New solution could double world tidal energy potential at half the cost

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The author proposes a new solution for accelerating world tidal power development, which could be economically and technically feasible in about 20 countries, where appropriate conditions prevail. It would have negligible environmental impact. Short articles in subsequent issues of H&D will deal with the potential in some specific regions,

The theoretical potential of tidal energy is about the same as that of conventional hydropower. However, hydropower production is more than three and a half times that of tidal production. The reason for this may be that the technical solutions used successfully for hydropower and chosen for most tidal energy studies are actually not well adapted to most tidal sites. A new approach, specifically proposed for tidal energy, is presented here. This solution could facilitate the production of 1500 TWh/year at a cost close to that of conventional hydro, and with less environmental impact.

World hydropower generation is more than 3600 TWh/year and is likely to double in the future. Tidal power generation, however, remains at only about 1 TWh/year.

This difference in development progress is surprising because:

- The theoretical potential is the same, at around 20 000 TWh/year.
- The density of energy is 10 GWh/year/km² for hydropower (3600 TWh/year for 350 000 km² of reservoirs) and for tidal energy the feasible energy supply is 12 GWh/year/km² for a tidal range of 4 m and 40 GWh/year/km² for a tidal range of 7 m.
- Many hydropower schemes on large rivers operate successfully with a 4 or 5 m head, which is the same as for the normal operation of the two main tidal plants in operation (La Rance in France and Sihwa in Korea).
- The extra cost associated with operating in salt water is low.
- Environmental impacts are lower for tidal energy.

It is therefore questionable whether the technical solutions used successfully for hydropower and studied for tidal energy are well adapted to the very specific conditions of the tides, which will be discussed here. A solution which seems much better adapted to these very specific conditions is presented and evaluated here.

1. Specific data of tidal energy

As most tidal energy in the world is available where the tides are semi-diurnal, slightly longer than 12 hours and virtually as high within the same day, the data below apply to such tides but the new solution proposed could apply to all cases.

The range of tides H (in m) varies over 14 days, with some days having spring tides, when H is 30 or 40 per cent higher than the average value H_m, and may occasionally reach 1.5 H_m, and other days having neap tides when H may be 70 per cent of H_m (or occasionally as little as 50 per cent). The available energy can therefore vary a lot within two weeks. But the annual and monthly energies remain fairly constant and are related only to the value of H_m and of the reservoir area.

Past studies over the past 60 years have essentially been based on H_m being more than 5 m. The corresponding world potential is quite a small part of the total potential, because the corresponding area is limited to several tens of thousands of km² and the technically feasible potential less than 2000 TWh/year. The global potential of a few well known places where H_m is more than 7 m represents a few hundred TWh/year. The potential with H_m between 3 m and 5 m is much higher: the potential per km² is lower, but the area represents hundreds of thousands of km²; the feasible potential is more than 5000 TWh/year and this could apply in about 20 countries.

During a half tide of six hours, the level of a tidal reservoir can be virtually the same as the sea level for some time. It may then be impossible to produce a lot of power for one or two hours.

For the same low head, and the same power, the cost of the civil engineering for a tidal plant is much greater than for a run-of-river hydro plant, because the plant head has to take into account the wave height and the total range of the spring tides.

In areas where there are significant tides, the conditions for the foundations of the dykes or powerplants are usually favourable, because the depth is 10 to 20 m below sea level and the soil is rock, sand or gravel. But the waves may be significant and reach considerably more than 5 m. The foundations and floods are key problems for the design and construction for dams, whereas waves are the key issue for tidal energy.

The environmental impacts of tidal plants are very different from those of hydropower. Tidal impacts may be generally lower, but the possible impacts on natural conditions and especially on biodiversity may prevent the development of some tidal sites (such as estuaries) or may limit the operation methods. This point, which was forgotten 50 years ago, is essential for future decisions.

A key point, therefore, is that the conditions for tidal energy are very different from those affecting traditional hydropower, and so the solutions may not be the same.

2. Present options for tidal plants

All studies to date have been based on the same principles as those for hydropower on rivers: to create a reservoir by dams or dykes, and to use the head created, with flow passing through turbines installed in a concrete structure.

2.1 The reservoirs (basins)

Various solutions have been studied which involve linking several basins hydraulically. This may improve the utilization of turbines; but these solutions may be unacceptable now for environmental reasons, because the relevant conditions of the tides along the shore are far from the natural ones.

Simple basins may be:

- Estuary basins similar to La Rance. They avoid the cost of dykes to close the basin, but environmental problems are more difficult, especially with the salt content. In any case there are relatively few large estuary sites worldwide.
- Artificial islands which avoid impacts along the coastline but the cost of long dykes increases to an unacceptable level the cost per kWh, except for very large islands which should be far enough from the shore to avoid sedimentation problems. It is difficult to find such cost-effective sites.
- The main potential is therefore essentially for large single reservoirs along the shore, but their impact should be acceptable and thus the tidal range and levels in the reservoirs as close as possible to the natural ones.

2.2 Conventional turbines

A horizontal axis bulb unit was developed 60 years ago specifically for the La Rance tidal plant in France. It can operate both ways and also pump. The power of a turbine may reach 30 or 40 MW. This solution has been used successfully in rivers generally with heads of 5 to 10 m; but the possible power is greatly reduced when the turbine is operated with a lower head.

At La Rance the power supplied for a 3 m head is 30 per cent of the rated power, and it is very low for a 2 m head. It is possible to design plants to operate with 2 m heads, but the power per metre is reduced to a few hundred kW and the concrete structure remains significant and costly. That means the corresponding cost per kW for the civil engineering is quite high.

