Severn Estuary: ideas for development

Alex Gokhman presents an idea for the development of an efficient and environmentally friendly tidal power plant for the Severn Estuary in the UK

TIDAL power plants with barrages can offer tremendous potential for the development of clean, renewable energy. Unfortunately, there are only limited sites throughout the world that would be suitable for the development of such systems – with one of the best sites in the UK at the Severn Estuary.

In January 2009 the UK Department of Energy and Climate Change (DECC) prepared a shortlist of five Severn Tidal Power options for evaluation. One of options was the Cardiff-Weston Barrage ebb generation power plant, which could have an installed power capacity of 8.64GW and a construction cost of £20.9B. It would provide 17,000GWh per year (up to 5% of Great Britain's annual energy consumption [1]). In October 2010 however, the Government withdrew its support for the Barrage, claiming that it would be expensive and too high-risk.

The author's research on an effcient and environmentally friendly Cardiff-Weston Barrage at the beginning of 2010 revealed that if the DECC concept of the plant were to be equipped with the Baker concept of the power equipment (see the following section), it could produce 32,665GWh per year at a construction cost very similar to the DECC concept as is. Moreover, the author's two-way generation tidal power plant with Baker concept of power equipment [2,3] could produce a total of 41,505GWh per year with just at 20% increase in construction costs, and a very limited effect on the environment.

Power generation at tidal power plants

Any power plant must ultimately supply the electrical grid with alternating current of a constant standard frequency (usually 50 or 60Hz). Until recently, to satisfy this requirement all hydro plants had turbines powering synchronous generators with their speed of rotation (synchronous speed) set to produce the standard frequency. The need to maintain synchronous speed under all conditions renders low head generation at conventional, particularly at tidal power plants, economically inferior. The situation drastically changed at the end of the last century with the introduction of effective electric current frequency converters. For example, Itaipu – one of the largest hydro plants in the world – feeds electricity to both Paraguay and Brazil, who have different frequency standards, using this technology.

Tidal plants with barrages use the water volume and the head created by the tide. It is clear that unutilized for power generation tide water volume per cycle is lost. The flow and head at the tidal plant will change drastically during each ebb/flood cycle of the tide.

The head variation at a tidal plant is 100%. Kaplan runners cannot work efficiently for such large head variation.

The first significant step towards the development of an economically acceptable tidal plant was the acceptance of power equipment having a Bulb turbine with axial propeller rotating with variable speed, AC generator, and the converter to standard frequency.

In 1984, engineers working under George Baker, who at the time was Vice President of the Tidal Power Corporation of Nova Scotia, reached this conclusion. It was presented in the update of a 1976-1977 feasibility study for the Bay of Fundy tidal power plant. The author will refer to this concept of power equipment for tidal power plants as the Baker concept of power equipment in the remainder of this paper.

The Baker concept of power equipment permits the turbine to work at heads, $0.2H_{max} \le H \le H_{max}$, at optimal operating regime and, therefore, significantly increases its yearly energy production. This makes the turbine less expensive, much simpler and, therefore, attractive for large tidal plants with 100-200 installed generating units.

However, the Baker concept applied to an ebb generation tidal plant (Canadian concept of tidal power plant) does not decrease its negative environmental impact.

As an alternative, the author proposed a two-way generation tidal power plant with one-way turbines and bypasses [2,3]. This two-way tidal power plant with the Baker concept of power equipment utilizes the energy of ebb and flood. With regards to the Cardiff-Weston Barrage, the two-way concept could produce 27% more energy per year than the Canadian concept if both are equipped with 216 bulb turbines having the same commercially available axial propellers, and will have a minimal impact on the environment. It is important to note that in order to find the annual energy production and the relative value of used water volume in comparison with the available water volume of the tide cycle for the DECC, Canadian, and two-way concepts (all using turbines which have been tested in recognized hydraulic laboratories), one does not need to carry out time-consuming experiments. This can be achieved via a specially designed operation simulation program that solves equations describing the process of power generation at tidal power plants.

Equations describing the process of power generation at tidal plants

The equation describing the change the water level in the basin is the well known nonlinear ordinary differential equation of the first order:

$$\frac{dZ_b}{dT} = \pm \frac{Q}{A_b\,(Z_b)} \quad (1)$$

where:
T is the current time in seconds, $Z_b = Z_b\,(T)$ is the water level in the basin, $Q = Q\,(T)$ is the flow emptying/filling the basin, and $A_b\,(Z_b)$ is the basin horizontal cross-section area as known function of Z_b.

In equation (1) the sign - is for the ebb generation and the sign + is for the flood generation.

The current head of tidal power plant is determined as:

$$H = \pm\,(Z_b - Z_t) \quad (2)$$

where:
$Z_t = Z_t\,(T)$ is the tide level as known function of time.

The flow in (1) is defined as:

$$Q = Q_t + Q_b \quad (3)$$

where:
Q_t is the flow passing through the turbines and Q_b is the flow passing through the bypasses in the main barrage.

In the case of the ebb tidal power plant $Q = Q_t$.

The flow through the bypasses in m³/sec:

$$Q_t = K_t\,(Q_{11})_c\,\sqrt{H}D_t^2 \quad (4)$$

where:
K_t is the number of turbines at tidal power plant, $(Q_{11})_c$ is the current value of Q_{11} in each turbine at the plant, and D_t is the turbine runner diameter.

