PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Indirect Utilization of Solar Energy [and Discussion]

Hermann Bondi and J. W. Jeffery

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Indirect utilization of solar energy

By Sir Hermann Bondi, F.R.S.
Department of Energy, Thames House South, Millbank, London, SW1P 4QJ, U.K.

The atmosphere can be regarded as a heat engine converting solar heat into the mechanical energy of wind, which in turn generates waves on the surface of the sea, so that both wind and wave energy can readily be traced back to the solar input.

Wind energy used to be a major source of power, but gave way to the much cheaper and more reliable source presented by coal. Looking to the future, we can certainly make much better windmills (15 % efficiency was perhaps the best in the past) but the improvement in size/cost ratio with increasing size drives one to large structures. A preference for disaggregated supply is needed to put even medium sized aerogenerators into the running, and a house-by-house supply would require quite sizeable structures. Really big structures, especially on the favoured hill top sites, would raise environmental questions that might drive one to off-shore locations, though of course these may well involve increased costs. Vertical axis as well as horizontal axis machines are being studied. Isolated locations, where the competition is less severe, might offer the first chance of economic viability without going to very large sizes.

Wave energy has the great merit of being dependent on a non-local supply. In particular, the longer waves with their high energy content may originate hundreds or even thousands of miles from the scene of exploitation, and so the system has a steadiness much greater than might be expected. Indeed, the U.K. is located in one of the World's most favourable positions.

Engineering exploitation is made difficult by the need for the apparatus to survive the wildest conditions and by the fact that, in many devices, the input is a large force with small displacement, a form of power for which there is little practical experience in its utilization. A variety of devices are being supported so as to establish where we should concentrate our effort. The potential size of the resource and its seasonal phasing in line with demand make this a most essential field of renewable development.

Introduction

It is frequently said that the atmosphere is a heat engine and, indeed, it does convert the incident heat arising from the Sun into various kinds of motion. I might perhaps mention the obvious: almost none of what is described in the earlier papers on biomass would function if, in addition to the conversion of solar energy into chemical energy within the plants, this marvellous heat engine did not transport desalinated water from the sea to land locations through wind, rain and snow. And so the very bones of our existence are entirely dependent upon what this heat engine can do. Indeed, when one thinks about its peculiarities, about the way the actual weather pattern is highly unstable, how the behaviour of winds does not depend only on pressure differences but, through the rotation of the Earth, leads to the transport of low pressure areas over vast distances, one appreciates the complexity of a system which is of fundamental importance.

Wind energy

The possibility of making use of the fact that we already have a heat engine in the atmosphere is, of course, far from novel. Making use of wind is an ancient and, to some extent, still continuing practice. The traditional old English windmills, now carefully preserved as romantic monuments, were at one time common features of the countryside. The efficiency of these mills is now thought to have been at best 15% in terms of the incident energy, the chief loss apparently occurring in the gearing which two hundred years ago presented a tremendous problem. In some areas, notably in Crete, they are still very much in use for irrigation purposes. In our part of the world and many other countries wind energy turned out, 150–200 years ago, to be inordinately expensive compared with energy derived from coal.