2.3. Operation with existing solutions

A reservoir (basin) can be operated one way or both ways. The two-way operation of tidal energy is as shown in Fig. 1, and has four advantages:

- Power can be supplied for 8 hours out of 12.
- The operating head is about 0.35 H, but the volume passing through turbines during the 8 hours is $2 \times 0.9 \times H \times S$ and the energy available:

$$\frac{0.35 \times 2 \times 0.9\, H^2 S \times g}{3600} = \frac{0.63\, H^2 S \times g}{3600} \text{ kWh}$$

- The annual energy is in the range of 3500 hours of the rated output.
- The tides within the basin are very similar to the natural ones, which is important for biodiversity. The tides are simply shifted by two hours. But the operating head of 0.35 H is: for average tides 2.5 m for the best sites; and, 1.5 m for most sites and the power supplied by a bulb turbine is quite limited and costly

The one-way operation is as shown in Fig. 2 (Sihwa); the turbined volume is about 0.7 SH under a 0.6 H head, the possible energy about:

$$\frac{0.6 \times 0.7 \times H^2 S g}{3600} \text{ or } \frac{0.42\, H^2 S \times g}{3600} \text{ kWh}$$

which is much less than the possible energy with two-way operation.

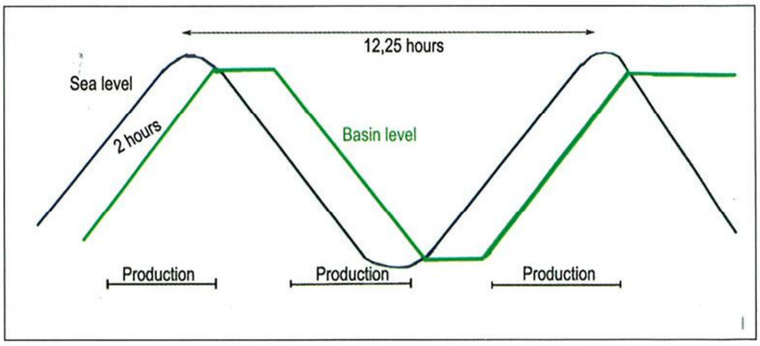


Fig. 1. Two-way tidal plant operation.

The advantage is a higher head for turbine operation. But this solution has three drawbacks:

- Operating for four hours out of 12 does not correspond well with power demand.
- Limiting the turbine utilization provides annual energy equal to 2000 hours of the rated value.
- Modifying the tidal levels and range in the basin may not be acceptable for biodiversity.

Bulb units are thus not well adapted to the most acceptable and largest utilization of tidal energy, and selection of this type of unit favours the one-way operation.

This may be the main reason for the lack of progress in tidal energy development over the past 60 years. Another reason has been the low cost of electricity from fossil fuels, but this has not prevented the present progress in conventional hydropower development.

The use of tidal plants with bulb units may, however, be of interest if part of the investment is paid for by side benefits beyond power supply, as it is in Sihwa for environment and if it associated with much thermal power.

A new turbine design, a vertical axis orthogonal unit, has been studied and tested in Russia (Fig. 3). It can operate both ways with an output of 0.75. The turbine

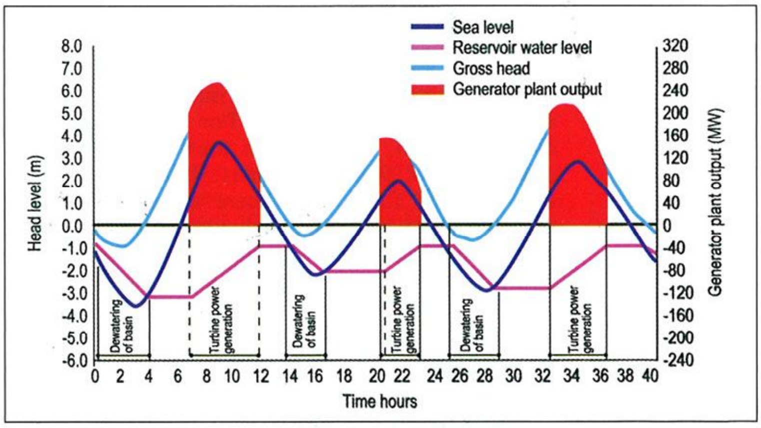


Fig. 2. Typical operating regime at the Sihwa tidal powerplant as flood generating system: The sea level (dark blue line) oscillates twice a day between + 3.0 and - 3.5 m, while the reservoir level (pink line) is kept between 1 and 3.2 m. Gross heads (light blue line) of between 5.2 and 2 m are created, which enable power to be generated for several hours every day (red areas). The maximum plant output is about 250 MW.

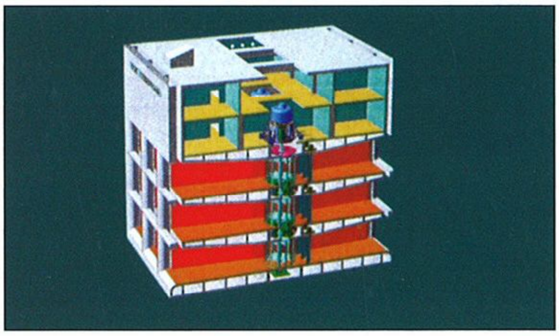


Fig. 3. The orthogonal turbine (Russian design).