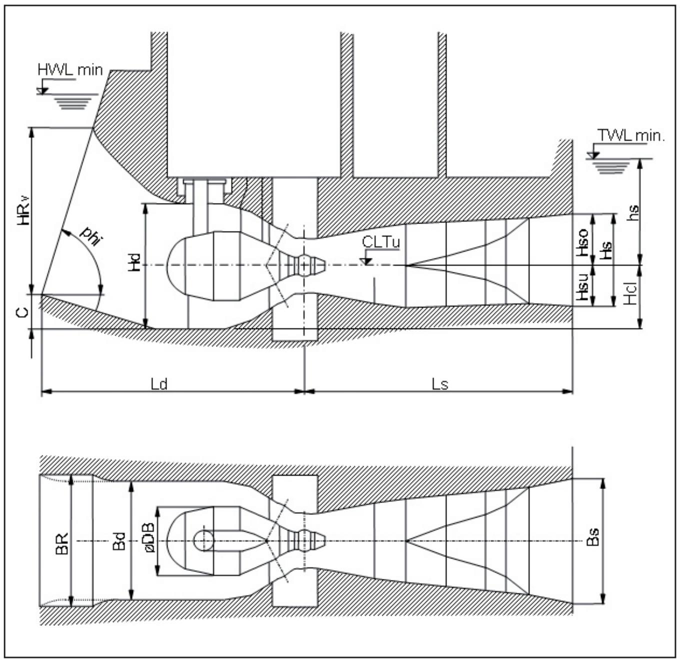
The flow through the bypasses in m³/sec:

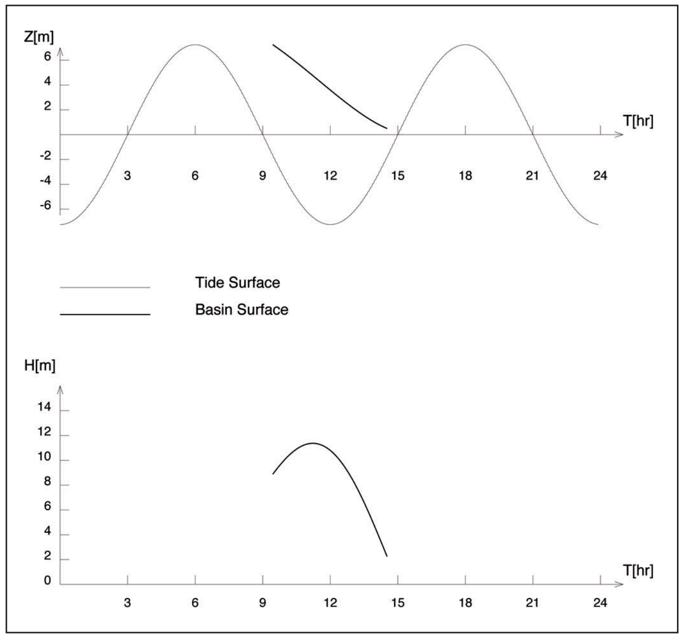
$$Q_b = C_d K_b B_b H_b \sqrt{2gH} \quad (5)$$

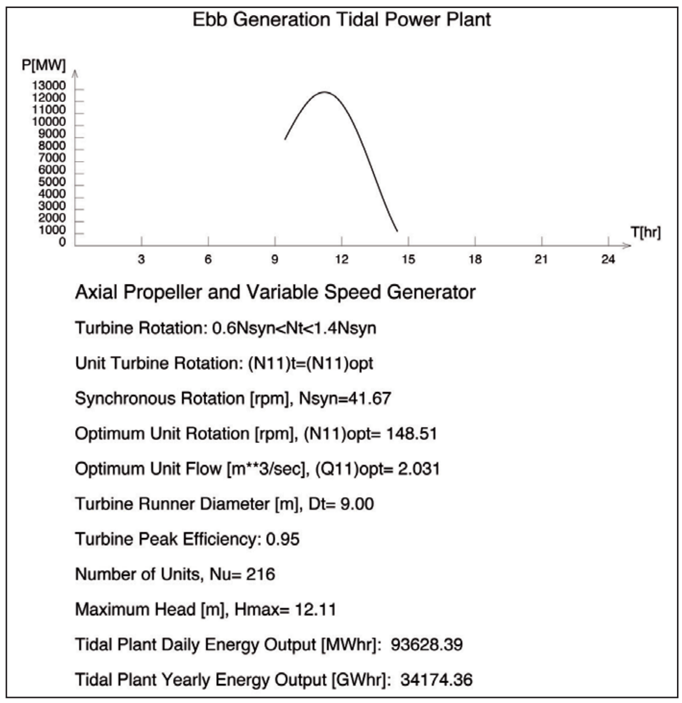
where:
$C_d = 0.60$ is the coeffcient of discharge, K_b is the number of working bypasses, B_b is width of bypass aperture, H_b is current bypass opening height, and $g = 9.81$m/sec² is gravity acceleration.

Consequently the current power of the power plant in MW is defined by the formula:

$$P_c = 0.000001 pg\eta_c Q_t H = 0.001 gn_c Q_t H \quad (6)$$







Above, left: **Figure 1. Commercially available Voith Bulb turbine with (Q_{11}) opt $=2.031m^3/sec$, $(N_{11})_{opt}$ = 148.51 rpm, and η_{max} =0.95. Figure used with permission of Voith for preliminary sizing information;** Above, right: **Figure 2. Plots of $Z_t = Z_t(T)$, $Z_b = Z_b(T)$, and $H = H(T)$ for ebb generation plant with Voith turbine, A.C. generator of variable speed, and a converter to standard frequency.** Right: **Figure 3. Plot of $P = P(T)$ and energy output for ebb generation plant with Voith turbine, A.C. generator of variable speed, and a converter to standard frequency**

where:
$\rho = 1000kg/m^3$ is the density of the water and
ηc is turbine effciency corresponding to current values of (N_{11}) and $(Q_{11})_c$.

In order to perform highly accurate numerical integration of equations (1–5) the program ENERGY was developed by the author and Dr. Dmitry Gokhman (Department of Mathematics, the University of Texas at San Antonio). ENERGY was verified and showed the relative error less than 0.5% in computation of all parameters. In the author's opinion it is evident, therefore, that the numerical results obtained by the program ENERGY do not require experimental verification, because the equations (1-6) adequately represent the process of power generation at tidal power plants. A paper containing a detailed description of ENERGY will be presented in future issues of International Water Power & Dam Construction.

