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A.B.

Cover illustration, Blakesley tower mill, 1899, by F.C. Gill.

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continued inside rear cover

TIDAL POWER: FROM TIDEMILL TO SEVERN BARRAGE

By Gordon Tucker

1. Introduction

Tidal power has been used on a small scale for centuries to drive waterwheels for corn-mills, and there were some electricity- generating tidemills in the last two decades of the nineteenth century. The impression of colossal power in the tides, as witnessed in the flow of large estuaries, has led to much thinking about the possibility of exploiting this power for the generation of electricity on a large scale. Nowhere has this thinking been more evident than in relation to the Severn Estuary, where the funnelling and resonance effects make the tidal rise and fall among the highest in the world (e.g. on the Cardiff-Weston line the mean range on spring tides is about 11m or 36ft). The trouble is that while the energy or power of the tides can be to some extent visualized, it is hard to visualize the energy actually generated by a country's electricity system or drawn from it by the consumers. It comes, therefore, somewhat as a surprise to learn that the total annual energy which could be extracted from **all the world's** tides would not be likely to be more than twice the present total annual energy demand on the British electricity network, [1] which is of the order of 200 terawatt-hours (TWh or 10^{12} watt-hours), perhaps more easily understood as 200 billion units. The prospect of **British** tides supplying a dominant part of Britain's energy needs is therefore small. Nevertheless, tidal power is inexhaustible and pollution- free and therefore not without its attractions. This paper traces the changes in thinking over the years, especially in relation to the Severn Estuary.

To set against the two advantages just mentioned, tidal power has the formidable disadvantage that the power is not continuously available; the tide ebbs and flows, so that there are four zeros of flow, or two peaks of height (or "head"), in every period of just over one day. Moreover, the time of the peaks varies from day to day. By no direct system can electricity be generated when it is most required, so that tidal power can be used, in all except a few limited special applications, only in conjunction with energy storage. In most of the small unambitious tidal- electricity systems proposed or tried in the last two decades of the nineteenth century, the storage was electrical storage in secondary batteries. In more ambitious systems a retiming of water flow was proposed by the use of multiple basins, but these involved a large loss of available power. In the Severn Estuary proposals of the 1920s and 1930s, pumped storage was involved, in which electricity generated from tidal power when it was not required was used to pump water from the estuary to a reservoir at a height of nearly two hundred metres, from which it could be used to generate another supply of electricity when the demand for it arose. However, once the national electricity grid became available in the 1930s, there was more possibility of absorbing power into the system by shutting down some thermal stations when it was available, and storage became less important. Now, in the 1980s, the grid has its own pumped-storage facilities, and any proposed tidal-power contribution has to be viewed merely as part of a very large and complex system. Thus the simplest tidal system is now generally the most attractive.

So far only technical and operational aspects have been discussed. There are two others which are critical too: economic and political.

It has always been hard to show a very marked economic advantage for tidal power. There is, of course, no fuel cost, and the life of the plant is likely to be long. But against this is the fact that the capital cost of the huge barrage involved is enormous and the time of construction is very long - say ten or fifteen years. Capital charges ensure that the electricity generated is not appreciably different in cost from that generated at thermal or nuclear power stations.

In the political field, however, these very disadvantages of high capital cost and long construction time can become great advantages, for they represent the creation of a large number of long-term jobs. It is not coincidence, therefore, that it is in periods of high unemployment (1920s, 30s, late 40s, late 70s and 80s) that so much is heard of the Severn Barrage proposal, and that there is relative silence in the prosperous 1950s and 60s. Another political attraction of tidal power is that there is no fuel supply that can be withheld during industrial disputes, nor can inflation seriously affect the cost of generation once the system is built. The possibly damaging effect of the system on the physical environment, however, could have adverse political repercussions; environmental considerations need to be handled with great sensitivity

2. Outline of history of tidal power proposals and practice.

2.1. Tide-mills.

The use of the tide for operating corn mills is many centuries old - certainly over seven centuries. The basic concept of the mill was no different from that of any other watermill; water flowed from a higher level to a lower level via a waterwheel, which thereby drove the machinery of the mill. The distinguishing feature of the tide-mill was that the water at the higher level was accumulated in a pond behind an embankment by the flow of the rising tide into the pond, through a sluice which closed when the pond was full and the tide started to fall. The waterwheel could be driven as soon as the tide had fallen sufficiently to clear the blades or paddles of the wheel. If enough water had been ponded in relation to the desired rate of work, work could be continued until the tide was rising again.

The tide not only goes through an approximately daily (25 hour) double cycle of high and low water, but also through an approximately fortnightly cycle of variation of the tidal range (minimum at "neaps", maximum at "springs"). There are other, less important, cycles too. So the amount of work that can be done by a tide-mill varies from day to day.

The ordinary waterwheel has more disadvantages in relation to a tide-mill than to ordinary water mills. As the wheel has a fixed axis, the tail-race level must be fixed just below it, yet the tide level may have fallen well below this; thus part of the head is wasted. The use of reaction turbines with a draught tube would avoid this loss.[2]

The period of work could be (but rarely was) extended by the use of two basins: one a high-level pond as before, the other a low- level basin emptying out through a sluice or sluices at low tide. The waterwheel operates in a channel connecting the two basins.

The number of tide-mills in Britain was once quite large, counted in hundreds, as shown by the researches of Professor Walter Minchinton and his colleagues.[3] Now none are left in commercial work, but at least three have been restored to working order, at Woodbridge (Suffolk), Eling (Hampshire) and Carew (Pembrokeshire).

At least one case of the use of the tide for generating electricity for the lighting of a house is documented. In 1894 it was reported that[4] that a house on the Cheshire coast was electrically lit from a 4 horse-power tidal plant. Batteries would have been necessary to obtain the light when required, the tidal power providing the charging current.

Just as ordinary water mills were rarely built on main rivers but rather on smaller side-streams in order to minimise the difficulty and cost of the engineering work, so tide-mills were usually built on small tidal creeks rather than on estuaries. An example which is now fairly well-known through restoration is the tide-mill at Carew, situated on a quite remote reach of the Cleddau estuary.

2.2. Early tidal proposals for electricity generation.

(a) In relation to the Severn Estuary.

First of all, it is worth mentioning that a proposal for a barrage across the Severn Estuary was made in 1846.[5] This was to be made at the Aust Passage, and was to carry road and railway links. Naturally, at that date there was no question of electricity generation, nor was there any suggestion of power being derived in any other way.