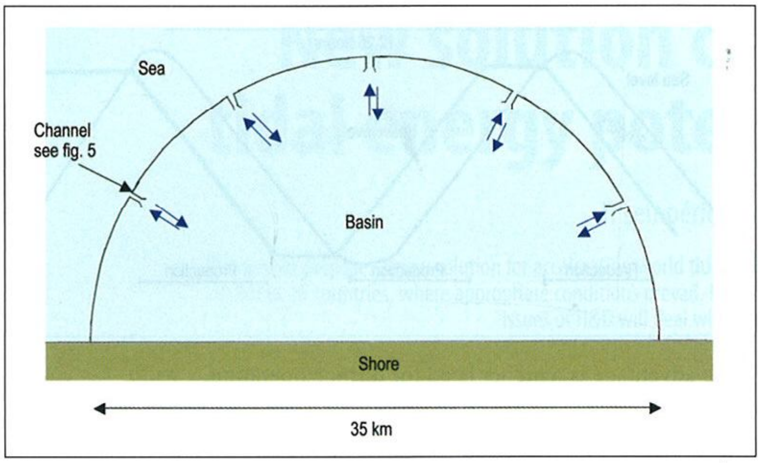


Fig. 4. Layout of the new solution.

design is quite simple. The output is, however, limited to about 400 kW/m for an operating head of 2.5 m and to 150 kW for 1.5 m. The cost of the civil engineering per kW is thus high for H_m in the range of 6 to 7 m, and very high for H_m values of less than 4 to 5 m.

This solution, which requires optimization and further experience, appears more promising than the bulb turbine, and may well operate both ways. It seems, however, more expensive for most schemes than the solution proposed below, at least for tidal ranges Hm of less than 5.

3. Present solutions for in-stream turbines

Wind farms are successful onshore and offshore because there are many places with sufficient wind speed for the use of cost-effective power units of 1 to 5 MW onshore, or 3 to 10 MW offshore. This success has favoured study and experimentation of the same principle applying to water streams for which the water speed is significant, that is, in areas with high tides. The power supplied by an in-stream turbine (in kW) is about: $0.2\ sV^3$, where s is the turbine area in m², and V the water speed in m/s.

The diameter of the turbine may be 12 to 20 m, and its area 100 to 300 m². For a large diameter, close to 20 m, and thus an area of 300 m², the power, in kW, is $60\ V^3$, that is, 0.5 MW for 2 m/s and 1.5 MW for 3 m/s. There are relatively few places where the water speed is more than 3 m/s for 1000 hours per year and more than 2 m/s for 3000 hours; therefore there is quite a limited potential for units of more than 1 MW supplying more than 2 GWh/year (when an offshore wind unit can supply 15 GWh/year).

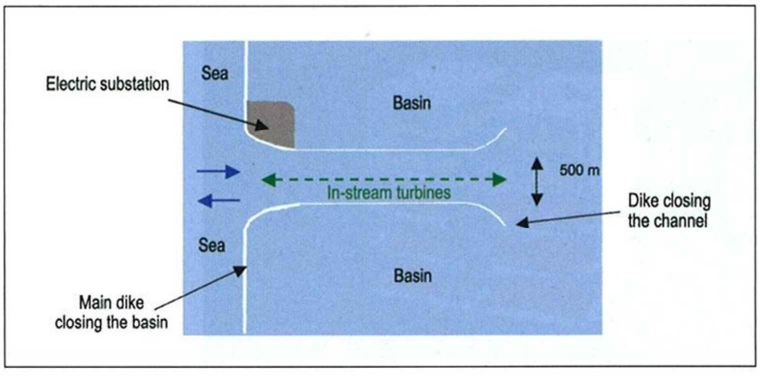


Fig. 5. The channel for the in-stream turbines.

The cost per kWh for installing, connecting to grid, operating and maintaining such a turbine in the open sea is usually much more than the cost of manufacturing it. Also the annual production will only be 2 GWh/year. There is therefore only a small world potential at an acceptable cost. Another drawback is that, over 14 days, most of the power supply will be within four days of the spring tides and there will only be a reduced power supply for one week out of two. The future of this solution in natural conditions is limited to some exceptional places; the feasible world potential may be 500 TWh/year, but the cost-effective potential seems to be less than 100 TWh/year.

In fact in-stream turbines would be very cost-effective if they could operate for most of the time with a constant speed of about 4 m/s in favourable marine conditions. But there are no such places naturally. The principle of the new solution is therefore to create such places artificially.

4. Principle of the new proposed solution

To meet power demand and maximize environmental protection, the best way to operate a tidal reservoir is both ways, with an average head of less than 40 per cent of the mean tidal range H_m, that means, 2 or 3 m for the best sites and 1 or 1.5 m for the majority of sites. Bulb units are hardly cost-efficient at heads of less than 3 or 4 m, and orthogonal turbines at less than 2 m.

A line of in-stream turbines operating with a flow speed of 4 m/s uses a head of about 0.10 m. As an example, turbines of 16 m diameter, spaced at 25 m between the axes, and placed at a depth of 25 m, with a flow rate of 4 m/s, can supply $0.2\ sV3$ which means about $0.2 \times \pi/4\ 16^2 \times 43 \approx 2500$ kW, and use about 3000 kW if the output is 0.8.

The corresponding flow is 25 × 25 × 4 m/s = 2500 m³/s and the head used for a line of in-stream turbines is:

$$\frac{3000}{2500 \times g} \approx 0.12 \text{ m}$$

Twenty rows of in-stream turbines would require a total head of 2.4 m, corresponding to the recommended head for optimum sites. If the lines are spaced at a distance of five diameters, that is, 5 × 16 = 80 m, the total length would be 1600 m.

The principle is thus to develop the tidal energy through in-stream turbines in long artificial channels, where the initial speed chosen can be maintained for most of the time. A value of 3.5 or 4 m/s seems advisable.