As a final result, ENERGY computes the energy produced by tidal power during one cycle, E_{cyc}, and the water volume used for one cycle of generation, W_{usc}.
Energy in MWhr is computed by the formula:

$$E_{cyc} = \int_{(T_{eb})_b}^{(T_{eb})_e} P_c dT + \int_{(T_{fl})_b}^{(T_{fl})_e} P_c dT \qquad (7)$$

where:
T is the time in hours, $(T_{eb})_b$ and $(T_{eb})_e$ are the times of the ebb generation beginning and end. $(T_{fl})_b$ and $(T_{fl})_e$ are the times of the flood generation beginning and end.

The water volume used for one cycle of generation in km^3 is computed by the formula:

$$W_{usc} = 10^{-9} \left[\int_{(T_{fl})_b}^{(T_{fl})_e} Q_t dT + \int_{(T_{flb})_b}^{(T_{flb})_e} Q_b dT\right] \qquad (8)$$

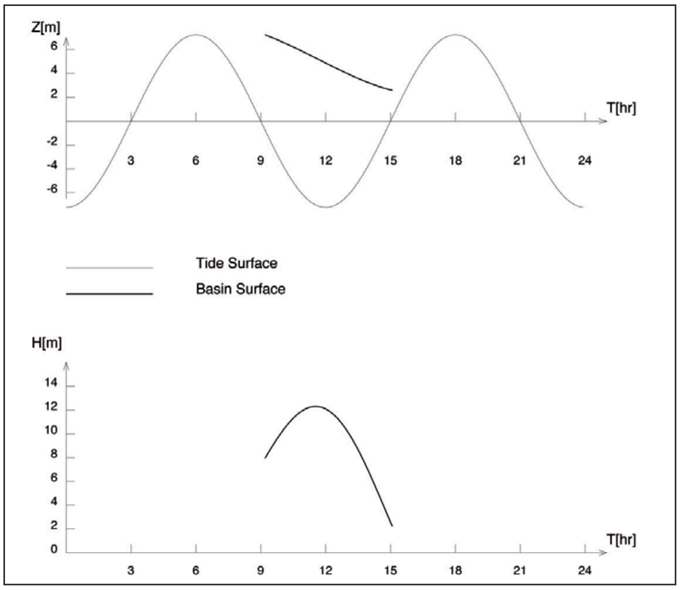
where:
$(T_{flb})_b$ and $(T_{flb})_e$ are the times at the beginning and the end of work of bypasses during the flood.

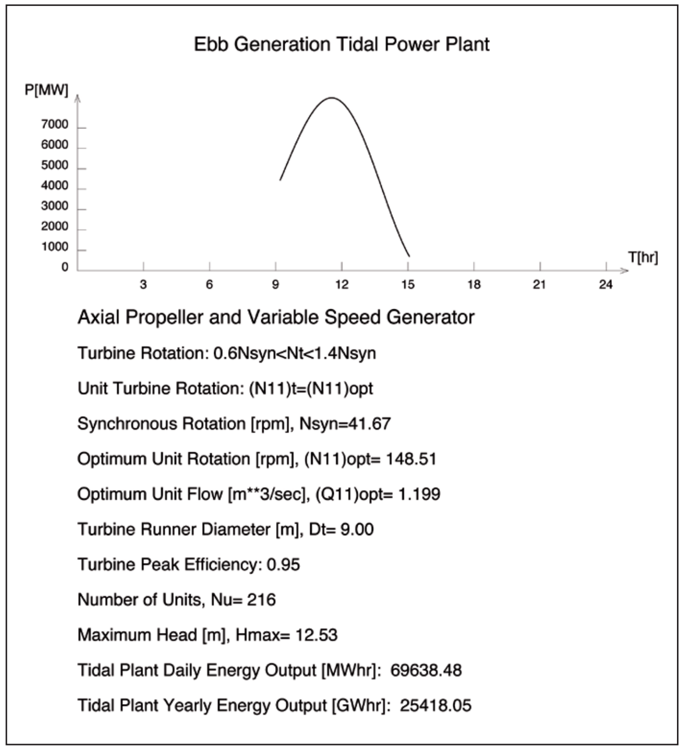
Comparison of the DECC, Canadian, and two-way concepts of the Cardiff-Weston Barrage

The following analysis was conducted by the author using the program ENERGY for the comparison of DECC, Canadian, and two-way concepts by yearly energy outputs in GWhr, $E_{year} = 0.73E_{cyc}$, and available volume usage ratio, $C_{avw} = W_{usc}/W_b$, W_b is the basin volume. The comparison was conducted for Severn Estuary tide amplitude, A_t = 7.25m and accepted by DECC D_t = 9.0m and K_t = 216 using the capacity curve, $A_b = A_b(Z_b)$, for the Bay of Fundy basin. The reason the capacity curve for the Bay of Fundy basin was used was that the author was unable to obtain the capacity curve for the Severn basin.

Commercially available Bulb Turbine offered by Voith Hydro

The author requested data from Voith Hydro for a Bulb turbine with a Kaplan runner suitable for the Severn tidal power plant conditions, accompanied with elevation and plan views of the turbine (see Figure 1). The author specified the diameter of the turbine, D_t = 7.5m and the maximum head, H_{max} = 12.0m instead of D_t = 9.0m and H_{max} =





Above: **Figure 4. Plots of $Z_t = Z_t(T)$, $Z_b = Z_b(T)$, and $H = H(T)$ for ebb generation plant with Bulb turbine [$(Q_{11})_{opt}$ =1.199m³/sec $(N_{11})_{opt}$ = 148.51 rpm, and ηmax =0.95], A.C. generator of variable speed, and a converter to standard frequency;** Right: **Figure 5. Plot of $P = P(T)$ and energy output for ebb generation plant with [$(Q_{11})_{opt}$ =1.199m³/sec $(N_{11})_{opt}$ = 148.51 rpm, and ηmax =0.95], A.C. generator of variable speed, and a converter to standard frequency**

14.5m. The reason for this was that the capacity curve for the Severn Estuary and the parameters on the DECC turbine were not available to the author at the time of request.

