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

Hydro (Including Tidal) Energy

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Hydro (including tidal) energy

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This paper reviews, on a world-wide basis, the production from hydro-electric installations and forecasts which have been made of potential water-power resources. Various types of development are described. It considers how hydro-electric resources can best be used in an interconnected electricity supply system with thermal and nuclear generation, including pumping to assist in the economic use of other fuels. Hydro-electric development in the United Kingdom is briefly described.

The availability of tidal energy is reviewed, and reference made to the Rance Tidal Power Station in France.

1. Hydro

1.1. *Production*

The United Nations' survey for 1970 shows that the world production of hydro-electric power was 4.24×10^{18} J (1178 terawatt hours) and formed 24 % of the total production of electricity from all sources.

Put in a more domestic context, this production was equivalent to 4.7 times the total electricity generated in the U.K. that year. For those who prefer to work in coal equivalent – that is, if generated instead from coal-fired plant – hydro power represented a saving of 600×10^6 tonnes.

Table 1 shows the production in 1961 and 1970 in the developed countries, centrally planned economies and developing countries. It is significant that while in 1970 the developed countries produced almost three-quarters of the world's hydro energy, the rate of development of hydro elsewhere over the past decade has been twice as fast. This trend will become more marked with the approaching exhaustion of hydro potential in the developed countries.

Table 1. World hydro production

	1961		1970		increase
	10^{18} J	TW h	10^{18} J	TW h	(%)
developed countries	2.07	575	3.05	847	47
centrally planned economies	0.32	89	0.67	185	107
developing countries	0.22	61	0.52	146	137
total	2.61	725	4.24	1178	62

1.2. *Hydro resources and their use*

Any review of estimates of potential hydro development has to be treated with considerable caution. The figure of 82.8×10^{18} J (23000 TW h) given at the 1968 World Energy Conference (that is, twenty times 1970 production) must in my view be regarded as more a technical than economic assessment and is probably optimistic by a factor of between 2 to 3. On this basis a more realistic assessment might be as shown in table 2. The pace and manner in which these remaining resources are exploited will be largely governed by the stage of industrial development of the country in which they are located.

Table 2. World hydro resources

	potential		developed, 1970
	10^{18} J	TW h	(%)
developed countries	4.68	1300	65
centrally planned economies	6.47	1800	10
developing countries	18.0	5000	3
total	29.15	8100	14.5

The maximum use of the available head of a typical river system can lead to a wide variety of types of installation. These can range from stations with large reservoir capacity located in the upper reaches of the catchment to less well regulated stations farther downstream, and finally, where the fall in the river is small but the flow large, a series of run-of-river stations each with the generating plant integral with a barrage constructed to create sufficient usable head.

The history of hydro-electric development in those countries initially with abundant hydro power shows that the first phase is usually the provision of dependable power from key stations with large reservoir capacity, followed only in the more final stages by the construction of run-of-river stations whose variable output can by then be more readily absorbed into the system.

1.3. *Developed countries*

The vast bulk of the remaining resources in developed countries now lies in Canada and this is increasingly being exploited, for use also in the U.S.A., by the use of long-distance transmission.

In Europe some 80% of the hydro potential is expected to be exploited by 1980. While there are isolated developments taking place in many countries the most significant work under construction is a series of run-of-river stations on the Rhone and Danube, which will also form part of an improved navigational scheme. There is also a trend to augment the output of existing schemes by the diversion of additional catchments.

In the U.K., and in Scotland in particular, virtually all the hydro resources have been developed. There are a few possible schemes but these are not economic at today's interest rates and too small to justify promotional problems.

In the U.S.A., Japan and Australia a high proportion of the resources have been exploited. Those schemes in hand tend to be multi-purpose, covering, as in Europe, irrigation, flood control, water supply and navigation.

1.4. *Centrally planned economies*

The major developments in Russia lie principally in Central Siberia, where, for example, some six stations in the 4000–6000 MW range are under construction or planned on the Angara and Yenisei rivers. The output of these and existing stations will be used initially to meet industrial expansion in the region. Other schemes in hand are in the Caucasus and in Central Asia. While the Russians are developing high voltage d.c. transmission towards Central Asia no plans extending these to Siberia to make use of the vast hydro resources there have been published.

Little is known about hydro development in China, where there are vast resources available. No doubt these will be developed to match industrialization, with the added multi-purpose incentives of flood control, irrigation and navigation.