The public supply of electricity began in 1881, and it therefore shows considerable initiative on the part of Bristol councillors that in November of that year they seriously discussed a proposal to dam the River Avon in order to use the tidal power (not just the ordinary river flow) to generate electricity to enable them to replace the gas lights in Bristol by electric lamps. Councillor Smith had consulted Sir Charles Bright (of telegraph fame), and Professor Silvanus P. Thompson had done some calculations. He estimated that the 4274 gas lamps in the city were using 40×10^{12} ft.lb. of energy per year, but that only one-twentieth of this would be needed to give the same light by electric lamps; i.e. 750,000 kWh (or units) or what we would now call 0.75 GWh (Gigawatt-hour). A dam at Totterdown, above Bristol, was estimated to be able to produce a tidal energy of 2.5 GWh (in modern terms) per year, and at the mouth of the Avon perhaps 20 GWh.[6] At this early stage in the history of electricity supply there was clearly no need to think of harnessing the Severn Estuary itself; its tributary estuary, the Avon, would be more than adequate.

A committee appointed by the Council to consider this matter reported at the beginning of January 1882.[7] They were "of the opinion that it is within the range of practicability to convey to Bristol ..... power obtained by the action of the tides, but are unable, without the aid of professional advice, to report how this may best be done...." and asked for £100 to enable them to get such advice. After much discussion this was agreed. The curious and disappointing thing is that no more was heard of the matter; the minute books and the press are silent. Latimer (1893) merely says that "the investigation led to no practical results",[8] and Wells (1909) says the same.[9] Probably the matter became completely overshadowed by the discussions about converting the river into docks.

(b) A few examples elsewhere.

Power from the tides remained a theme of interest during the next 40 years, as the following examples show.

Poole Harbour, 1881. The surveyor proposed the electric lighting of the town of Poole by the use of tidal power from Poole Harbour, a large almost enclosed tidal inlet.[10]

Bombay, India, 1886. Tidal power proposal being seriously discussed by local journals; battery storage system.[11]

Sullivan Harbour, Maine, U.S.A.. Large tidal lagoon filled through a narrow gorge; to be used for generating electricity to light the town.[12]

River Seine, France, 1890. Two two-basin tidal power systems proposed producing thousands of horse-power.[13]

Barrage across Irish Sea, Kintyre to Northern Ireland, 1894. An ambitious project with a power station at each end.[14]

Santa Cruz, Pacific Coast, 1895. The electricity to light the town and drive the street-cars. Claimed to be actually in progress and near completion, but no more heard of it.[15]

Cuxhafen, then Husum, Germany, 1908-12. Two-basin scheme of about 5000 horse-power apparently received Government sanction; purpose to supply a large part of Schleswig-Holstein.[16]

Bay of Fundy, New Brunswick, Canada, 1919. Scheme to utilise the world's highest tidal range.[17]

2.3. Electricity-generating proposals for the Severn Estuary, 1920-present time.

Apart from one or two rather tentative proposals before 1918,[18] the first serious proposals for a large-scale electricity- generating Severn Barrage scheme appear to have arisen immediately after World War 1 from a number of sources, important among which was the Great Western Railway, which was primarily concerned with getting a better transport link across the estuary, and saw the barrage as a possibly economically-attractive way of doing this. The first intimation appears to have come from an article in *The Times* on 26 November 1920, but it was on 29 November that a further article attributed the scheme to Mr J. F. Pannell, an employee of the G.W.R.. Apparently separately, however, the Water Power Resources Committee of the Board of Trade had been giving preliminary consideration to a Severn Barrage, and issued its report on 1st December 1920.[19] This was basically a list of possibilities and problems, but had a favourable tone. There was no electricity grid at this time, and it is interesting that it was thought "very likely that the whole of the energy could, in due course, be absorbed locally. The application of a portion of the energy to railway traction in the dense traffic districts of the South Wales coalfields ... is indicated." Storage was envisaged as a possibility but "means for making economical use of intermittent supplies of energy must not be ignored." Nevertheless, high-level pumped-storage was an integral part of the system described in *The Times* on 26 November 1920, and in the account in *The Electrician* on 3 December 1920 (p.659). The barrage was to be roughly on the line of the Severn Tunnel.

There was much discussion of the scheme in Parliament over the next few years, a major attraction of it for M.P.s being the relief of unemployment. Indeed, it was frequently in debates on unemployment that the matter of the Barrage was raised.

During the dozen years after the 1920 report, there was much consideration of the Barrage scheme by official committees and consultants, and the most important results were the reports of Professor A. H. Gibson of Manchester, published in May 1929 and October 1932,[20] concerning the hydraulic problems, and of the Severn Barrage Committee of the Economic Advisory Council, published in 1933,[21] concerning the scheme as a whole. Articles in the technical press also explained and discussed the project.[22] The scheme was much the same as in 1920, with high- level pumped storage. It is described in Appendix 1.

Table 1 has been prepared to present a summary of the main features of the principal Severn Barrage schemes from 1920 to the present, and details will not be discussed at this stage.

There was further discussion, but World War 2 interrupted it for a while; then in 1943 a new Panel was appointed by the Minister of Fuel and Power, and this reported in 1945.[23, 24] The barrage itself was to be much the same as in the previous proposals, but there were two important differences: a fundamental one, that there was to be no pumped-storage of any kind, because the development of the national grid had made it possible to envisage absorbing the scheme into the national network, so that it no longer required a localised system; and a more arbitrary one, that there was to be no associated transport system for road or rail.

Again, nothing more was done, and there seemed to be a lull in the subject during the period of growth of affluence. It was the work of university engineers (Dr T. L. Shaw at Bristol, Professor E. M. Wilson at Salford) that brought it out again around 1970. Recently it has been to some extent the environmental movement that has "raised its profile", and very serious proposals are now put forward. They will be discussed in later sections.

2.4. Electricity-generating proposals (and actualities) using tidal power in estuaries other than the Severn, 1920-present time.

In Britain, a very comprehensive survey of tidal power potentialities was made in 1923 by Davey,[25] whose book had over 260 pages, with maps, and discussed 63 possible locations in Britain. By modern standards these were not all ambitious schemes in terms of capacity, but the output power, if all were realised, would have been about 2000 MW continuous. The advantage of a distributed scheme like this, with stations from the south coast of England to the north of Scotland, was that tidal peaks would be distributed over the whole day, and that assuming a full electricity grid system, there would be no need for storage. The scheme was, of course, far before its time, and made demands on capital investment which no private or public body could meet in a foreseeable period.

