of radius R, in a location in which the mean annual wind is v. The numerical factor is $2.5 \times 0.5 \times 0.75 \times \frac{16}{27} \pi$.

It is necessary to take into account three further efficiency factors. One will refer to the conversion of the mechanical power of the rotor to electricity, and this will be about 0.95. Another refers to the efficiency with which the electric power will produce hydrogen. This is usually taken as 0.75, but it is capable of being improved to 0.85 (Gregory *et al.*, 1972*a*). The third further factor is the fuel-cell efficiency. There are now fuel-cells with efficiencies of 50% (Aaronsen, 1971). However, the Pratt and Whitney cells which were used employed natural gas as fuel and, if hydrogen were the fuel, the efficiency would be greater. The factor 0.65 (Bockris & Srinivasan, 1969) is an acceptable projection.

Multiplying these efficiencies (0.95 × 0.85 × 0.65) by the factor 1.7, derived above, gives 0.88. Thus, the equation for transduction from wind to electric power at a distance, after passing through electrolysis and reconversion to electricity, is:

$$P_{elec} = 0.88 \rho v^3 R^2 \qquad (5)$$

At 25°C, ρ is 1.29 10^{-3} g.cc^{-1}. Let R be 100 m, and v the mean annual wind in k.p.h., then:

$$P_{elec} = 2 \times 10^{-4} v^3\ MW \qquad (6)$$

This equation is the power produced over a period of a year by a rotor of 100 m radius.

Let v = 30 k.p.h. Then:

$$P_{elec} = 5.4\ MW \qquad (7)$$

There are many regions in the world with mean annual winds of 30 k.p.h. (*ca* 19 m.p.h.).

THE EXISTENCE OF HIGH-VELOCITY WIND-BELTS

Examination of plots of wind data which cover many years, suggest that the mean annual wind for a location is a reproducible property. Locations in which local topography interferes (such as cliff-tops) will give abnormalities over short distances, and altitude (h) is important. Thus it has been found (L. F. Mullett, pers, comm.) that:

$$\frac{v_1}{v_2} = \left[\frac{h_1}{h_2}\right]^{0.2} \tag{8}$$

Over the sea, winds commonly blow more strongly than on land.

Below 30–40° of latitude, surface winds are about 32 k.p.h. (*ca* 20 m.p.h.) on the edges of anticyclones, and they are rhythmically available. The wind system south of the 30th parallel gives rise to a regular pulsation of medium-velocity winds (Mullett, 1956). These winds are related to those called by mariners 'The Roaring Forties'. Wind-driven vehicles in this area are known to maintain a speed of 27 k.p.h. (*ca* 17 m.p.h.) for long periods, and this figure substituted in equation (6) gives 3.8 MW.

In respect to height, Mullett's observations showed mean annual winds of 42 k.p.h. (*ca* 26 m.p.h.) for ridges several hundred metres in length and about 300 m high. Such ridges could be the site of generators which would give 15 MWs per rotor of 100 metres' radius.

Isovent lines* which show velocities above 25 k.p.h. (*ca* 16 m.p.h.) occur, for example, on the east coast of the United States southwards to North Carolina (Heronemus, 1972); on the west coast of much of Ireland (Stodhart, 1973) and Scotland, and in Alaska (Wentink, 1973), Hawaii (E. Teller, pers. comm. 1974), and the western coast of Chile (Stodhart, 1973).

WIND-ROTOR SIZE AND NUMBER OF ROTORS

Let us take the proposed hundred-metres rotor as giving the equivalent of 4 MW throughout the year. Then, in an affluent community of 10^6 persons with 10 KW per person (industry, transportation, etc.) (Hammond, 1972), the number of rotors needed would be $\frac{10^4}{4} = 2{,}500$.

The minimum distance between rotors depends on wind-shadow, and this must be reduced to a negligible quantity. The requirement may set 5 diameters (1 km) between each rotor. With these assumptions, an aerogenerator station (100-m rotors) supplying a town of 1 million people with its entire energy needs, would be spread (e.g.) over a square with a side of about 50 km.

There are many ways of arranging the rotors. One might be to arrange groups of them, 10–20 in number, in association with a central hydrogen generation and storage system (Heronemus, 1972).

* Lines on a map showing parts of Earth on which mean annual wind velocities are constant.—Ed.

Figure 1 (Mullet, 1956) shows one possibility in which a 200-metres-high rotor rests upon rollers. The design would avoid the strain-on-the-axle difficulty and have a gyroscopic stiffness in resisting wind-thrusts. Other possibilities are shown in Figs 2 and 3.