Such channels could be obtained by creating a long dyke to form a large reservoir along the shore and opening the reservoir to the sea by channels equipped with 10 to 20 lines of in-stream turbines (Figs. 4 and 5).

The length of the channel could be 1600 m for a tidal range of 7 m and an operating head of 2.5 m. It would be reduced to 1000 m and 10 or 12 lines of turbines for a tidal range of 4 m and a head of 1.5 m.

5. Data for the proposed solution

Instead of several in-stream turbines in a natural place, it is proposed to install a larger number of turbines in an artificially created place to achieve improved production, this specific solution could justify a specific name such as Tidal Gardens (TG).

A site for Tidal Gardens (Fig. 4) would be a large basin open to the sea by 1 to 2 km-long channels where 10 or 20 lines of in-stream turbines (green plants!) would be placed. The area of the basin could be several hundred km² or possibly thousands of km², with about one channel per 100 km². Smaller basins could be used with one channel. Most future sites would be along the shore. A typical basin could then form a semi-circle along the shore.

The concept of a channel (TG) linking the basin to the sea is shown in Fig. 5.

The length would be based on the mean tidal range as well as turbine data. The width could be around 500 m for very large basins, or 100 to 200 m for small ones.

The depth could be 15 to 20 m below the low sea level; this may require some dredging or filling. To allow for a significant water speed, the bottom should be lined, for instance by 0.50 m of concrete placed in calm water.

The channel sides would be formed by dykes 25 m high, supporting a low head and greatly reduced wave impact. They could be as shown in Fig. 6(a).

The channel would be separated from the sea by gates, to be opened for about 4 hours within a six-hour half tide. The differential head on the gates would be quite low, but the wave impact might be high. Solutions similar to those for spillway gates could be used, but the specific conditions may favour solutions specific for the construction method. Individual designs would also be possible.

For the dyke closure, recent progress in breakwater design and dredging efficiency favours a solution as shown in Fig. 6(b), which would be suitable for an optimal programme of large schemes.

6. Operation of the new (TG) solution

It includes three phases during a six-hour half tide.

During the time when the basin is at sea level, the gates of the channel are closed for 1 or 2 hours to create a gap of 1 or 2 m between the sea and the basin; no power is produced.

During 3 or 4 hours of power supply, the number of open channels and in-stream turbines in operation is based on two objectives: to optimize the use of available power and to maintain the optimum flow speed in the channels for the best turbine efficiency. This speed, which would be defined at the design stage, could be obtained permanently by adjusting the number of turbines in operation according to the difference in head between the sea and the basin. If a channel is fully open, with no turbine operating, the water speed will be about 6 or 8 m/s; according to the number of turbines operating and thus using the energy through the channel, the water speed can be reduced to the optimum value for the turbines. The power supplied by a channel is thus approximately proportional to the head differential, and the total power supplied is in accordance with the width and number of channels fully open. It is thus possible in the case of any head to use the energy and the turbines optimally, with a fixed value of flow speed which is optimal for the turbine's performance.

For one hour, the head will decrease from about 2 m to zero, the number of operating turbines will reduce progressively, and the water speed in the channel will be maintained close to 4 m/s until a few minutes before the level in the basin and sea equalizes.

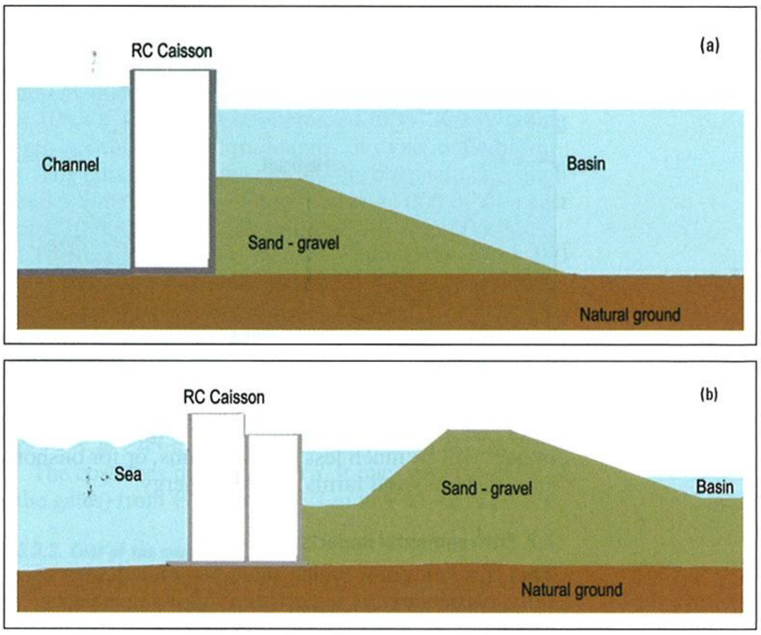


Fig. 6(a). A channel dyke; and, (b) main dyke.

7. Environmental impacts of tidal schemes

Many studies for tidal energy were carried out 50 years ago when environmental impacts were generally not a particular focus of attention. Most of the proposals from that time would therefore tend to be unacceptable now.

The impacts must be studied for modern designs, which take in account environmental problems. These are considered below for large schemes operating both ways. In these cases, a large basin would be open to the sea by long, wide and deep channels, where in-stream turbines would be installed. The water speed in the channels would be around 4 m/s.

There are three impacts to consider: visual, environmental, and socio-economic impact.

These should be compared, for the equivalent energy production, with the impacts of other renewable energies.