1.5. *Developing countries*

As indicated earlier, more than half the world resources are in the developing countries and a negligible proportion has been harnessed. Only a limited number of sites have been studied closely but it is evident that, among many other countries, Africa and South America in particular have very substantial potential.

It is unfortunate that at present where hydro is abundant the demand for it is small and that meantime energy, at a time of shortage and high cost elsewhere, is flowing to waste. However, much of the world's long term anticipated growth in energy needs is linked with increase in population and industrialization of the developing countries, and many of these countries are well endowed with hydro. It would seem that economic and political factors will encourage such countries to maximize the use of these indigenous hydro resources to meet much of their growing energy needs rather than compete unnecessarily for world-wide reserves of fossil fuel. Similarly, high energy prices will probably encourage the greater use of transmission as a means of utilizing surplus hydro, and there will almost certainly be an increasing trend back towards the location of electrically intensive industries in these hydro-abundant countries.

2. Pumped storage

2.1. *World-wide scene*

It may appear inappropriate in a discussion on energy resources to refer to pumped storage – a device which consumes more energy than it produces. On the other hand, the introduction of pumped storage into a thermal generating system enables that system to be operated more efficiently with overall economy of fuel. Furthermore, it offers an additional means of using nuclear fuel to replace fossil fuel.

It is not surprising, therefore, that with the growing use of large base load thermal sets there has been increasing interest in peak load plant in the form of pumped storage. The progressive exhaustion of conventional hydro-electric sites in developed countries has been a further incentive to seek out plant with similar flexible operating characteristics.

For these reasons, while the first use of pumped storage for electricity supply goes back to the 1930s in Germany, its real development took place after the war, as can be seen in figure 1. As a result, the pre-war capacity of 1000 MW rose to 20000 MW in operation by the end of 1972, half in Europe and the balance mainly in the U.S.A. and Japan. A similar amount of plant is under construction.

The first major installation in the British Isles was in the early 1960s with the 360 MW scheme at Ffestiniog in North Wales, and was followed in the mid-1960s with a 400 MW station at Cruachan in Scotland. Under construction are two stations of about 300 MW, one at Foyers in Scotland and the other at Turlough Hill in Southern Ireland. The Generating Board are at present seeking Parliamentary approval for a further scheme in North Wales with a capacity of 1440 MW.

2.2. *Siting and plant considerations*

The basic requirements for an economic pumped-storage development are the existence of upper and lower reservoir sites in close proximity with a difference in level of at least 150 m. The site should be within reasonable distance of centres of load and off-peak generation.

A feature of many overseas schemes is the creation of hilltop reservoirs. With a more natural reservoir site the opportunity is usually taken to collect any run-off from the adjacent catchments so as to improve the overall economics of the scheme. Indeed, several pumped-storage installations are developments of conventional hydro-electric sites where the natural flows were too small to give a viable scheme.

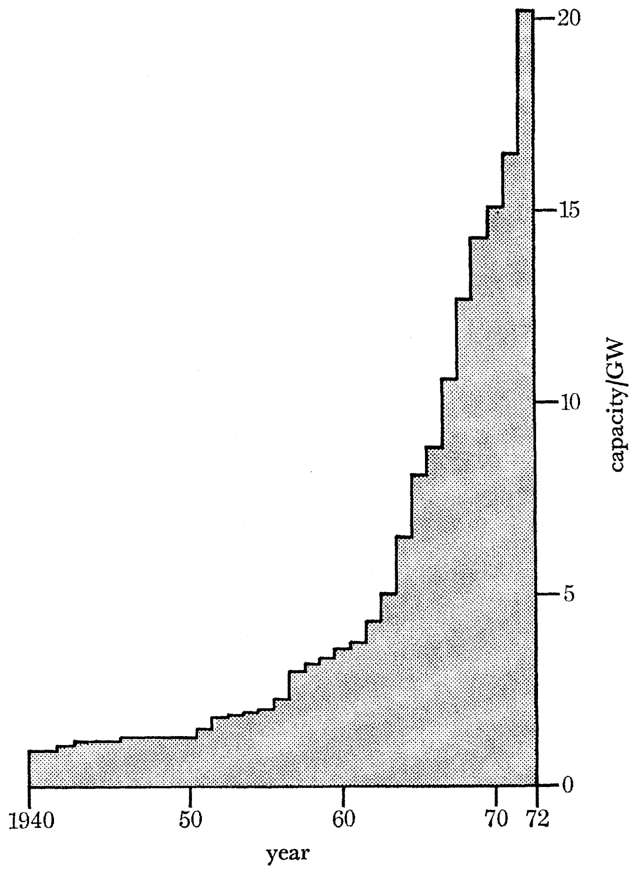

Figure 1. World pumped storage capacity (in operation).