More recently, suggestions for barrages in the Solway Firth, in Morecambe Bay, and at Strangford and Carlingford Loughs in Northern Ireland, have been put forward,[26] but with comparatively little support.

Probably the world's only modern operational tidal power scheme is that on the Rance Estuary in France. This was commissioned in 1966.[27] By modern concepts, it is quite a small plant; the maximum generating capacity is only 240 MW, and the total net energy supplied in a year is only the order of 0.5 TWh (or 500 million units). But it has many pioneering features of operation. The turbo-generators are fully reversible; not only can the turbines respond to water flow in either direction (i.e. to either inflowing or outflowing tide), but they can also work as pumps when the generators are supplied with electricity from the grid and used as motors. This gives great flexibility of the times during which generation takes place, and can increase efficiency by enabling overfilling or overemptying to take place. As an example, suppose generation takes place on outflow. The inner basin would normally be filled on the flood, the sluices closed, and then when the tide has ebbed enough to give a head, the basin will be slowly emptied through the turbines. Now suppose that towards the end of the flood tide, electricity has been drawn from the grid to drive the turbines as pumps and overfill the inner basin by say 0.5m. Only enough electricity will have been needed to lift the water 0.5m. But when this extra water is used to drive the turbines, it works with a head of several metres, and thus generates much more energy than that taken for pumping. Overfilling of this kind is a feature now of most tidal power proposals.

Date of proposal	Approx. position of barrage	Maximum generating capacity (MW) (note1)	Max. energy supplied in average year (TWh) (note2)	Average generating capacity (MW) (note3)	Capital cost £M	Cost per KWh	Pumped-storage high level	Pumped-storage low level	Rail/ road crossing
1920	Severn Tunnel	650	1.36	160	30	0.62d	yes	no	yes
1933	Severn Tunnel	778	1.60	184	50	0.23d	yes	no	yes
1945	Severn Tunnel	800	2.36	270	40	0.20d	no	no	no
1970	Lavernock-Brean Down (Cardiff-Weston)	3500	1.19	140 (note4)	1000	?	no	yes	?
1974	Aberthaw-Watchet	8500	25.00	2900	2500 +	?	no	2-basin scheme	no
1981	Lavernock-Brean Down	7200	12.90	1470	5660	3.10p	no	no	no
1986	Lavernock-Brean Down	7200	14.40	1640	5543	3.00p	no	no	?
1986	2Km below Severn Tunnel ("English Stones")(note5)	972	2.80	320	1150	2.90p	no	no	probably

Note 1. This is the maximum capacity of the installed equipment.

Note 2. Assumes that all energy that can be supplied is taken. There is a small yearly variation of maximum tidal energy available.

Note 3. This is the quantity in previous column divided by the number of hours in a year.

Note 4. This scheme is conceived primarily as a pumped-storage facility for the National Grid and only secondarily as a means of feeding additional energy into the system; hence the small quantities in this column and the preceding one.

Note 5. This is the less-favoured of the two 1986 schemes.

TABLE 1. Summary of the Severn Barrage electricity-generating proposals.

The 24 turbo-generators, each of 10 MW, are of the 'bulb' type, in which each complete machine set operates in a tube in the dam, and the turbines are of propeller type. Although in Severn Barrage proposals the machines are much larger, they are now always of this type. Overfilling of the inner basin for ebb generation is accepted as a standard feature of most of these proposals.

A Russian pilot plant to demonstrate a new method of construction was commissioned in 1968,[28] at Kislayaguba on the Barents Sea. Instead of the cofferdamming method used at La Rance, this scheme used prefabricated caissons, each containing sections of the power station, towed to the site and sunk onto a prepared bed. The method was so successful that it has been proposed for all recent Severn Barrage schemes.

New ideas being considered for other areas, such as the Bay of Fundy, include the direct production of compressed gas instead of electricity from the tidal power, the storage of this gas in underground caverns (e.g. former salt deposits), and its use to generate electricity as and when required.

3. Severn Barrage proposals of the 1980s.

Interest in the Severn Barrage continued throughout the 1970s, and the proposals described in Appendixes 2 and 3 were followed by others, described in Department of Energy papers[29,30] and elsewhere. In 1978 the Secretary of State for Energy set up a committee under the chairmanship of Sir Hermann Bondi to assess the feasibility of a Severn Barrage. The findings of this committee were published in 1981.[31] They were generally favourable, but even after the expenditure of £2.3M on the study, they felt that there were too many areas of doubt and ignorance for a decision to be made. So they recommended that a much larger study should be undertaken at a cost of about £20M. This was agreed, and a consortium of six interested firms was set up with the name "The Severn Tidal Power Group" with funds at least partly provided by the Department of Energy. The group's studies were published in 1986.[32] Although they had to leave room for a Government decision regarding the placing of an Enabling Bill before Parliament, they were firmly of the opinion that the "building of an energy generating barrage on the recommended Cardiff Weston alignment would be of great value and a permanent asset to the country." The government's response was the funding to the extent of £1.42M of a £4.26M study of outstanding problems to be undertaken in equal parts by the Government, the CEGB, and the Severn Tidal Power Group, and to be managed by the latter. The plan was outlined in a consultation document[33] published in February 1987. That is how the matter stands at the time of writing.

The barrage proposals referred to above are described briefly in the following sections.

3.1. Energy Paper 46 (1981).

Regarding the location of a barrage, this paper pointed out that the range of tide decreased as one went further out in the estuary, so that, although a longer barrage further out would, by enclosing a disproportionately larger volume of water, manage to generate more energy that one closer in, the cost per unit of energy would be greater. A balance has therefore to be struck where a worthwhile amount of energy is generated at a cost per unit not significantly above the minimum. In this report the recommended location for a barrage was the line from Lavernock Point to Brean Down, enclosing the two small islands of Flatholm and Steepholm, as shown in Figure 1, and there indicated as "First Stage". This would have 160 turbine-generators, each 9m diameter and of 45 MW generating capacity, giving the total generating capacity of 7200 MW shown in Table 1. The estimated total energy output in an average year would be just under 13 TWh, i.e. 13 billion units, at a cost of just over 3p per unit, which is less than the cost per unit from a thermal station but higher than that from a nuclear station. Thus the economic attractiveness of tidal power depends on the proportion of nuclear capacity in the national system. With the low proportion at present in Britain, tidal power has a potential economic advantage.