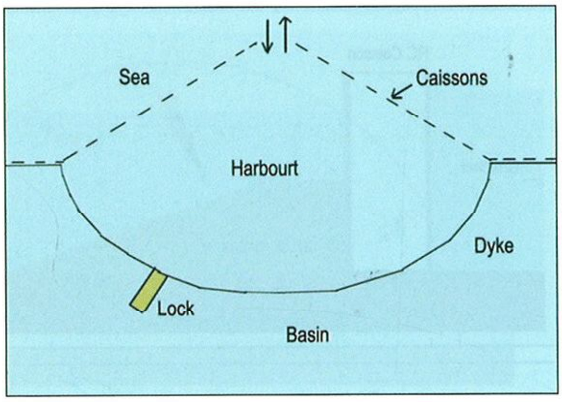
7.1. Visual impacts

Tidal plants cannot be seen because they use underwater in-stream turbines.

The dykes are about 10 m above sea level. Most are 10 to 20 km from the shore and are therefore hardly seen. Links with the shore could be used for tourism and fishing harbours (Fig. 7).

Fig. 7. Main dyke at the shore.

Fig. 8. Possible future additional large harbour.



For an equivalent amount of energy, the visual impact will be much less than for dams, or for onshore and offshore wind farms, or solar energy.

7.2. Environmental impacts

This is a key point which must be studied very carefully, particularly as regards the following aspects:

- With two-way operation, the tides in the basin will be virtually the same as for natural tides. The tidal range is reduced by 10 per cent, but may even be kept the same if some pumping facilities are added at a small additional cost (see section 9).
- The waves along the shore will be greatly reduced.
- The movement of sediments generated along the shore will be substantially reduced.
- The salt content of water will be unchanged.

The environmental impacts on shore and close to the shore may thus be more favourable than unfavourable. Reducing the natural sedimentation of gulfs could be very useful. The impacts close to the dyke and to the channel will be less favourable, because the sea bed will be modified by the construction. Moreover, sand brought through the channels during storms will remain within a few kilometres of the channels, and will require dredging. However these impacts apply to only 10 to 20 per cent of the basin area, and most of the basin area will experience less impact from sedimentation than would be the case in natural conditions.

Fish will cross the channels at a speed of 4 m/s, in conditions similar to those in places with turbines installed offshore in natural streams. The impact of noise and vibrations of turbines should be checked, and turbines could possibly be optimized accordingly.

All impacts can be studied at the first prototype schemes, on a scale of several tens of km², before larger schemes are undertaken.

7.3. Direct socio-economic impacts

These major schemes will not involve any relocation of people. A social advantage is that a great deal of employment will be created locally, and at factories prefabricating the turbines and manufacturing the dyke caissons.

With the proposed construction methods (see section 12), there will be little disturbance onshore during the projects.

In the event of any damage to the main dyke caused by extraordinary storms, there will be no human risk (similar to risks from dams failures) and quite easy repairs.

7.4. Indirect socio-economic impacts

The creation, along coasts, of very extensive calm areas (the costs of which are covered by the revenue from power supplies) could provide important opportunities for economic development in many countries. The reduction in large waves, elevated sea levels, and sedimentation would favour various developments along the shores, including small harbours and sandy beaches.

These calm basins would also be favourable for fish farming and shipping.

By dredging it would be possible to create large islands alongside the dykes. These islands could be used for tourism, or in some cases for large industrial schemes such as thermal plants, oil refineries, chemical plants, or large harbours.

The dykes, the cost of which will be covered by the power supplied, could protect cities along the shore from exceptional storms. It may be adapted accordingly.

It should be possible to operate the schemes in such a way as to reduce by 1 or 2 m the maximum water level along the shore, even in the case of very large rivers; this could mitigate the major problem of the general increase in the sea level in various countries such as in China, Vietnam and perhaps Bangladesh.

7.5. Shipping

Locks could be created between the sea and the basins as required. Small harbours could also be built along the shore.

Very large harbours in deep water could be created at a low cost alongside the main dyke, using the same caissons, and separating them from the dyke (see Fig. 8).

8. Examples of data and costs

Most cost effective tidal sites will have basin areas, S, of between 100 and 2000 km², and an average tidal range, H_m, of between 3 and 7 m. Approximate evaluations of power capacities and costs are given below for S = 500 km² and H_m = 5 m.

8.1. Physical data

During a half tide of about 6 hours, it is possible to keep the gates closed for 2 hours and to discharge most of the tidal range H within 4 hours. It is possible to discharge 75 per cent of H under an average head of 0.45 H, or 90 per cent of H under an average head of 0.35 H. This last solution is possible with the proposed technical solution, and it keeps the tidal range in the basin close to the natural one. Calculations can be made accordingly.

The discharged volume is $0.9 \times 5 \text{ m} \times 500 \times 10^6$, and the flow may be fairly constant for 4 hours with a flow of:

$$\frac{0.9 \times 5 \times 500 \times 10^6}{4 \times 3600} \approx 160\,000 \text{ m}^3\text{/s}$$

To achieve the best utilization of the turbines, the water speed in the channel is kept quite constant, for example 4 m/s, with a channel depth of about 20 m and a total width of the channels of:

$$\frac{160\,000}{4 \times 20} = 2000 \text{ m}$$

For example in the form of five channels 400 m wide.

The channel flow will remain quite constant, but the head between the basin and the sea will be about 2 m for two hours and lower for a further two hours. The number of rows of turbines in operation can be adjusted for this head.

During spring tides, the gates will be opened for five hours instead of four; the average head will be slightly higher, but the water speed will be maintained at around 4 m/s.

During neap tides, a channel may remain closed, the operation could be limited to three hours and the water speed in channels kept at about 4 m/s.