At that time the author was working using the Bay of Fundy capacity curve, H_{max} = 12.0m, and D_t = 7.5m. The other parameters specified by Voith were:
Maximum efficiency, η_{max} = 0.95; Optimal unit flow, $(Q_{11})_{opt}$ =2.031m³/sec; Optimal unit rotation, $(N_{11})_{opt}$ = 148.510 rpm; Cavitation coefficient at optimum, $\sigma_{opt} \approx 1.2$.

As can be seen in Figure 1 for the turbine with D_t = 7.5m draft tube exit height, $H_s = H_{su} + H_{so}$ = 12.838m, and draft tube exit bottom, H_{su} = 2.474m, therefore, draft tube exit upper part, H_{so} = 10.364m. Accepting a simple scaling of the Voith turbine to D_t = 9.0m, H_{so} = 12.437m and, therefore, this turbine with suction head, $h_s \geq$ -12.437m, will not be more expensive than Voith turbine (the upper edge of the draft tube cannot be above minimal tail water level, TWL_{min}).

The Voith Bulb turbine with D_t =9.0m under H_{max} =14.5m cavitation free work at optimum operating regime requires:

$$h_s = 10.3 - \sigma_{opt} H_{max} = -7.1\text{m}$$

It is clear that the maximum value of cavitation coefficient providing cavitation free operation for a Voith Bulb turbine working only at optimal operating regime requires:

$$(\sigma_{opt})_{max} = \frac{10.3 - H_{so}}{H_{max}} = 1.6$$

So there is still room for an increase of $(Q_{11})_{opt}$ without an increase of capital expenses for construction if one uses the Baker concept.

Performance of the DECC concept for Cardiff-Weston Barrage

The main parameters of DECC concept are included in its report [1]: Number of units, K_u = 216; Turbine runner diameter D_t = 9.0m; Operating speed of turbines, N_{op} = 50rpm; Total power, P_{tot} = 8640MW; Energy production per year, E_{year} = 17,000GWhr.

The value of H_{max} is not specified in the Black & Veatch report [1]. The author obtained this value by analyzing the Severn plant as if it used the Baker concept of power equipment.

The resulting maximum head was taken to be H_{max} = 12.69m.
Now combining equations (4) and (6) one can get:

$$\eta_{op}(Q_{11})_{max} = \frac{P_{tot}}{0.001 g K_t H_{max}^{1.5} D_t^2} \quad (9)$$

Equation (9) gives for DECC data η_{max} $(Q_{11})_{max}$ = 1.139m³/sec. So accepting the Voith value of maximum efficiency, η_{max} =0.95, one gets for the DECC concept $(Q_{11})_{max}$ = 1.199m³/sec.

Performance of the Canadian concept for Cardiff-Weston Barrage with a Voith Bulb Turbine

The main parameters of the power equipment are:
- Number of units, K_u = 216
- Turbine runner diameter D_t = 9.0m
- Synchronous speed, N_{syn} = 41.66667rpm
- Maximum efficiency, η_{max} = 0.95,
- Optimal unit flow, $(Q_{11})_{opt}$ =2.031m³/sec
- Optimal unit rotation, $(N_{11})_{opt}$ = 148.510rpm.

Accepted by the author frequency converter will function for turbine rotational speeds $0.6N_{syn} \leq N_t \leq 1.4N_{syn}$. The reason for selection of such variation in turbine speed is that according to information obtained by author at TEMCo – Tower Electric the predominant factor in the cost of frequency converter is its maximum power, not the range of frequency variation. Therefore, the range of variation in N_t was selected in order to provide less than 1% of E_{year} due to this limitation. The results of computations by ENERGY are shown in Figures 2 and 3, E_{day} = 93,628.39MWhr, E_{year} = 34,174.36GWhr. As can be seen from Figure 3 there is the energy loss caused by the operational limitation of frequency converter as indicated above, $(E_{lost})_{day}$. This value of $(E_{lost})_{day}$ can be found by comparing it with ENERGY output showing the results of computation of the ebb generation plant with the two-way generation plant for the Severn with identical power equipment, but without Frequency converter limitation, $0.6N_{syn} \leq N_t \leq 1.4N_{syn}$ which in this case is 94,174.53 MWhr.

Consequently, $(E_{lost})_{day}$ = 94,174.53MWhr – 93,628.39MWhr= 546.14MWhr, or only 0.58% of energy without Frequency converter limitation. Therefore, the yearly energy output of 34,174.36GWhr for this concept is two times higher than the DECC energy output of 17,000GWhr. What is interesting is that the yearly energy output of 25,239.36GWhr for the plant with the Baker concept of power equipment having DECC value of $(Q_{11})_{opt}$ =1.199m³/sec (see Figures 4 and 5) is also 49.5% higher than DECC energy output of 17,000GWhr.

It is clear to the author that the DECC concept for the Severn application had two significant deficiencies. The first results from its acceptance of a synchronous speed Kaplan runner instead of Baker concept of power equipment, which was known at that time of the DECC studies, and was commercially available. This equipment selection led to a much smaller energy output even with the same value of $(Q_{11})_{opt}$ =1.199m³/sec. It also led to an increase of at least 40% in the cost of the turbine runners. That cost for 216 turbine runners is a significant part of the total capital cost for the Severn plant. In addition to that, it would introduce a risk of environmental accidents, because it is very likely that continuous daily operation of oil-filled Kaplan runners in 216 machines could result in frequent spillage and oil pollution of the waterway. The second deficiency is caused by the acceptance of $(Q_{11})_{max}$ =1.199m³/sec which was not required by the value of suction head, h_s.

As was mentioned above, the maximum absolute value of suction head, h_s, must be smaller than the upper part of the draft tube exit, H_{so} = 12.437m. So, with the Voith value of h_s = -7.73m for $(Q_{11})_{opt}$=2.031m³/sec there was not any reason to except $(Q_{11})_{max}$ = 1.199m³/sec.