Good sites, such as that at Cruachan, are unfortunately hard to obtain. Coastal cliff sites offer possibilities but require precautions to prevent percolation from the upper reservoir into the local freshwater supplies. A more recent idea is the underground excavation of the lower reservoir with the upper reservoir located at ground level.

2.3. *Use on the system*

To the system operator the attraction of pumped storage lies in its dual role of very fast response peak load generating capacity to replace loss of plant elsewhere, and a pumping load which can be switched on at night to avoid shutting down high-merit thermal plant. As a consequence, significant system fuel savings result from the more planned and level operation of thermal plants, including a reduction of spinning reserve, hot standby and other duties. Added to these are the fuel savings resulting from the replacement of peak load generation from low-merit thermal plants with energy pumped at night from high-merit plant. The case for pumped storage, both on economic and fossil fuel conservation grounds, becomes greater when the

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

amount of nuclear power on the system exceeds the night load and becomes available for pumping, thus effectively providing peak load power from nuclear energy.

There are limits, however, to the amount of pumped storage which can be used on a system since there is a finite amount of low duration peak load. Pumping is normally only economic at night and weekends, and if demands of longer than 6 h duration are to be met this can only be achieved by additional upper reservoir capacity or by increasing the pump capacity relative to the turbine capacity. The economic penalty of increasing pumping capacity may be high but could be justified in the future with a large nuclear programme.

FIGURE 2. Principal tidal power sites.

3. TIDAL ENERGY

3.1. *Sites and potential*

Tidal energy was used in the Middle Ages in small tide-mills along the Atlantic coasts of Britain, France and Spain, but as other power sources became available they fell out of use. However, there has been continuing interest in the development of large scale tidal power schemes for the generation of electricity. The places where high tidal ranges occur are shown on figure 2, interest having been centred on Brittany, the Severn, the Bay of Fundy in North America and the White Sea and the Sea of Okhotsk in Russia.

High tidal ranges occur due to the funnelling effect of particular shallow coastal estuaries and gulfs. The construction of a tidal barrage may increase or reduce the tidal range, depending on the resonance characteristics of the estuary. The other important parameter is the volume of the basin impounded by the tidal barrage, as this, together with the vertical range of tides, dictates the capacity of the site.

It has been estimated that the total output of sites capable of practical development is of the order of 1.26×10^{18} J (350 TW h) per annum. As this is only one and a half times the consumption of electrical energy in the U.K. it is clear that the potential contribution by tidal energy to world energy requirements is limited.

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

3.2. *Development problems*

The main drawbacks to development are the cost, the lunar rather than solar cycle of the tides, and the amplitude range of about 3 to 1 from spring to neap tides. As a consequence, generation at a development with a simple single basin scheme operating on the ebb-tide rarely coincides with the demands on the electrical supply system; such schemes do not save investment on other power stations and can only be credited with fuel savings. Complicated multiple-basin schemes to re-time some of the energy so as to produce some firm power would be much more costly.