8.2. Power evaluation

Throughout half a tide, a volume of $0.9 \times 5 \times 500 \times 10^6$ will be used under an average head of 0.35×5 m; for a turbine output of 0.85 and a hydraulic loss of 25 per cent in the channel, the energy is:

$$\frac{0.35 \times 5 \times 0.9 \times 5 \times 500 \times 10^6 \times 0.85 \times 0.75 \times g}{3600} \approx 7 \text{ GWh}$$

and, for 705 tides per year, an annual energy of $7 \times 2 \times 705 \approx 10\,000$, that is, 10 TWh/year.

During operation for four hours the flow will remain quite constant but the head, that is, the power supplied is lower for two hours and the necessary capacity is about 7 GWh/3 hours = 2.3 GW. This capacity should be increased by about 20 per cent for flexibility and a better utilization of spring tides, that is, $2.3 \times 1.2 \approx 2.75$ GWh.

An in-stream turbine supplies (in kW) $0.2 \times s \times V^3$, s being the turbine area and V the water speed. For a diameter of 16 m (s being about 200 m^2) and a water speed of 4 m/s, the capacity is $0.2 \times 200 \times 4^3 \approx 2500$, that is, 2.5 MW. The site requires 1100 turbines of 2.5 MW, or 220 turbines per 400 m-wide channel.

These turbines may, for instance, be in rows of 16 turbines (25 m between axes) spaced by 5×16 m = 80 m, that is, 14 lines and a channel length of $14 \times 80 \approx 1100$ m.

8.3. Costs

The cost includes three principle components: the turbines, channels and main dyke.

8.3.1. Turbines

For a large number of units placed in calm waters close to a substation, the cost should be close to that of a wind plant of similar design and the same capacity. A figure of €1200/kW, that is, €3 million per turbine, is assumed below. This cost should be increased by 15 per cent to account for the financial costs during construction, making a total of €1380/kW. Assuming 7 per cent per year for depreciation and interest and 3 per cent for operation and maintenance, the cost is:

$$\frac{1380 \times 10\% \times 1000}{3600} \approx 38 \text{ €/MWh}$$

This value does not vary with tidal range or the basin area.

8.3.2. Cost of the channels

The total area of the channels is $2000 \times 1100 = 2.2 \times 10^6$ m^2 for 2.75 GW, that is, 0.8 m^2 per kW. The total length of channels is $5 \times 1100 = 5500$ m.

The channel cost includes three components:

- The cost of the base concrete, 0.50 m thick, at a cost of €200/m^3, that is, 0.8 m^2 $\times 0.5 \times 200$ = €80/kW
- The cost of dykes, that is, two dykes, see Fig. 6(a) using 40 m^3 of reinforced concrete per metre at a cost of €700/m^3 for a total dyke length of $2 \times 5500 = 11\,000$ m, that is, $11\,000 \times 40 \times 700 \approx$ €310 million / $2.75 \times 10^6 \approx$ €110/kW to be increased to €120/kW taking into account some extra lengths of dyke in the basin.
- The cost of the gates closing the channel, 22 m high and $5 \times 400 = 2000$ m long, that is 44 000 m^2 at a cost of €10 000/m^2 or €440 million/2.75 ≈ €160/kW.

The total cost for the channels is thus 80 + 120 + 160 = €360/kW to be increased by 25 per cent for unforeseen and miscellaneous items, and by 20 per cent for financial costs during construction, that means, an investment of $360 \times 1.25 \times 1.20 \approx$ €530/kW.

For 7 per cent per year of this investment value, and 1 per cent for operation and maintenance, the annual cost per kW is €43 for 3600 hours per year, or €12/MWh.

The cost does not vary with S. It may vary (because of the gates) from €10 for $H_m = 7$ m to €15 for $H_m = 3$ m.

8.3.3. Cost of the main dyke

For a 500 km^2 area, this may be evaluated as the cost of a semi-circular dyke along the shore. The diameter will be 35 km, and the length of dyke $35 \times \pi/2$, or 55 km.

The cross section may be as shown in Fig.6(b), which combines a breakwater (such as for the recent Tanger harbour) with a wide dyke built by dredging in calm water, supporting the rather low head between the sea and the basin.

The cost per m may be as follows:

- Reinforced concrete 50 m^3 $\times$ 700 €35 000
- Sand and gravel dyke 1500 m^3 $\times$ 3 = €4500
- Dyke protection 100 m^3 $\times$ 50 = €5000
- Total = €44 500

Increased with a 20 per cent contingency to cover studies and other miscellaneous items, and by a further 20 per cent for financial costs during construction, for 55 km this results in

€55 000 × 44 500 × 1.2 × 1.2 = €3.6 billion.

The annual cost may be 6 per cent for capital costs and 1 per cent for operation and maintenance, that means, about €250 million for 10 TWh or €25/MWh.

The evaluation of €25/MWh for the main dyke cost is for: $H_m = 5$ m and $S = 500$ km^2.

This varies as $(5/H_m)^{1.5}$ because for the same area the power varies as $H_m{}^2$ and the cost per metre of dyke very approximately as $\sqrt{H_m}$.

Accordingly, for $S = 500$ km^2, the cost of the dyke will be €25/MWh for $H_m = 5$ m, 20 for $H_m = 7$ m, 35 for $H_m = 4$ m.

It varies as $(500/S)^{0.5}$ because, for the same shape basin, the power is quadrupled when the dyke length is doubled.

The costs above are for a straight shore; they could be greatly reduced for a more favourable topography of the shore, such as a gulf.