Ebb generation, without pumping to increase the flood level, and with no pumped-storage system in the estuary to permit re-timing of the supply, was the plan. This avoided the use of reversible pump-turbines, which are less efficient than straight turbines. But a possible second-stage development was suggested, as shown in Figure1, with a long embankment and then sluices and turbines, reaching to Minehead; this would operate in the flood-generation mode and thus provide electricity over an additional period. However, the cost per unit was a good deal higher, and the building of this second stage could be foreseen only if the general power scene in the country changed considerably.

Ebb generation is more effective than flood generation because the area of the basin is greater at high-tide level than at low- tide level, and the basin therefore empties more slowly than it fills up.

The document also discusses the possibility of a barrage right across the estuary from Minehead to west of Aberthaw, i.e. even further out than that proposed by the CEGB in 1973-4 (see Appendix 3), but this was shown to have no economic attraction.

In case it is not obvious, it is perhaps worth mentioning that in all Severn Barrage schemes, provision has had to be made for shipping to and from the various ports in and connected to the estuary within the barrage, notably Sharpness and Gloucester in all schemes; and Avonmouth and Bristol, and Newport and Cardiff, in more recent schemes. This is done by inserting locks in the barrage at the most suitable place for shipping, i.e. in the deep-water channel. The locks in the 1981 scheme are clearly marked in Figure.1.

3.2. Severn Tidal Power Group (1986).

This very detailed study followed the suggestions of *Energy Paper 46* by considering a barrage on the Lavernock-Brean Down line (always referred to as the Cardiff Weston line), but also considered a less ambitious barrage scheme on a line about 2Km below the Severn Tunnel (the "English Stones" line) put forward by one of the firms in the consortium. As a result of the more detailed studies it was concluded that it would be worthwhile to use the turbines as pumps to overfill the basin at the flood, and Fig.2 shows a graph of the water heights against time for a typical cycle. It was also thought that the adoption of 160 turbines of 9m diameter and 45MW capacity, as recommended in *Energy Paper 46*, was too much of a step in the dark; instead 192 turbines of 8.2m diameter and 37.5MW capacity were chosen for the Cardiff Weston scheme. The costs are shown in Table 1, and it will be seen that for the longer barrage, the total energy produced is greater and the cost per unit lower than in the 1981 scheme, mainly because of the use of overfilling of the basin, especially at periods of low tidal range. The financial performance of the shorter barrage is good, but it is not very ambitious and has too many unknown factors relating to the movement of sediments. The Cardiff Weston scheme is recommended for adoption. The consortium considered that it would be difficult to finance it entirely by private risk capital and that there should be Government assistance.

The contribution to employment would be considerable: 280,000 man-years of direct and 140,000 man-years of indirect employment, followed by over 25,000 permanent jobs, direct and indirect.

3.3. Firm Power Contribution and national significance of tidal power.

In the reports which form the basis of this Section 3 of the paper, a term "Firm Power Contribution" is used which has important implications. It is defined as the installed capacity (in MW) of a thermal or nuclear generating station which would have to be provided to meet the same demand with the same margins in the system that the tidal station could meet. Obviously this is very different from the peak output from the tidal station, and is equally obviously related to the storage capacity of the national network, and to the temporal pattern of demand. But for the Cardiff Weston scheme, the Firm Power Contribution is given as 1,100MW. This is not very different from the generating capacity of a modern nuclear station; the Heysham station under construction is rated at 1,320MW. So if we had the Severn Barrage, we could manage with one less nuclear station or perhaps one less coal-fired station. In view of the popular emotional antipathy to nuclear stations and the proven environmentally-lethal acid rain from coal-fired stations, this would be a very welcome thing. It is difficult to see why we still await a decision.

In Table 1 there is a column "Average Generating Capacity", which is a term coined by the present author. It is useful in being more obviously calculable than "Firm Power Contribution", and in giving some sort of picture of the size of the scheme in comparison with ordinary stations.

A statement from *Energy Paper 46* on the subject of storage is worth quoting without comment:-

"Storage is a property of the overall electricity supply system and the amount of storage must be chosen in the context of the overall system, not by having regard to one particular type of generating plant. The need for extra storage is thus decided by examining various possible ways in which the electricity supply system might develop with and without tidal power.

Analysis shows that except in the case of systems with a high proportion of nuclear power, **the introduction of tidal power would not lead to the need for more storage. Tidal power may be injected directly into the system displacing the operation of other plant."**

3.4. Constructional Methods.

The basic system of construction of the barrage is to use plain embankment made of dredged estuarial material lined with stone for those portions which are in mean depth of less than 15m and which have no operational function, and to use prefabricated caissons of reinforced concrete in deeper water and to carry the sluices and the turbine-generator units. The length of the section containing the turbines is 3.6Km and this has to be in deep water; thus the alignment of the barrage is to a large extent dictated by this. Because of this factor, the STPG concluded that the alignment shown in Figure 1 should be changed to make the turbine section run more nearly west-east, and the barrage would therefore leave the island of Steepholm outside the basin.

The caissons would be built on a special site at the side of the estuary, and the machinery would be fitted into them before they were towed into position and sunk on to a prepared bed.

While a decision on the exact landfall of the two ends of the barrage was deferred, yet a preference was expressed for points slightly to seaward of Lavernock Point and Brean Down.

Locks to enable shipping to pass through the barrage have to be provided, and since these require to be in deep water, they have to be in the deep channel near the Welsh side which is not used by the turbines. There is some uncertainty as to the size of lock to be provided, but provision for ships of 150,000dwt is discussed, with dredged channels of minimum depth of 11m. Rather than build the locks in caissons, it is preferred to cut them through artificial sand islands.

3.5. Environmental Factors.

Even a casual thought shows that the presence of a barrage scheme alters the environment greatly, although it proves very difficult to estimate the effects with any sort of precision. Within the basin enclosed by the barrage the cycle of variation of water level is grossly changed, with a twice-daily upper level (assuming overpumping