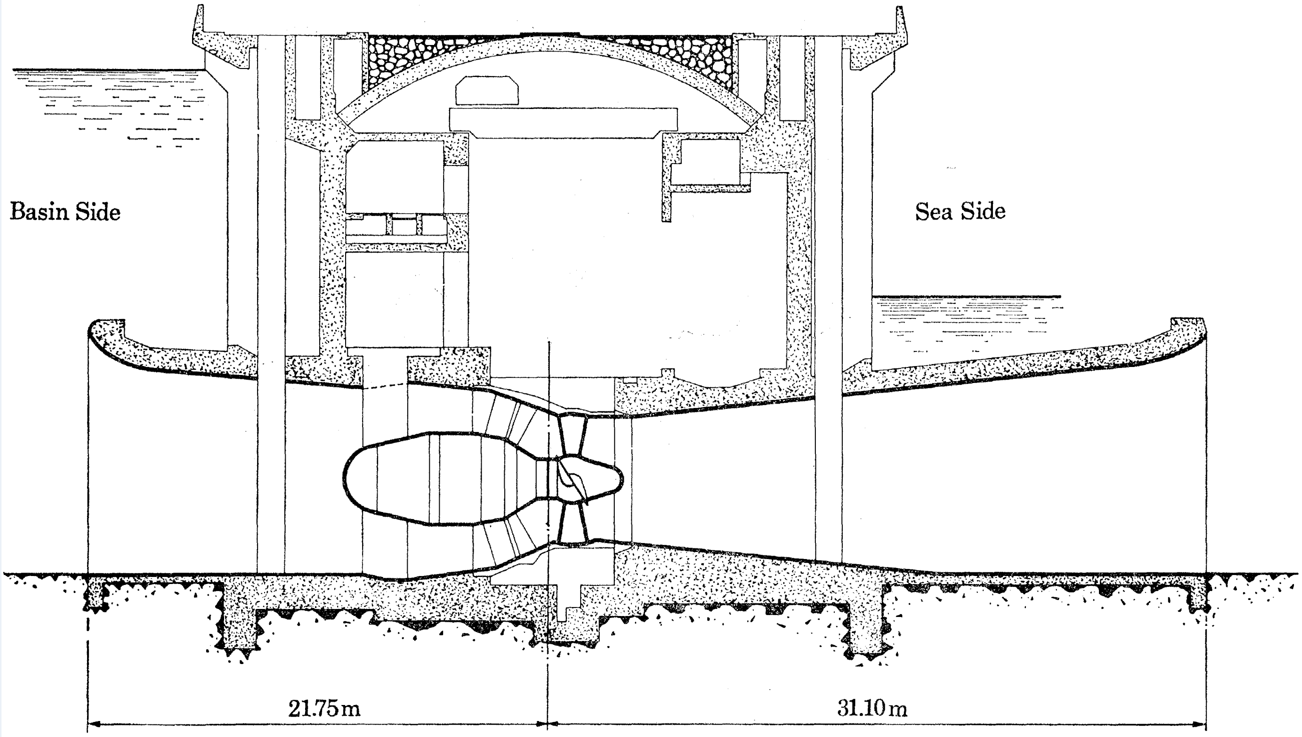

FIGURE 3. Rance tidal power station.

3.3. *Rance scheme*

The development of the horizontal reversible bulb turbine by the French, as shown in figure 3, resulted in the building of the 240 MW Rance single-basin scheme in 1966 to generate with flow in either direction; in addition, the machines can pump to increase the effective head range or ensure stored water, allowing some credit to be given for firm power. The scheme, believed to have been very expensive, was to have been the forerunner of a large scale double-basin development on the coast of Brittany at Iles de Chausey with a capacity of 3000 MW and an output of 46×10^{15} J (12.8 TW h).

3.4. *Russia*

The Rance Station was built in the dry between cofferdams, but current thinking, in order to save construction cost, favours the use of large prefabricated units which would be floated to site and sunk on prepared foundations. This method was adopted by the Russians at the small Kislaya Station north of Murmansk, which was commissioned in 1968 as a forerunner of the

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

2000 MW Mezen Bay project on the White Sea. It is reported that feasibility studies on this project were started in 1971 and that a vast project (25000 MW) on the Sea of Okhotsk is under consideration.

3.5. *British Isles*

In the British Isles, where there are a few favourable sites on both coasts of the Irish Sea, the Severn Scheme was studied by a government commission which reported in 1945. Judged against the saving in coal which would result from the annual production of 8×10^{15} J (2.2 TW h), this 800 MW scheme was considered to be uneconomic at the prevailing low interest rate of 3 % per annum. Since then there have been significant advances in the development of low head turbines and in civil engineering techniques and a much larger scheme has been envisaged. Nevertheless, the current higher level of interest rates must make any such scheme unattractive unless the costs were shared in a multi-purpose development incorporating improved road and harbour facilities.

3.6. *North America*

On the other side of the Atlantic there have been a succession of investigations into tidal developments within the Bay of Fundy involving both Canada and the U.S.A. Out of these have come four separate schemes, totalling about 5000 MW of capacity with a production of 53×10^{15} J (14.8 TW h) of energy. Recent investigations have shown that developments would only be economic at an interest rate of not more than 4 %. However, fresh interest into these projects has led to the setting up of a Tidal Power Corporation in Nova Scotia to carry out further investigations.