8.3.4. Cost comparison with other solutions

The cost as evaluated above includes three components:

- The cost of €38/MWh for turbines, based on a cost of turbines of €1200/kW. This cost of €1200/kW for hundreds of 2.5 MW units which can easily be placed in calm waters, with short transmission links, should not be very different from the cost of onshore wind mills of similar unit capacity.

• The average cost of €12/MWh for the channels varies between €10 and 15 according to the tidal range. The cost per kW of the turbines and channels of €1200 + €450 = €1650 is slightly higher than the cost per kW of onshore wind mills, but the annual power supply is about 2000 hours of the rated power for windmills and 3600 for in-stream turbines.

The total cost per MWh of the turbines and channels may thus be lower than the cost of onshore wind farms. This is also true for tidal ranges of 3, 4 or 7 m.

The cost of bulb units operating both ways is much higher, because the operating head is less than 3 m for the best sites, and less than 2 m for tidal ranges of 4 m; also, the power produced per metre of structure is limited to several hundred kW while the cost of the civil works remains high. The cost per MWh can therefore be high even for the best sites and very expensive for tidal ranges of 4 m.

The cost per kW of a bulb plant operating one way will be lower than for both ways, because the operating head is higher, but the annual supply will be much less (2000 hours of the rated power in Sihwa and La Rance).

The orthogonal turbines studied in Russia appear more attractive; they are designed for operation both ways and are quite simple machines. But their power supply per metre of structure remains low, and the cost of civil works per kW is quite high for a tidal range of 6 m and very high for a tidal range of 4 m.

The cost of the main dyke has been evaluated as €25/MWh for a site of 500 km², 55 km of main dykes and a tidal range of 5 m.

For the best sites, such as the Severn (UK), Chausey (France), and Fundy (Canada), where the dyke length is lower compared with the basin area, the cost per MWh may be €10, and the total power cost €60/MWh.

But the new solution has a larger potential with sites where there is 3 or 4 m of tidal range because there are worldwide many sites of such tides range with areas of hundred km² with a sea depth under 20 m. For a tidal range as low as 3.5 m and a 500 km² area, the cost of the main dyke may be $25 \times (5/3.5)^{1.5} \approx$ €40 and the total cost €50 + €40 = €90/MWh. For such large schemes, the tidal plant operation has a favourable impact on shore where the waves, the exceptional high water level and the sedimentation are reduced and a part of the dykes cost may be paid by these advantages.

The worldwide cost effective tidal energy potential is thus much higher than it has been estimated in the past.

9. Pumping facility may increase the power supply

In the example above, for a mean tide of 5 m, the tidal range in the basin is 4.5 m. To obtain the same range as the natural one, it would be necessary to pump $0.25 \text{ m} \times 500 \times 10^6 \text{ m}^3$ within 1.5 hours, that is, 23 000 m^3/s under an average head of 1 m, with an output of 0.75 this requires an installed capacity of 300 MW.

The cost of such plants, which may require specific bulb units, could be quite high. An example could be €2000/kW, that is, €600 million in total, increasing the total investment by 8 per cent. But for an increase in tidal range of 10 per cent, the energy supplied will be increased by 15 or 20 per cent. This additional investment could therefore be very cost-effective and maintain the natural tide, which will reduce environmental impacts. The utilization of these bulb units for supplying power gives also flexibility for the overall power supply.

It may also be possible to use specific units only for pumping at a lower cost.

10. Utilization in the grid and energy storage

Tidal power has the advantage of being a reliable and easily predictable form of energy, but there are two associated variations in power supply:

- during a half tide of six hours; and,
- over 14 days (spring and neap tides).

Within 6 hours, two-way operation supplies power for 4 hours; it is thus advisable to store 2 hours of average power supply. For the example above, of 10 TWh/year, the average supply will be 10 000 GWh/8640 hours ≈ 1.15 GW to be stored for at least two hours, that is, 2.3 GWh.

It is possible for most tidal sites to use few per cent of the tidal basin for a pumped-storage plant, for instance with two basins, one operated between 10 and 20 m below the lower sea level, and the other between 10 and 20 m above. The stored energy for two 1 km² basins, would be:

$$\frac{10^6 \times 10 \times 30 \text{ m} \times g \times 0.75 \text{ (output)}}{3600 \times 10^6} = 0.6 \text{ GWh}$$

Storing 2.3 GWh requires an area of $2 \times 2.3/0.6 \approx$ 8 km².

A pumped-storage plant could be built along the main dyke, in the dry, between cofferdams, requiring 15 km of dykes. This work could be done in calm water, after closure of the main dyke, that is, at a cost per km of dyke of about €20 million/km: €20 × 15 = €300 million for 1.15 GW, or about €300/kW.

The total investment for pumped storage would then be about €1000/kW, that is, 1.15 billion and an annual cost of about €120 millions for 10 TWh, that is, €12/MWh. It should be noted that there would be a 20 per cent loss of power through storage, applying to one third of the power supply, that means, 20 per cent × 1/3 ≈ 7 per cent × 75 ≈ €5/MWh.

The total cost of the storage will then be €12 + 5 = €17/MWh, but the power supplied may be used when required and especially during periods of peak demand.

If there are several tidal schemes within the same country, with different tidal regimes, the need for storage will be reduced.

The need for energy storage may also be reduced or eliminated if a lot of thermal power is used in a country. The investment in pumped storage could then be postponed for some decades.

Over 14 days, the power supply will be about 60 per cent of the mean supply for three or four days of neap tide, that means, a lack of power for 40 per cent × 80 hours. The corresponding storage for 30 hours may be possible, but requires very large areas and major extra costs. It will probably often be less expensive, during neap tides, to use some power from hydropower, biomass, gas or coal.