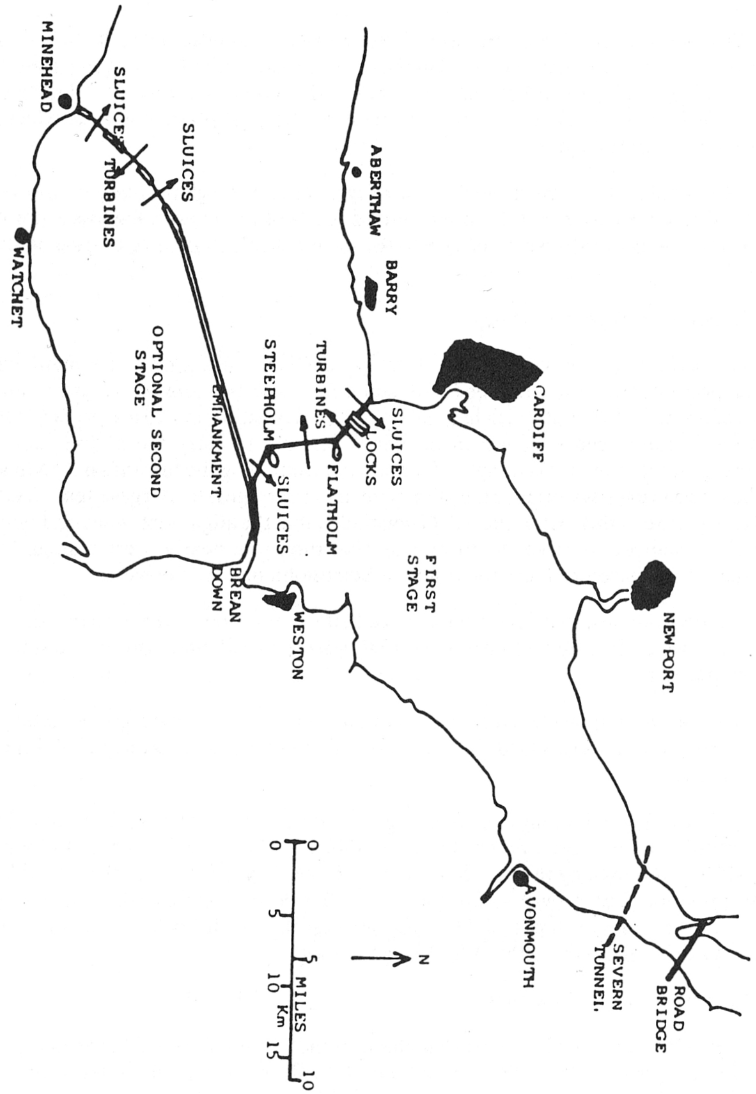

Figure 1. The Severn Barrage proposals of 1981.

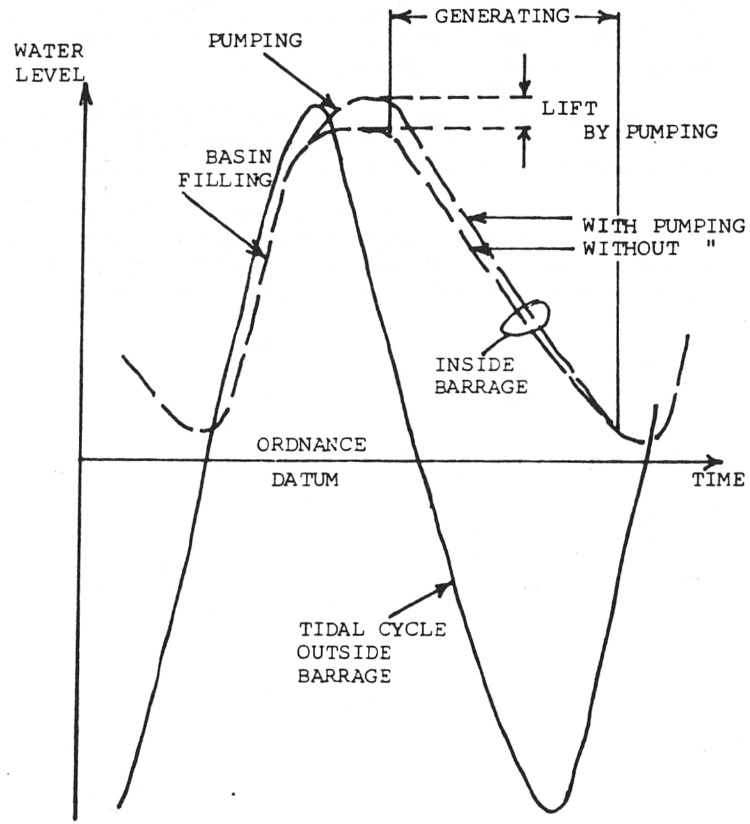

Figure 2. Water levels at the Barrage with and without pumping. (1986 scheme)

as described) roughly equal to that of spring tides, and a lower level slightly above normal meantide level. This would affect birds and plants.

The barrage obviously affects the movements of sediments. Much less mud and sand would be kept in suspension within the basin than at present. This matter is much more serious for the shorter English Stones barrage, where it is estimated that half the storage capacity could be lost in between 10 and 100 years by increased sedimentation. Salinity, and water quality generally, could be affected by the barrage. The reduced turbidity would lead to greater biological activity. The different water levels would probably adversely affect drainage and increase effluent concentration. Fish could be damaged in passing through sluices and turbines.

Some of the environmental effects are likely to be harmful, but some are likely to be beneficial.(34) And we must remember the point already made that the barrage scheme would require one less nuclear or coal-fired station to be built.

The environment would also be affected by a decision to make a road across the barrage. The network of connecting roads which would have to be built, while providing welcome employment, would absorb much land and be detrimental to the landscape, and lead to some pollution of the atmosphere by noise and fumes.

APPENDIX 1.

Description of the Inter-War proposals with High-Level Pumped Storage.

As stated in section 2.3, there was continuous consideration of the Severn Barrage proposal between the original statements in 1920 and the Report of the Severn Barrage Committee in 1933; during this time the scheme varied only in points of detail as various parts of it were worked out by consulting engineers and other experts. Therefore what we shall do here is give a summary of the scheme as described in 1933.

The site of the barrage is shown in Figures 3 & 4. Navigation would be continued and suitable locks and piers, etc, would be provided. Road and rail transport would be provided partly along the line of the barrage. The electrical energy output from the barrage itself, assuming 67 of the 72 turbines were working, would be

4.68GWh on each spring tide

3.19GWh on each mean tide

1.3 GWh on each neap tide.

Over the average year, the total potential output from the generators would be 2252GWh or 2.25TWh. It was estimated that the cost of this would be about 0.18d per KWh. It was, however, also recommended that a high-level pumped-storage scheme should be provided to enable the energy to be supplied to the grid at controllable times and at controllable rates. This would have a pipe-line between the River Wye at Tintern and the high-level reservoir at Trellech Grange (see Figure 5). Some of the energy generated at the barrage would be used to pump water up to the reservoir, and the water from the reservoir would be used to generate electricity by machines at Tintern when the demand arose. The reservoir would have a top water level of 500ft. above Ordnance Datum, and at this level an area of about 750 acres. It was estimated that the energy stored between 500ft. and 450ft. would be about 20.5 x 10^6hp-hours, and between 450ft. and 400ft. about 6.5 x 10^6hp-hours. The total energy stored between 500ft. and 400ft. would be about 27 x 10^6hp-hours, or in electrical terms, about 20GWh. As this was more than four times the energy generated at the barrage even on a spring tide, there was clearly no need to worry about the reservoir filling and emptying on every tide; the daily variation in level would be relatively small, but there would be variation more nearly approaching the full amount over fortnightly and longer periods. As the water was from the estuary, it would be salt, or at any rate brackish, and there would therefore be an environmental problem different from that of ordinary hydro-electric systems. There would also be an environmental problem at Tintern; the pumping and discharging of so much water would affect the salmon fishery and alter the silt deposition.