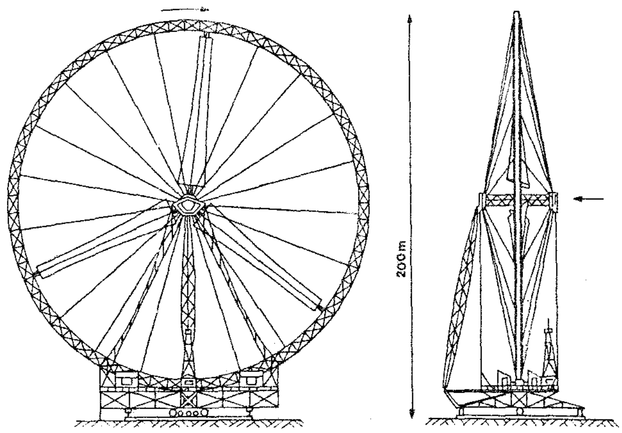

FIG. 1. *A design for a wind generator which does not bear weight on a central axle (Mullett, 1956).*

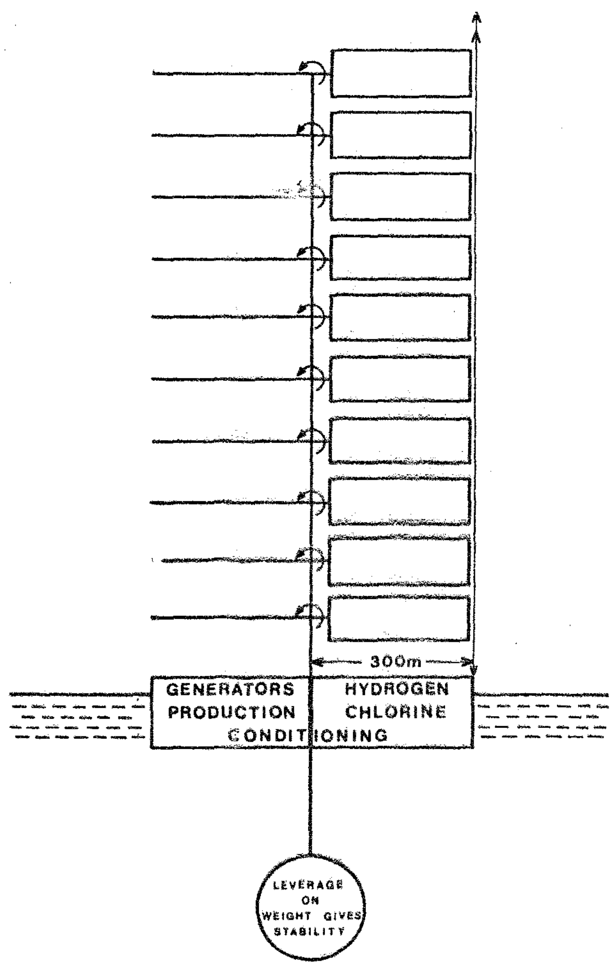

FIG. 2. *Possible design for a large sea-borne generator with individual wind-panels (aluminium frames and sail-cloth) to rotate the central drive-shaft and then rotate themselves to the minimum profile position for rotation direction against the wind.*

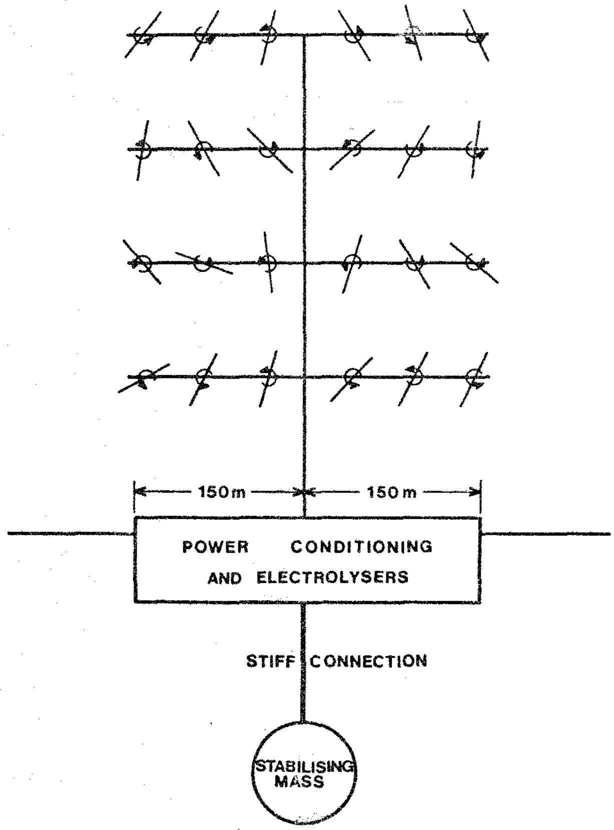

FIG. 3. *Alternative sea-borne generator with a major rotor having a wide radius. A large number of smaller rotors could be used, with a motor generator attached to each.*