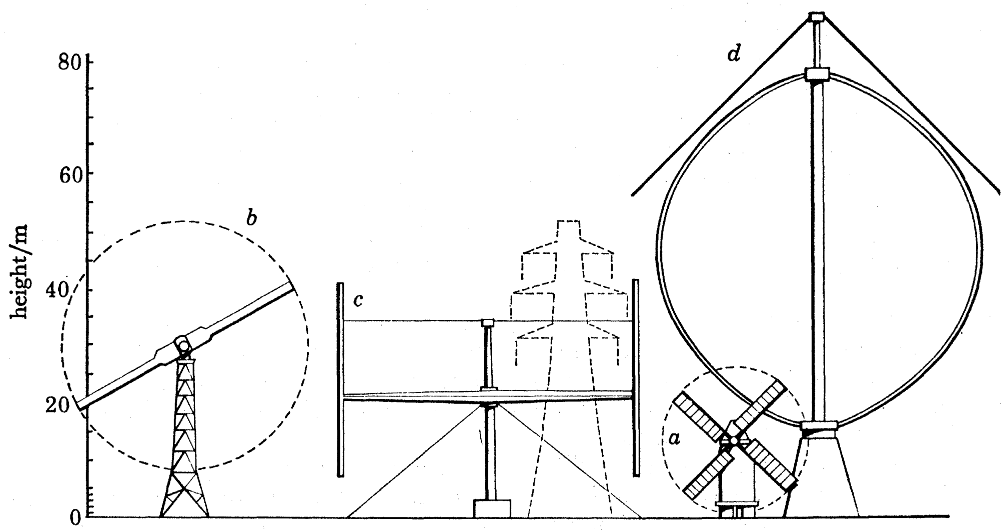

Figure 1. Various designs of aerogenerator (to scale): (*a*) traditional British windmill, (*b*) modern design for horizontal axis machine, (*c*) large vertical axis design (Musgrove, Reading University), (*d*) large vertical axis design (U.S.A.–E.R.D.A.). (Scale illustrated by 400 kV electricity pylon.)

Now the question for the future is how this balance, now heavily weighted in favour of fossil fuels, will develop. Will windmills ever find a place in the energy scene? We can certainly make much more efficient wind machines than was possible in the past. The price of coal, or of other fossil fuels, may not stay at its present level. Indeed, it is now more expensive in relation to some other things than it was 150 or 200 years ago. And so there is considerable interest in what can be done with wind power in our day. At all times one is limited by one's technology and how far one can advance it and develop it, which reflects on the cost of the energy produced.

A point that seems to emerge very clearly from almost any study of windmills is that the ratio of delivered energy to capital investment improves as the size of the machine increases, until sizes are reached where we run out of technology. The stresses in large machines can be very high and some of the major experiments in various parts of the world have run into trouble. It is not a simple thing to build an economic windmill for our day. In this country we are working now on a detailed design of a machine delivering about 4 MW; this is physically quite a sizeable structure. But the questions that immediately arise with anything like that are, first, will there be enough wind to drive it and secondly, if the weather gets really rough will it survive?

Figure 1 shows some drawings, to scale, of wind machines that are being and have been considered. Figure 1*a* is, of course, the good old-fashioned windmill which we all know; alongside it is one of the electricity pylons with which we are all familiar and which gives an idea of size. Figure 1*b* is a modern design of a horizontal axis windmill; figures 1*c* and *d* are both vertical axis windmills, which do not have quite that amount of past experience behind them, although they have been designed and existed in ancient times too. Figure 1*c* is a design evolved in this country by Musgrove at Reading, and *d* is a truly enormous American design. Machines of this kind can certainly be developed, but at a price – and that price is partly money, but there is also the environmental cost to be considered. Those concerned with the electricity supply industry know only too well that putting pylons all over the country does not always meet with applause. There is some freedom in selecting the site for electricity pylons and, in fact, it is preferable not to site pylons on the most prominent, most windy positions. With wind machines we have a situation where, to get the high wind speeds and a good power output, we need to go to hilltops. Those on the western side of the country are particularly favourable, but are often located in beautiful countryside and this would undoubtedly lead to problems of acceptability. And the need for sites with a good wind régime raises the question of how many very good sites there are. If one considers the 4 MW size for which we are having the detailed design done, then even if there were no environmental objections, satisfactory performance would probably be confined to a very few hundred favourable sites throughout the land mass of the British Isles.

An alternative approach which certainly merits very serious examination is to go offshore. There are many areas of the seas around Britain that are very shallow and neither particularly scenic nor used by shipping: sandbanks, the Wash, Dogger Bank and various other areas. At sea, because of the lack of obstacles, wind strengths are usually rather higher than over the land and more persistent: on the other hand there would clearly be extra costs both in construction and in transmission of power. But this is quite a serious possibility which is being examined.