The use of pumped storage evidently increased the cost of electricity supplied to the grid, and also reduced the overall amount of energy because of losses in the additional processes involved. It was estimated that in one year about 700GWh would

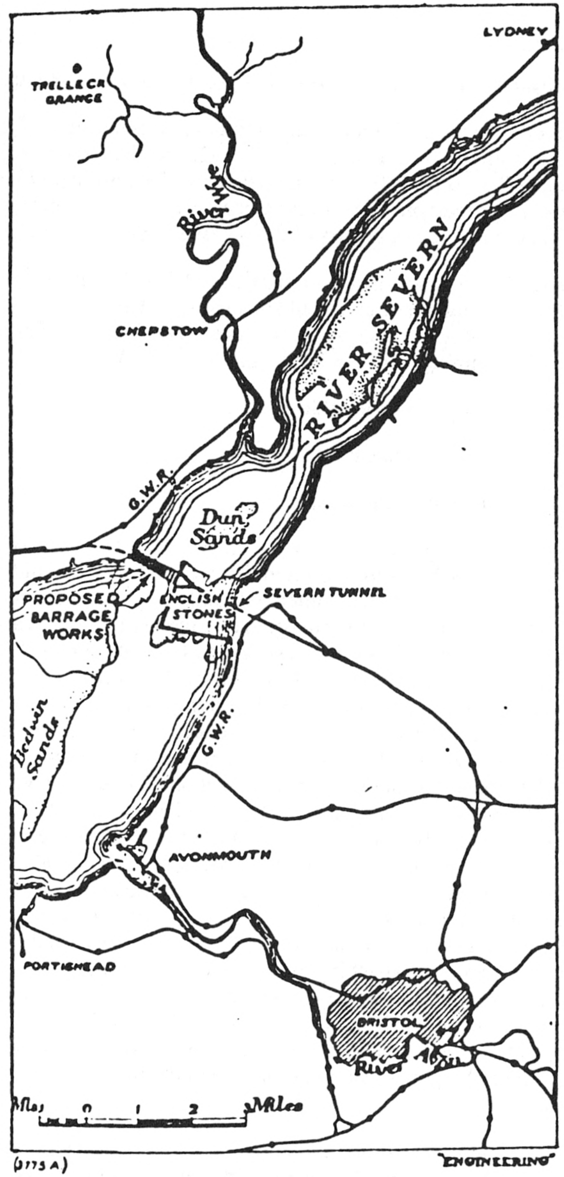

Figure 3. Map of the Severn Barrage Scheme , 1933. (*Engineering,* 7th April 1933)

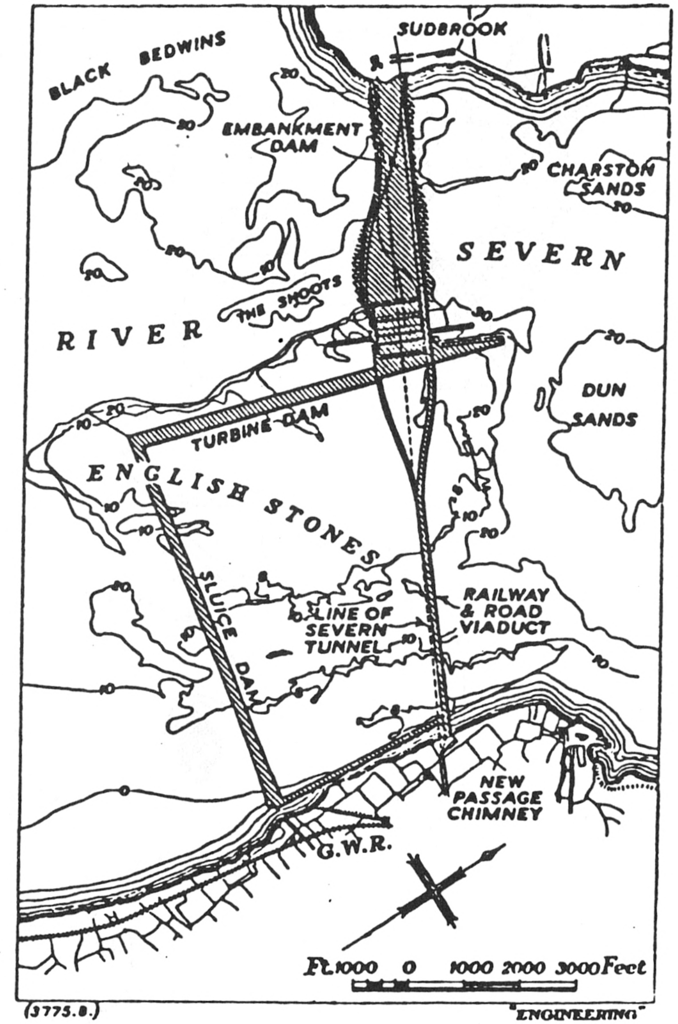

Figure 4. Map of the Severn Barrage Scheme, 1933. (*Engineering,* 7th April, 1933)