Two-way generation tidal power plant with bypasses

In 2008 the author received a patent for the "Two-way generation tidal power plant with one-way turbines" [2]. This was developed to use the Baker concept of power equipment while utilizing the energy of both ebb and flood. However, this concept of a two-way tidal power plant will only produce more energy than an ebb generation plant only when a very large number of units is used. In the case of the Severn project, it would require the use of 350 units which would be uneconomical. In addition to this, the plant would use almost half of the available tide volume and, would, therefore, have the same negative effects on the environment as an ebb generation plant with the Baker concept of power equipment.

In 2009, following development of the ENERGY program, the author tried to use sluices bypassing the water in parallel with the powerhouse during final phases of both ebb and flood generation. The results shown by ENERGY were very encouraging. The two-way plant produced substantially more power than the ebb generation plant. The two-way plant would also use the water volume per cycle almost equal to the available tide volume, with minimal effects on the environment.

In 2009 the author applied for a patent for the "Two-way generation tidal power plant with bypasses" [3]. Figure 6 shows a schematic plan of a two-way generation tidal power plant with one-way turbines and with bypasses participating in generation. The tidal power plant comprises the main barrage (3) and the powerhouse (6) with one-way turbines between the bay shores (1) and (2). The powerhouse (6) is located at the shore (2).

The head reservoir (8) is formed by the head barrage (10) located in the basin (5), the powerhouse (6), a part of the main barrage (16) located between the powerhouse (6) and the shore (2), and the shore (2) between the head barrage (10) and a part of the main barrage (16). The tail reservoir (7) is formed by the tail barrage (9) located in the outer bay (4), the powerhouse (6), and a part of the main barrage (15) located between the powerhouse (6) and the tail barrage (9).

The following sets of sluices are included:

- Sluices (14) located at the head barrage (10) and connecting the head reservoir (8) with the basin (5).
- Sluices (13) located at the part of the main barrage (16) and connecting the head reservoir (8) with the outer bay (4).
- Sluices (11) located at the tail barrage (9) and connecting the tail reservoir (7) with the outer bay (4).
- Sluices (12) located at the part of the main barrage (15) and connecting the tail reservoir (7) with the basin (5).
- Bypasses (17) located at the part of the main barrage between shore (1) and the tail barrage (9) and connecting the basin (5) with the outer bay (4).

A two-way generation tidal power plant shown in Figure 6 works in

Figure 6: Schematic plan of a two-way generation tidal power plant with one-way turbines and with bypasses participating in generation

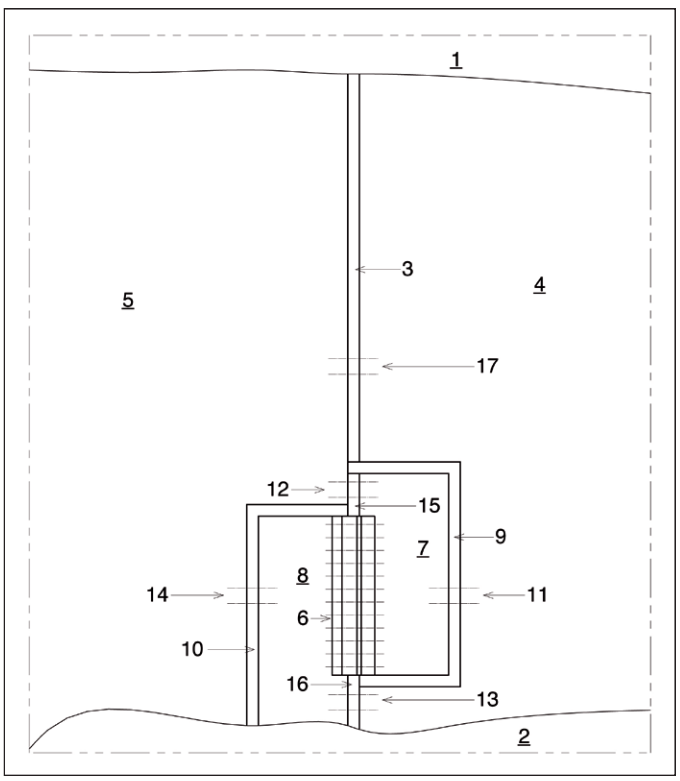
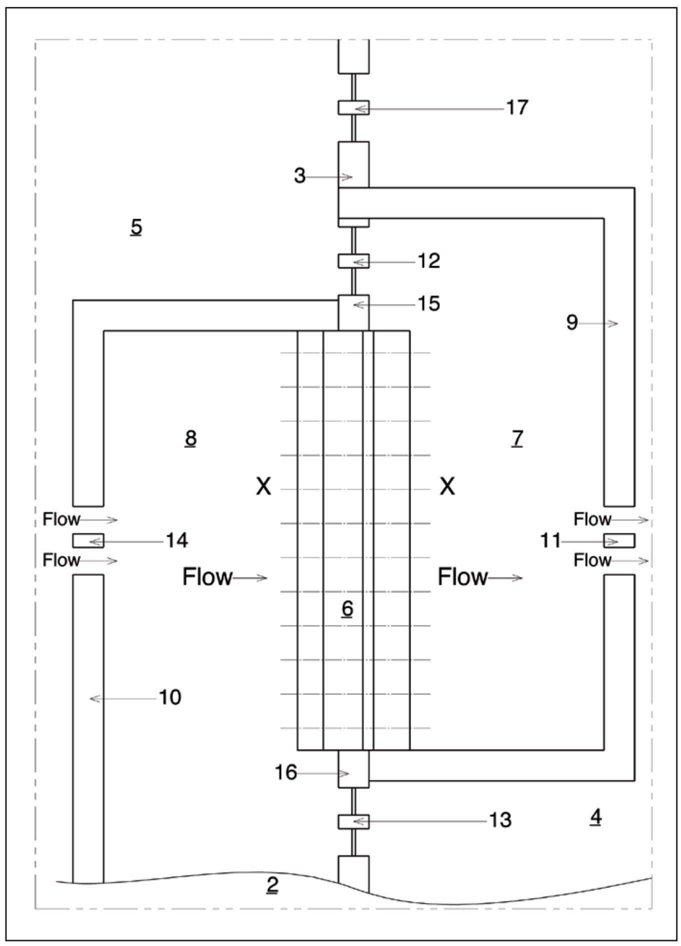


Figure 7. Schematic plan of a two-way generation tidal power plant with bypasses participating in generation during the initial ebb phase



four different operating regimes: the initial ebb phase, the final ebb phase, the initial flood phase, and the final flood phase.