Even at 4 MW we may only just be at a size that begins to be economic for feeding electricity into the grid. However, there are quite a number of regions in the country where electricity is markedly more expensive than the national average. There are many island sites that are uneconomic to connect with the grid and where electricity is produced by local diesel generators burning oil which has to be brought expensively in barrels because there is no jetty available to receive a tanker of any size. In locations of this kind a markedly smaller size of wind generator could be economic now. Again, if you look overseas, particularly at the developing world, there are many places exposed to steady, regular winds, in the trade wind zone in particular. Here there is a strong possibility that significant local wind energy generation may be competitive. The problems in each particular application are to know how complex the machine has to be and where it is to be used – how isolated is the site, what is the competition from other available forms of power? And the last, I think, is universally the fundamental question.

Wave energy

So far we have been considering methods of making direct use of the energy of the wind. We now turn to the possibility of making use of wind energy indirectly, through the fact that the winds create waves on the surface of the ocean. Clearly this has one disadvantage that the transfer process is basically rather inefficient, only a relatively modest fraction of wind energy being transferred to the energy of the waves. If it were otherwise it would not be so windy at sea. On the other hand, the waves, particularly the long waves of the open sea, travel very substantial distances. Thus one is no longer dependent upon having the high wind strength at the point of use. Waves may well be generated by winds at quite a distance from the shores of Britain. The longest waves, particularly, can easily travel thousands of miles across the Atlantic and even come from fairly far south. It is indeed an interesting point, which I always find very intriguing, that by just looking at the wave régime at a shoreline you can make a pretty good guess as to how big the sea is beyond the horizon. By looking at the breakers on the Australian east coast you learn that the Pacific is huge; if you go surfing at Polzeath you know that you are not shielded by Ireland any longer but have the entire fetch of the North Atlantic to your advantage.

Figure 2. Sites of highest available wave energy.

Wave energy is of particular interest to the United Kingdom because this is a situation where we are pretty obviously a leading country in the world. We have shores which are very exposed to waves, and not only are the oceans round us rather wild but the peak of ocean activity coincides quite well with the winter peak in demand for energy and, particularly, for electricity. Thus there is a big incentive for us to investigate thoroughly and deeply this field which is both promising and technologically absolutely fascinating.

Figure 2 is a map showing the regions of the highest incidence of wave energy on our shores: regions where there is a long, unobstructed fetch for the waves where they can arrive from considerable distances away. An important feature brought out by this map is that the very fruitful looking area of northwest Scotland is far from major centres of electricity consumption. Even in the southwest, one is not exactly near to centres of consumption, so that transmission is bound to be a problem in both regions. Whereas the technology of getting energy from wind has a long and respectable ancestry, this is in no sense so for waves. And indeed the technological problems presented are exceptionally severe.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

What one is having to face is not just the problem of a varying incidence of the waves, not just the severe problem of survivability in the worst circumstances – and the worst circumstances round our shores can be pretty bad indeed. Above all, engineers are faced with the technologically strange case of having to produce energy from a natural motion that has low angular velocities but is capable of generating high torques, whereas almost all our technology is based on regular high angular velocities in fast running machines and low torques. If you add to this the fact that the wave motion is always irregular (even with a good swell it is somewhat irregular; with medium and short waves it is highly irregular), then the problem of digesting this into a form that can be mastered for the generation of electricity is seen to be formidable.

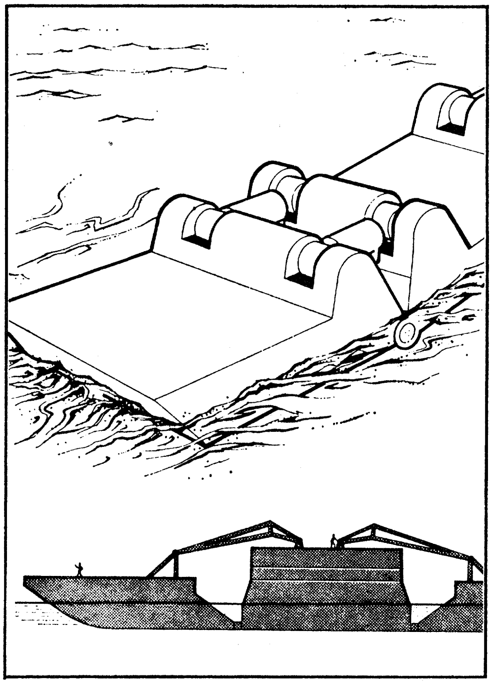

FIGURE 3. Artist's impression of one example of a wave energy device, the 'Cockerell Raft'.