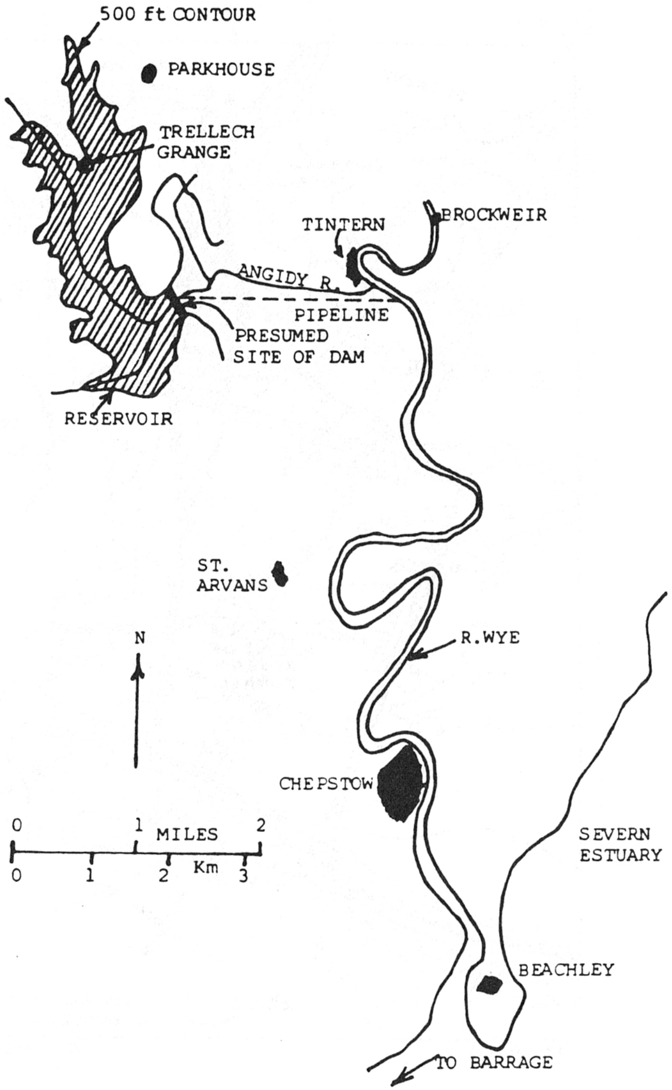

Figure 5. Proposed pumped storage scheme, 1933.

be supplied direct to the grid from the barrage, and about 900 from the pumped storage system, making about 1600GWh/year in all instead of the 2250GWh/year available from the barrage. The cost per KWh would be increased by 0.23d, but this was still only about two-thirds of the cost from the most efficient coal-fired generating stations of that period.

The total cost of the scheme was estimated as:-

Barrage and power station	£25,457,574
Reservoir and storage station	£11,468,901
Extra transmission lines	£1,500,000
Road, railway and harbour	£12,000,000
Making a total cost of about .	£50M.

The time of construction would be about 15 years, and the labour force (direct and indirect) would rise to a peak of nearly 28,000 in the 13th year, with an average over the 15 years of about 12,000.

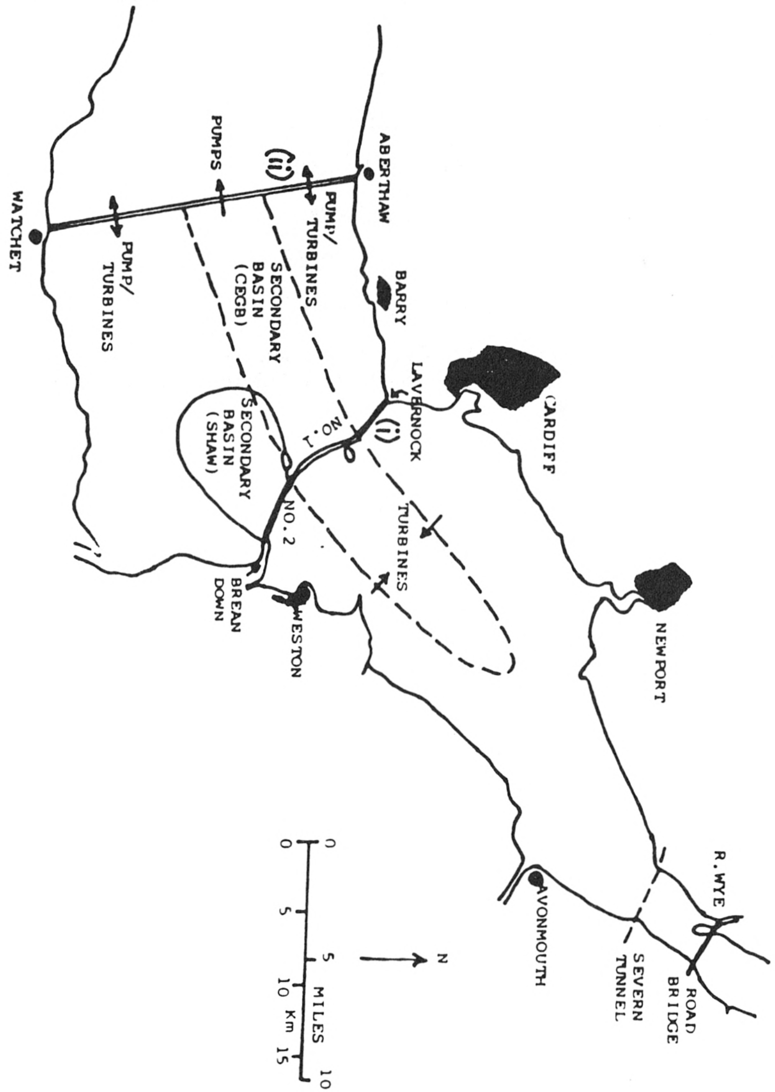

Figure 6. The Severn Estuary showing (i) Shaw's scheme of 1970. (ii) CEGB scheme of 1973-4.

APPENDIX 2.

Description of the Low-Level Pumped-Storage Proposal of 1970.

The proposal by Dr T L Shaw(35) was for a main barrage (see Fig. 6i) between Lavernock Point and Brean Down, incorporating the island of Flat Holm but passing just north of Steep Holm; the length was about 8 miles. A roughly-oval secondary basin was to be formed by a dam making a wide sweep southwards through Steep Holm and round to Brean Down, with a length of about 13 miles, enclosing an area of about 17.5 sq. miles with a mean depth below OD of about 60ft. The main shipping channel lies to the north of this basin. The capacity of the secondary basin is about 60% of that of the main basin. Reversible turbines (i.e. turbines which can operate in either direction of water flow and can also be driven as pumps) are fitted in the barrage in two sets, one (No.1) between the main basin (or upper estuary) and the sea, and the other (No.2) between the main and secondary basins. There is no connection between the secondary basin and the sea.

Cheap night power from the grid would be used to ensure that the main basin is full (i.e. a few feet above high-tide level) and the secondary basin is empty at the start of each day.

Generation during the day would take place in machines No.1 when the tide is sufficiently low (e.g. for a period of about 5 hours, not necessarily in one stretch), and in machines No.2 for the remainder of the period. Then at night, electricity from the grid would be used to drive both machines No.1 and No.2 as pumps to refill the main basin and empty the secondary basin.