Figure 7 shows a schematic plan of a two-way generation tidal power plant with bypasses during the initial ebb phase. As can be seen from this figure the flow from the basin passes via open sluices (14) to the head reservoir. After passing through the turbines of the powerhouse to the tail reservoir the flow finally passes to the outer bay via sluices (11). Sluices (12) and (13) and the bypasses (17) are closed during this operating regime and, therefore, there is no water flow from the basin to the outer bay in parallel with the turbines of the powerhouse.

Figure 8 shows a schematic plan of a two-way generation tidal power plant with bypasses during the final flood phase. As can be seen from this figure the flow from the outer bay allocated for the powerhouse passes via open sluices (13) to the head reservoir. After passing the turbines of the powerhouse to the tail reservoir it finally passes to the basin via sluices (12). There is also flow from the outer bay to the basin via bypasses (17) in parallel to the flow passing via the powerhouse.

Performance of Two-way Generation concept for Cardff-Weston Barrage with Voith Bulb Turbine

As mentioned earlier, the loss of energy output in the Canadian concept of the Severn power plant caused by the limitation imposed by the frequency converter on the operation is equal to 0.58%.

The results of computations by ENERGY presented in these sections (Figures 9, and 10) do not include this loss, and only relative increases in energy outputs will be used as the results of these comparisons. As can be seen from Figure 10, the energy output of a Two-way concept of tidal power plant and $(Q_{11})_{opt}$ =2.031m³/sec is 28.5% higher than of the Canadian concept tidal power plant with identical power equipment.

So using E_{year} = 34,174.36GWhr for ebb with the same equipment but with Frequency converter limitation, the yearly energy output for a two-way plant, E_{year} = 34,174.36 × 1.285 = 43,914.05GWhr. Also, the computations by program ENERGY show that used basin volume, W_{use} , is 1.933km³ for Canadian concept and 3.115km³ for Two-way concept. So, with the available basin volume, W_{ava} =3.588km³, the volume usage ratio, $C_{avw} = W_{use} / W_{ava}$ is 0.539 for the Canadian concept and 0.868 for the two-way concept.

Summary

In order to compare the DECC, Canadian, and Two-way concepts of this plant we need to know the capital necessary for construction of these three concepts and the unit energy cost.

The unit energy cost for this comparison was accepted to be 0.031 £/kwh [1]. The capital required for the DECC concept of the Cardiff-Weston Barrage was around £20.90B. As mentioned earlier, the turbine runners for the DECC concept can be assessed to be 40% more expensive than the propeller runners of the Canadian concept, however in the DECC concept the mechanism for the wicket gates is absent, instead a closing device at the turbine inlet is used. It would therefore be conservative to assume that the Canadian concept is at least 10% less expensive than the DECC concept, or approximately £18.81B. According to a preliminary opinion by San Francisco-based specialist in hydraulic structures, Frank Hamill, Pe.E., a two-way concept will be about 20% more expensive than the Canadian concept, or £22.57B. The results of the comparison between the DECC, Canadian, and Two-way concepts are summarized in Table 1.

As can be seen from Table 1, the DECC concept would have been less efficient and cost effective than the Canadian and Two-way concepts. The difference between the Canadian and the Two-way concepts with regards to return on investment is not that great, and may change in favour of the Canadian concept with more accurate assessment of the plant construction capital for the Two-way concept. However, the difference in available volume usage ratio in favour of the Two-way concept is very large and appears to make this the best choice for the Severn.

However, this conclusion is preliminary and requires re-computation of the Yearly Energy Generations and Available Volume Usage Ratios using the ENERGY program with capacity curve, $A_b = A_b (Z_b)$, for the Severn Estuary basin.

Table 1:

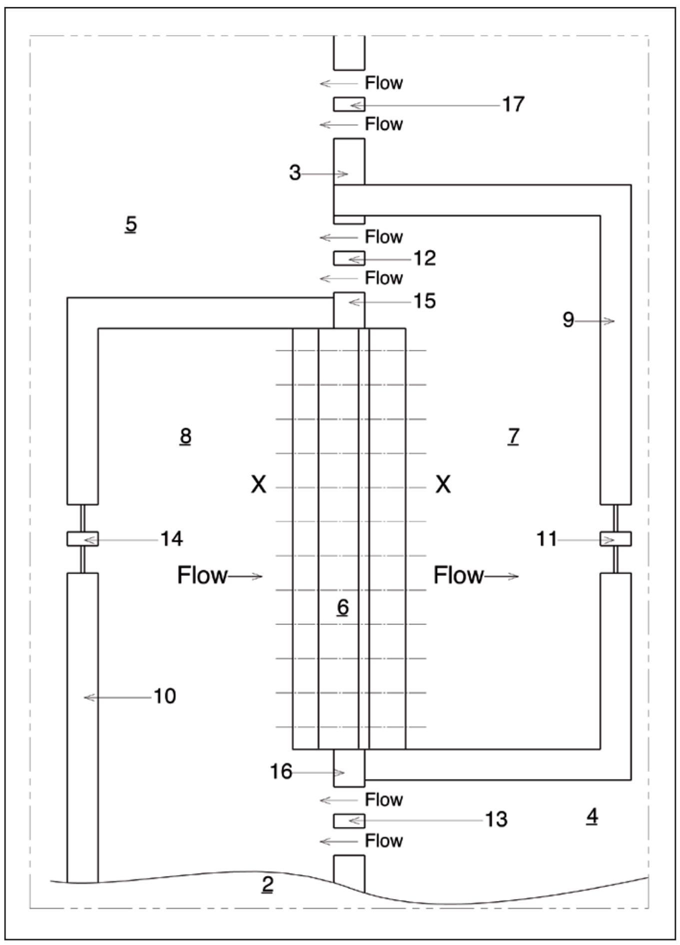
Comparison of the DECC concept with the Canadian and Two-way concepts equipped with commercially available Voith Bulb turbines