THE PRODUCTION AND TRANSMISSION OF HYDROGEN

These topics have been dealt with elsewhere (Bockris, 1973, 1974, 1975). Sea-water electrolysis could be made practical (Bockris, 1975), although chlorine would be produced with oxygen at the anode and would have to be treated chemically with the production of hydrogen chloride which would be rejected into the sea. Several methods (*Ibid.*) exist for doing this, but they imply the construction of auxiliary chemical plants and this is not yet allowed for in cost estimates. Thus, one could be based on a reaction of the Cl_2 with H_2O to form O_2 and HCl which would re-equilibrate with NaCl in sea-water. In deep water, it might be cheaper to carry out the electrolysis at depth (producing hydrogen at 100 Ats, say, and thus avoiding the need to compress it for storage). Venting chlorine at depth of 1.2 km and allowing it to flow ultimately into the free atmosphere might lead to equilibration with water ($Cl_2 + H_2O + 2HOCl$)* before Cl_2 reached the surface. Alternatively, one could pipe the electricity from the sea-borne wind-farms to land and use 'fresh' water to which (non-consumable) sodium hydroxide would be added. The amount of water needed is large: natural waters usually contain some saline constituents.

* A referee comments that he would 'strongly oppose sea-water electrolysis... as perchlorate (HOCl) is a powerful biocide (which, by the way, is used for sterilizing water). Piping the produced electricity to land would therefore' be environmentally preferable.—Ed.

ENVIRONMENTAL CONCERNS

Environmental considerations of hydrogen-associated energy systems have been quantitatively reviewed by Plass (1974). There are no drawbacks to the production of energy by the wind-hydrogen path. It would even overcome the objection that large-scale solar energy-farms would consume much silicon. The rotors would be made of aluminium or iron, both of which are plentifully available.

As regards position, it would be preferable to put the rotors on the sea (Heronemus, 1972), which would correspond to other suggestions for sea-borne energy generators (Bockris, 1971).

STORAGE

There are three ways to store hydrogen† on a massive scale (Jones, 1971; Gregory *et al.*, 1972*b*; Bockris, 1973, 1974, 1975; Veziroglu & Basar, 1974):

(1) Underground in natural or artificial cavities.

(2) As a liquid. For large-scale storage, the cost of liquefaction (about U.S. 50 cents per MBTU) favours the former suggestion.

(3) Underwater storage (Heronemus, 1972). For a town of one million people, 10 vessels, each of about 200 metres' radius, would be needed to store the hydrogen at 100 Ats if the necessity of one month's reserve is assumed.

COST ESTIMATES

The cost estimates for the wind generators cover a fairly wide range. The lower limit would probably be achieved in mass production (Table II).

If one takes \$500 per kW, the cost per kWH of hydrogen energy at T thousand miles from the source would be (U.S. dollars, p is the cost of money in per cent per year):

$$\left[\left[\frac{500p}{100 \times 8760}\right] 100 + 0.15T\right] \text{ cents per kWH + maintenance.}$$

TABLE II

Cost Estimates for a Wind-based Hydrogen Energy System.

	\$ per kW
Wind generators	100–300
Electricity generator	50–150
Hydrogen production	100
Undersea storage facility	50
Fuel cell	150–350
Totals	450–800

† A referee comments that it would be valuable to review also other means of storage, particularly in pumped water.—Ed.

If T = 1 and p = 10, and maintenance is 10%, the cost would be: 0.79 cents per kWH.

DEVELOPMENT OF WIND-ENERGY COMPARED WITH OTHER INEXHAUSTIBLE SOURCES

The technical difficulty, and cost, of developing massive wind-energy generation, would be relatively small. Only developmental work would be necessary. The practicality of the 100-m rotors that have been assumed must be established. Dealing with the chlorine from sea-water poses a fairly severe problem in electrochemical engineering. But the tasks are far less onerous than those facing, for example, the underground gasification of coal, the disposal of atomic wastes, or the confinement of plasma. The absence of all environmental and material problems or need for new engineering methods increases greatly the likely speed of development.

If engineering considerations alone prevailed, wind-energy could contribute significantly to world energy supplies before A.D. 1990. Further, the energy is abundant and, when once pilot plants had functioned, building of stations to take over from oil could proceed rapidly wherever the necessary capital was available. It seems to constitute a more likely avenue for the supply of inexhaustible, abundant, clean energy than any others that are at present being pursued or discussed.

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SUMMARY

To circumvent the coming energy crisis the development of new sources is popularly associated with the gasification of coal and with atomic breeder reactors, although solar and nuclear fusion sources are distant possibilities. But coal is limited in supply and breeders will not be ready in time to replace the remaining oil and natural gas; wind offers a more likely possibility.

The practical equation for electricity obtained after conversion to hydrogen, passage, and reconversion to electricity, is:

$$P_{elec} \simeq 2 \times 10^{-4} v^3 \text{ megawatts}$$

for a rotor of 100 m radius in a location where the mean annual wind is v k.p.h. Thus, for v = 30, $P_{elec} \simeq 5$ MW per rotor.

The concept of large sea-borne rotors in high-velocity wind-belts with long-distance hydrogen transmission offers a more readily attainable (and more environmentally acceptable) prospect than atomic, or solar, possibilities.

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