The Department of Energy is supporting the investigation of a number of possible routes for extracting power from the waves. Some of these are fairly well known and are illustrated in figure 3. These are the rafts that were developed by Sir Christopher Cockerell and his group in the south of England. These articulated rafts are moved by the waves and it is their relative motion that is used to generate energy. Technical problems centre on the hinges and on the methods to be adopted for power take-off. On the other hand, with such relatively well understood shapes, the survivability problem is somewhat less than in other designs. We have a one-tenth scale set of these in the Solent off Beaulieu, where they have been performing for some time and providing valuable operating experience.

Another type that is well known are the ducks developed by Dr S. Salter of Edinburgh University. Here, floating bodies, specially shaped to extract efficiently energy from the waves, are mounted along a long straight rod (the spine) and the motion of each of a string of these bodies relative to the spine generates the energy. The spine maintains itself in an average position with these various ducks, as they are called, along it. Again we have a one-tenth scale model in operation, this time in Loch Ness near Inverness. Here we use the long fetch of Loch Ness, where, under southwest winds which are fairly common, waves are generated and interact with the model to give a good picture of what things would be like in a full scale system at sea.

There are other devices which are being tried: there is, in particular, a method pursued by the National Engineering Laboratory designed to turn the motion of the water into air motion, which then drives an air turbine. The device consists of a floating body with a set of cells open to the sea. As the water goes up and down it pumps air in and out of the cell through suitable valves to drive an air turbine. Transferring the motion from water to air removes many of the mechanical problems of gearing to convert an erratic motion into useful power. This concept is not new: about a decade ago the Japanese used this system to power light-buoys for navigational purposes. In these, a small unit working on this principle provides the few watts which are required to power the buoy. The Japanese, under the leadership of Cdr Masuda, have now moved to experiments on much bigger systems in which we are also participating. These consist essentially of a catamaran with two floating bodies joined by a deck that supports cells underneath in the water. On top of the deck are mounted the air turbine and valve sets. This vessel is now actually on station off the Japanese shores.

It is very hard to predict the future for wave power. It is certainly a big resource. The amount of energy that hits us on an ordinary winter's day, which is, after all, the time of maximum energy demand, is very considerable, measured in tens of megawatts per kilometre. The total power of the waves breaking on our coasts is probably rather in excess of our total electricity generating capacity in the country. On the other hand, it still remains to be investigated how much of this can be converted to useful power, at what cost, with what degree of reliability, and with what capacity to survive particularly high seas or avoid dragging its moorings and so becoming a danger to all and sundry. What the costs of this type of energy will be is also something that we do not yet know. However, we are most determined to find out. To learn about these very novel kinds of technology will take time. I do believe that, a few years from now, we will have a very much better idea than we can have today about what can be done with wave power, what fraction of the incident energy can be harnessed and at what cost and what risk.

Discussion

J. W. Jeffery. Martin Ryle in his review article 'Economics of alternative energy sources' in *Nature* (12 May 1977, pp. 111–117) has shown the possibility of producing from wind power more electrical energy (960×10^6 GJ/year) than the whole output of all our power stations at present (770×10^6 GJ/year). The only attempt to refute the detailed calculations in this review (letter from Dr Clements of A.E.R.E., Harwell, *Nature*, 4 August 1977, p. 396) was demolished the following week by Martin Ryle (*Nature*, 11 August 1977, p. 482).

If space heating is included in the electricity load the peak power required is some three times the average. How would such a large variation be dealt with in such a situation? The answer can be given in the words of Mr D. J. Miller, Director of Engineering of the S.S.E.B., 'I think the answer must be a reliance on energy storage devices – there is no other practical way of doing it' (Royal Institution Conference on 'Nuclear Power and the Energy Future', Oct. 1977, p. 167).