Concept	DECC	Canadian	Two-way
Yearly Energy Generation	17,000 GWhr	34,174.36 GWhr	43,914.05 GWhr
Yearly Revenues from Energy Production	£0.53B	£1.06B	£1.36B
Plant Construction Capital	£20.90B	£18.81B	£22.57B
Return Time on Invested Capital	39.4 years	17.7 years	16.6 years
Water Replaced from Basin per Tide Cycle	<1.000km³	1.933km³	3.115km³
Available Volume Usage Ratio	<0.281	0.539	0.868
Power Generation Time per deim	<10 hours	10.0 hours	15.0 hours

New ideas for the Bulb turbine in the Baker concept of power equipment

The new ideas presented in this Section are based on the author's two inventions: "Hydraulic Turbine and Exit Stay Apparatus" [4] and "Hydraulic bulb turbine with mixed-flow propeller runner" [6]. Theoretical analysis conducted by the author shows that these two inventions could improve the energy production of the Canadian and Two-way concepts of the tidal plant, however, this of course needs to be experimentally verified. Therefore, the values of E_{year} and W_{use} presented should be viewed as definite indications of possible improvements.

Figure 8. Schematic plan of a two-way generation tidal power plant with bypasses participating in generation during the final flood phase



Exit stay apparatus

The use of exit stay apparatus (ESA) in hydraulic turbines increases the efficiency and significantly decreases the pressure pulsations in the draft tube. The experiments with medium-high head vertical Francis conducted in 2007 at Hydraulic Laboratory of Laval University, Canada, [5] demonstrated that ESA increases the efficiency up to 1.2% and significantly decreases the pressure pulsation in the draft tube cone at operating regimes with $N_{11}=(N_{11})_{opt}$ and $Q_{11}>(Q_{11})_{opt}$ without changing σ of the turbine.

The author's analysis of these experiments in relation to Bulb turbines with axial flow and mixed-flow propellers – conducted in 2008-2009 – shows that in these turbines, with an increase of Q_{11} and $N_{11} = (N_{11})_{opt}$, the efficiency will gradually decrease without an unacceptable increase in pressure pulsations in the draft tube, and without changing σ, when comparing the same turbine without ESA.

The required value of submergence, $h_s = 10.3 - \sigma H$. So at the operating regimes with smaller value of H (where the increase of Q_{11} is important for the increase of E_{year}) the higher value of sigma can be accepted without causing cavitation in the turbine. The functions $\sigma = \sigma(Q_{11})$ and $\eta = \eta\ (Q_{11})$ were numerically inputted by the author into the ENERGY program, which resulted in increases in the value of Q_{11} at the regimes according to the formula for h_s and finds corresponding value for η.

The author strongly believes that use of ESA at tidal power plants will not introduce the negative impact on the safety of fish passing through the turbines. There are two major factors defining the safe passage of the fish through the stationary cascades of exit vanes: the minimum distance to the vane inlet edge from the runner blade exit edge and the minimum distance between adjacent exit stay vanes. The computations of these distances for ESA with four meridional vanes give the minimum distance from the runner blade exit edge at the periphery which is equal to 1.57m and the minimum distance between adjacent vanes at the ESA crown equal to 2.1 m (see Figure 11). However, in order to prove that ESA does not cause the fish mortality experimental verification must be undertaken. If the experiments show that the distance of 1.57m is not large enough to assure the fish safety the ESA can be moved further from the runner without causing appreciable changes in the turbine quality and price.

Hydraulic Bulb turbine with mixed-flow propeller

The elevation view of the Bulb turbine with mixed-flow propeller and Exit Stay Apparatus is shown in Figure 11. As can be see in this figure, the substitution in the Bulb turbine of an axial propeller with mixed flow propeller (6) and adding Exit Stay Apparatus (7) requires only changes in central parts of the turbine following the bulb (4).

The substitution of an axial flow propeller with a mixed-flow propeller with $(N_{11})_{opt}$ =130rpm allows for an increase in the value of $(Q_{11})_{opt}$ without decreasing the turbine axis level ∇Z_{ax}. This was proved by designing a Bulb turbine with $(Q_{11})_{opt}$ =2.830m³/sec using the program INNA.

The values of σ at the optimum predicted by this program were very close to those obtained by numerous laboratory experiments in Hydraulic Laboratories of the world (LMZ, Russia; Allis-Chalmers, US; Ganz, Hungary). In the Baker concept of power equipment the turbine without ESA works only at optimum, so it is experimentally proven that the Bulb turbine with mixed-flow propeller can have $(Q_{11})_{opt}$ =2.830m³/sec without increasing the cost of construction. Carried out by the author, theoretical analysis of the losses at the peripheral runner profiles indicates that the peak efficiency of such a turbine will be the same η_{max} =0.95 as the commercially available Voith turbine. However, this value of peak efficiency has not been experimentally verified [6,7].