The environmental effect of raising the upper level of the main basin by a small amount would not be expected to be large, nor would serious land drainage difficulties be expected. The effect of the low-level secondary basin should be nil, as it is entirely isolated from the land.

In a programme like this, the output power could be 3500MW over 24 hours, i.e. the energy generated would be 42GWh; but the energy absorbed at night would be 38.75GWh, so that the net daily output would only be 3.25GWh. Clearly the scheme is intended primarily as a pumped-storage facility for the grid, but with a net generating capacity. In this concept it differs from all the other schemes considered.

APPENDIX 3.

Description of the CEGB Continuous-generation Scheme of 1973-4.

This scheme,[36] like Dr Shaw's of 1970, used a secondary basin which was preferably isolated from land. As shown in Figure 6ii, the main barrage was to be further down the estuary, approximately between Aberthaw in South Wales and Watchet in England, and the secondary basin was to be inside the main enclosed basin (or upper estuary). Another important difference was that the scheme was conceived primarily for generation and not as a pumped-storage facility. The secondary basin was therefore not intended to have its minimum water level much below low-tide level, and filling of the high basin and emptying of the secondary basin could in principle be by gravity through sluices at appropriate states of the tide, although pumping would probably be used. With suitable proportioning of the basin sizes and with suitable operating programmes, it was estimated that with turbines of 6000MW capacity between high and low basins, and 2500MW capacity between high basin and the sea, a continuous (though not constant) output could be maintained throughout the year, providing about 25 TWh of energy to the grid. Operation on the basis of generation only during a limited day-time period appeared not to improve the performance.

The capital cost was estimated at £2500M-plus.

References

1. E. M. Wilson, "Energy from the sea - tidal power", *Underwater J.*, August 1973, pp 175-186, see especially p.175.

2. Technical aspects of tide-mill design are well discussed by D. H. Jones, "An analysis of tide mill operation", *Trans. 6th. TIMS Symposium,* 1985, pp.123-136.

3. W. E. Minchinton and J. Perkins, "Tidemills of Devon and Cornwall", *Exeter Papers in Industrial Archaeology*, Exeter, 1971;

W. E. Minchinton, "Tidemills of England and Wales", *Trans. 4th TIMS Symposium*, 1977, pp.339-353; and many other papers and books.

4. *Electrical Engineer,* **13,** 1894, pp.33.

5. "Embankment across the Severn", *Pembrokeshire Herald,* 27th March 1846, quoting from *Herepath's J.*

6. Report of Town Council Meeting, *Western Daily Press,* 10th November 1881.

7. *Ibid,* 3 January 1882.

8. J. Latimer, "Annals of Bristol in the 19th century", 1893, p.513.

9. C. Wells, "History of the Port of Bristol", 1909, p.225.

10. *The Electrician,* **7,** 22nd October 1881, p.353.

11. *Ibid,* **18,** 31st December 1886, p.161.

12. *Electrical Engineer,* **2,** 20th July 1888, p.46.

13. P. Decoeur, "Continuous utilization of tidal power", *Le Genie Civil,* **17,** 1890, p.130; abstract in *Proc. Inst. Civil Engrs.*, **102,** 1890, p.337.

14. *Electrical Engineer,* **13,** 9th Febuary 1894, pp.160-1.

15. *Ibid,* **16,** 20 December 1895, p.697.

16. *Electrical Times,* **33,** 21st May 1908, p.505; **41,** 2nd May 1912, p.462, **42,** 19th September 1912, p.268.

17. *Ibid,* **56,** 11th December 1919, pp.462-3.

18. L. B. Bernshtein, "Tidal Energy for Electric Power Plants", (Translated from Russian), Jerusalem, 1965, p.259.

19. Third Interim Report (Tidal Power) of the Water Power Resources Committee, board of Trade, HMSO, London, 1920.

20. Republished together as "Construction and Operation of a Tidal Model of the Severn Estuary", HMSO, 1933.

21. Report of the Severn Barrage Committee, HMSO, 19th January 1933, reprinted 1945.

22. Articles in *Engineering*, **135**, 17th March 1933, pp. 307-8; 7th April, pp. 394-6; 2nd June, 1933, pp.599-600.

23. Report on the Severn Barrage Scheme, by Panel appointed by Minister of Fuel and Power, HMSO, 1945.

24. Editorial, "The Severn Barrage", *Engineering*, **159**, 2nd March 1945, pp.171-2.

25. N. Davey, "Studies in Tidal Power", Constable, London, 1923.

26. E. M. Wilson, "A feasibility study of tidal power from Loughs Strangford and Carlingford with pumped storage at Rostrevor", *Proc. Inst. Civil Engrs.*, **32**, 1965, pp.1-29.

27. "La Rance Tidal Power Scheme", special number of *Revue francais de l'Energie*, No.**183**, September-October, 1966. Also illustrated booklet, "The Tidal Power Stations of the Rance", Ref.A/20, issued by the French Embassy in London, 1967.

28. Full account given by E. M. Wilson in reference1.

29. "Tidal Power Barrages in the Severn Estuary", *Energy Paper No.23*, Dept of Energy, HMSO, May 1977.

30. "Severn Barrage Seminar, 7th September 1977: Report of Proceedings; Written Contributions", *Energy Paper No.27*, Dept. of Energy, HMSO, 1978.

31. "Tidal Power from the Severn Estuary", *Energy Paper No.46*, Dept. of Energy, HMSO, 1981.

Vol.1: Report to the Secretary of State for Energy. (111pp)

Vol.2: Analysis, studies, reports and evaluations. (459pp)

32. "Tidal Power from the Severn", Thomas Telford Ltd., London, 1986.

Vol.1: Report. (97pp)

Vol.2A: Engineering and economic studies, Cardiff Weston scheme. (Approx. 300pp)

Vol.2B: Engineering and economic studies, English Stones scheme. (Approx. 250pp)

33. "Severn Barrage Development Project; Description of studies to be undertaken during 1987/8: *Consultation Document No.1*", Severn Tidal Power Group, Febuary,1987. (Discussed, with diagrams, in *The Times*, 17 Febuary 1987.)

34. "A Severn Barrage", text of an exhibition, Woodspring Museum, Weston-super-Mare, 1981. Available from the Museum, price 65p.

35. T. L. Shaw and G. R. Thorpe, "Integration of pumped-storage with tidal power", *J. Power Division of Proc. American Soc. of Civil Engrs.*, **97**, January 1971, pp.159-180.

36. J. D. Denton et al., "The potential of natural energy sources', *CEGB Research*, No.**2**, May 1975, pp.28-40, espec. pp.36-39.