The optimum storage time may, however, be between 2 and 30 hours, such as 10 hours using 8 per cent of the area of the main basin. The cost of storage will be close to €25/MWh.

This extra cost for storage has some major advantages:

- Power may be available for use at peak times.
- The pumped-storage plant will have a quick response time.
- The pumped-storage plant may also be used in combination with other energies such as wind. It may be the most cost-effective way for storing energy and it may thus be advisable to increase the pumped-storage capacity up to 1.5 or 2 GW for 10 hours.

11. Association with wind energy

In many countries, it will be cost-effective to use the tidal basins for wind energy, installing wind turbines over the dykes and within the basin.

For the example above of 500 km^2 and 55 + 11 = 66 km of dykes, it may be possible to place, within an area of 300 km^2, 600 turbines of 5 MW (100 over the dykes and 500 in the basin where they can be maintained in calm water). The transmission lines will be short. The investment per kW will not be much higher than for onshore wind farms, and the annual production will be greater because the wind conditions are better at sea. The annual supply may be 600 × 5 MW = 3 GW × 2500 hours = 7.5 TWh/year, at a direct cost close to that of onshore wind energy.

The pumped-storage plant foreseen for the tidal energy storage can be used for the wind energy storage.

At many tidal sites, the wind energy may therefore be just as important as the tidal energy, and very cost effective.

12. Construction methods and schedule of works

For schemes with a reasonably small area, such as 50 km^2, the best solution may be to build in the dry, using cofferdams, as was the case at La Rance and Sihwa.

For schemes of hundreds or thousands of km^2 and dykes tends of kilometres long, it seems preferable to use marine construction methods; it should be stressed that construction work at sea can be complex and expensive if there is exposure to waves, but can be efficient and cost effective in calm water.

The main dyke will mainly be formed by prefabricated caissons placed when there are no significant waves, and by dykes in sand and gravel placed by large marine dredgers operating in calm water behind the caissons.

The channel works include the dykes, as mentioned above, the bottom lining and the gates, which can be installed in calm water. A calm site can be created by the channel dykes and by some caissons of the main dyke, to be used for a few years in front of the gates during the construction of the gates.

The schedule of works could then be:

1. Two years of preliminary work, including the construction of a small harbour which can later be used for tourism or fishing (Fig. 7).

2. Four years for the main works: each channel could be built within two years and several channels could be built simultaneously. Turbines could be brought to the site and installed by marine equipment in calm waters, and with a very flexible schedule. Most of the main dyke can also be built during this phase, but part of it must remain open to keep the water speed between the sea and basin at less than 2 or 3 m/s.

3. Some months will be required to close the main dyke, with all channels open, and to start the power supply.

4. The pumping facilities, the pumped-storage plant and possible wind farms will be built after the closure of the main dyke, within cofferdams so in calm water. The bases for the wind turbines, to be placed at a depth of about 20 m, can be prefabricated within one of these cofferdams at a low cost. All of these works can be carried out immediately or postponed for some decades.

Prefabrication of caissons and turbines may be at a constant rate over four or five years, which is very cost effective.

13. Impact of large tidal plants on the natural tidal range

Tides are very complex phenomena and a local high tidal range is very often associated with resonance effects. In large tidal schemes, using a significant part of the energy may significantly modify the natural tidal range close to the basin. This variation depends on the power generated and the operation method. It may be more than 10 per cent of the natural range and reduce by 20 or 30 per cent the available power. This applies mainly to sites with high tidal ranges and much less where the tidal ranges are only 3 to 5 m.

The impact of this problem will therefore be rather limited with the solution proposed:

- The reduction of power supply may be significant for sites with mean tidal range over 5 m but a reduction in power by 20 per cent will increase the cost per MWh by 10 per cent and these sites will remain cost effective.
- The impact on sites where the average tidal range is 3 to 5 m will probably be low or non-existent, and these sites represent most of the potential.

14. World potential and possible implementation

The possibility of using large areas where the tidal range is 3 to 5 m doubles the world potential and favours the use of tidal energy in countries which have not yet studied this possibility.

The turbine, channel and dyke designs may be quite similar in most countries. Experience of some preliminary sites 50 or 100 km^2 may be completed in 2025 and large sites may then be implemented worldwide.

A realistic potential of 1500 TWh/year of tidal energy and 500 TWh/year of associated wind energy is likely. This is more than half of the present hydropower or the present nuclear energy, for about same cost, with fewer environmental impacts.

15. Conclusion

For the same potential, hydropower supplies 3600 TWh/year and tidal energy 1 TWh/year.

For environmental reasons, the main use of tidal energy should be with large basins along the shore operating a tide with a water level about 2 m above or below the sea level.

The powerplants which are similar to conventional hydro plants, and which have been studied over the past 50 years, are too costly for such low heads.

The new proposed solution opens basins to the sea via channels 1 or 2 km long, in which in-stream turbines can be placed, to operate in optimal conditions. One can summarize three major advantages:

- The cost for sites with a high tidal range is much lower than with traditional solutions.

• The cost efficiency applies also to the vast potential of sites with a tidal range of 3 to 5 m.
• The environmental impacts are far less than for conventional hydropower; the natural tides are maintained in the basins but high waves, storms and exceptional high water levels can be avoided along the shore.

This solution may have an economic potential of considerably more than 1000 TWh/year and could be applied in 15 or 20 countries with very favourable economic impacts.

The corresponding potential and impact in these countries is planned to be analysed in a future issue of *Hydropower & Dams*. They may be very different from the past studies. ◊

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