3.7. *Summary*

While much effort and ingenuity has been devoted to tidal power, an economic solution has yet to be demonstrated. It has to be accepted that with the present technology, the low concentration of power in the sea, even at the most attractive sites, must lead to physically large and thus expensive works; also that the energy produced is rarely in phase with man's needs. These present a formidable challenge.

Discussion

Mr P. Wilson (*Gilbert Gilkes & Gordon Ltd, Kendal, Westmorland*)

Mr Wilson said that he was the Chairman of a firm of water-turbine manufacturers and that he was not going to ask Mr Vernon a question but that the point which he wished to make could have been a question to the Secretary of State. He would have liked to have asked Mr Peter Walker if the government would immediately instruct the River Authorities to stop making a levy on all in England and Wales who generated electricity by water power.

In accordance with clause 58 of the Water Resources Act 1963 the River Authorities had powers to make a charge for river water which they claimed was 'abstracted' when used for power generation. As a result many small hydro-electric units had been closed down and there was little likelihood that any more would be installed. No attempt had been made to introduce such legislation in Scotland, where there would have been an immediate outcry.

The generation of hydro-electric power did not use up coal, oil, nuclear material or any of the world's limited resources and should, therefore, be encouraged to the full. He was certain that it might not be long before the owner of quite a small hydro-electric plant might be greatly envied by his neighbours. In his opinion it was ridiculous to make a charge on those who used water power when there was likely to be a fuel crisis and when, in any case, it was acknowledged that there would soon be a big increase in the price of all fossil fuels.

K. R. Vernon

I was surprised to learn from Mr Wilson that small hydro-electric stations in England and Wales are charged for abstraction of water, particularly as these small schemes must return the water almost directly and unpolluted to the river concerned. One justification of a charge, however, would be the improvement of dry weather flows in the river consequent upon the provision of a reservoir storage capacity upstream.

From enquiries received at my office I known there is a real interest throughout the country in small sites with hydro-electrical potential, and it would be a pity if unjustifiable levies prevented their development.

S. H. Salter (*Bionics Research Laboratory, School of Artificial Intelligence, University of Edinburgh*)

Power from sea waves?

The energy available from a wave can be calculated from the change of potential energy as the water above sea level falls down into the trough. This can provide

$$\text{power} = kw\rho A^2 g\sqrt{(g\lambda)},$$

where w is the width, ρ the density of water, A the amplitude, g the acceleration of gravity, λ the wavelength, and k a constant $= \frac{1}{6}\sqrt{(2\pi)}$ for triangular waves.

Observations of waves in the North Atlantic show that power levels between 10 and 100 kW/m may be expected. I have been testing wave-tank models in which more than 50 % of the energy is extracted. There are obvious problems concerned with storage, transmission and maintenance, but if the technique can be extended to full scale then the electrical requirement of the U.K. could be satisfied by a few hundred kilometres of installation floating out at sea off the west coast of Scotland. (See Draper, L. & Squire, E. M., 1967, Waves at Ocean Weather Ship *India* (59° N, 19 W°). *Trans. R. Inst. Nav. Arch.* **109**, 85–93.)

K. R. Vernon

Mr Salter drew attention to the potential power of sea waves. In connexion with tidal projects I mentioned the formidable challenge of harnessing the low concentration of power in the tides. This applies equally to utilization of wave power, which would have the same disadvantages as tidal power of not always being available when required and not saving investment in other power stations. It is interesting nevertheless to learn Mr Salter has managed to extract more than 50 % of the theoretical energy in wave tank tests.

Mr N. E. Butcher (*Open University in Scotland*, 60 *Melville Street, Edinburgh*)

I wonder if Mr Vernon would comment on the possible contribution that could be made to our energy requirements by windmills linked to pumped water storage, since there would appear to be no great shortage of wind in Britain.

K. R. Vernon

The same basic problem of intermittent output applies to windmills so that the value of their output is limited to fuel savings. Linking windmills to pumped storage schemes would not overcome this inherent economical disadvantage. On the practical side my Board cooperated with the Electrical Research Association in the construction and operation of a 100 kW wind-power plant in Orkney in the early 1950s. Severe problems were experienced with the stability both of the structure, which was 24 m high, and of the rotor which was 15 m in diameter. In addition, there were difficulties with the control of the feathering blades. Despite modifications to the plant it was concluded then and our opinion still is that large windmills were not practical or economical for public electricity supply.