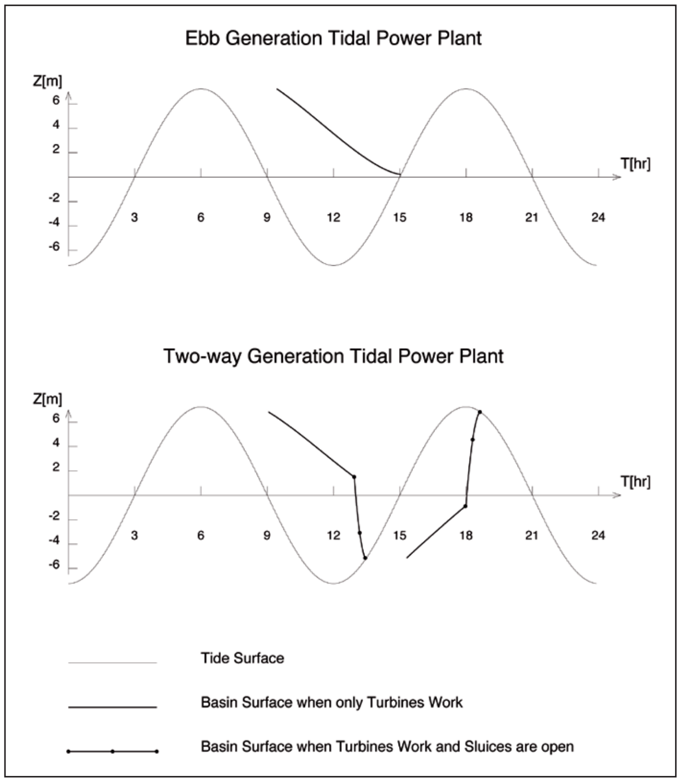


Figure 9. Plots of $Z_t = Z_t$ (T), $Z_b = Z_b$ (T), for Canadian and Two-way concepts equipped with Voith Bulb turbine.

Table 2

Comparison of the DECC concept with the Canadian and Two-way concepts equipped with Bulb Turbines having mixed-flow propellers and exit stay apparatuses

Concept	DECC	Canadian	Two-way
Yearly Energy Generation	17,000 GWhr	41,396.85 GWhr	61,283.30 GWhr
Yearly Revenues from Energy Production	£0.53B	£1.28B	£1.90B
Plant Construction Capital	£20.90B	£18.81B	£22.57B
Return Time on Invested Capital	39.4 years	14.7 years	11.9 years
Water Replaced from Basin per Tide Cycle	<1.000km³	2.874km³	3.249km³
Available Volume Usage Ratio	<0.281	0.801	0.906
Power Generation Time per deim	<10 hours	10.2 hours	14.8 hours

Performance of Canadian and Two-way concepts with Exit Stay Apparatus and Mixed-flow Runner

As can be seen from Table 2 the use of mixed-flow propeller and exit stay apparatus in Bulb turbines could lead to tremendous increase in yearly energy generation, E_{year}, in comparison with the DECC concept.

Comparison of all concepts with respect to the adverse effects on the environment

Oil pollution

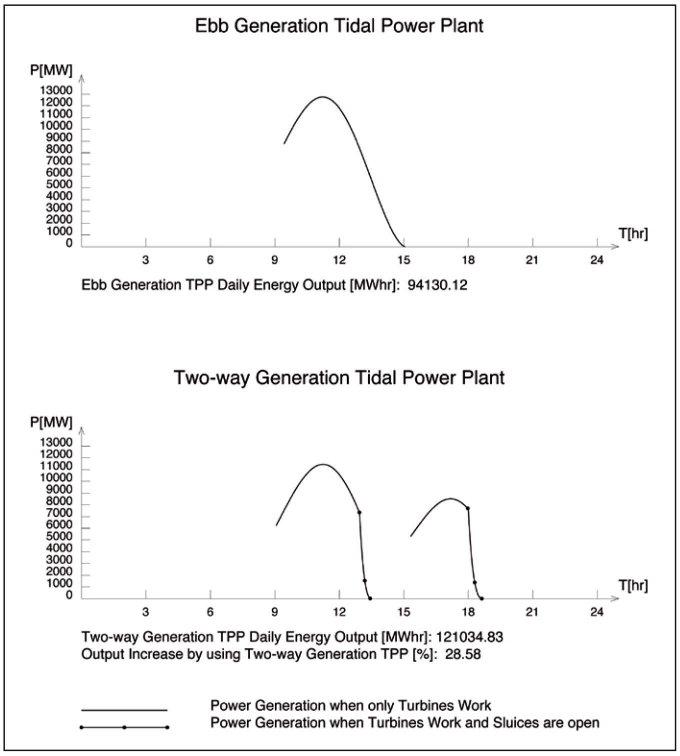
The DECC concept could result in significant pollution caused by 216 units with Kaplan runners, whereas the two other concepts would have zero pollution as both use propeller runners.

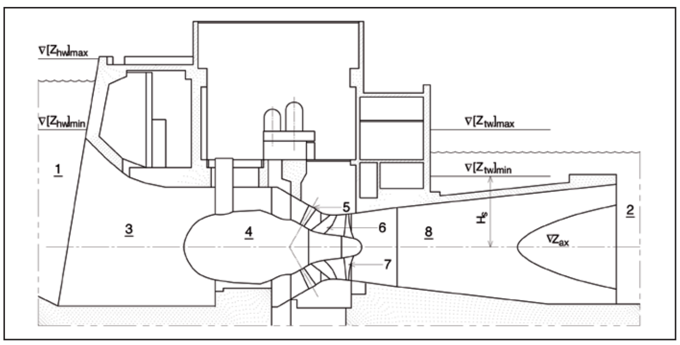
Danger to fish

Again the DECC concept could pose significant danger to the fish because of its 216 units with Kaplan runners. The two other concepts would have minimal danger because of the use of propeller runners. However, as mentioned earlier, this must be be proved experimentally.

Change of physico-chemical properties of water in the basin caused by the smaller than one value of available volume usage ratio, C_{avw}.

- DECC concept – extremely high adverse effect ($C_{avw} < 0.281$).
- Canadian concept with Voith runner – strong adverse effect (C_{avw}= 0.539).
- Canadian concept with mixed-flow runner and Exit Stay Apparatus – significant adverse effect (C_{avw} = 0.801).





Above, top to bottom; **Figure 10. Plot of P = P (T) for Canadian and Two-way concepts equipped with Voith Bulb turbine; Figure 11. The elevation view of Bulb turbine with mixed-flow propeller and Exit Stay Apparatus**

- Two-way concept with Voith runner – mild adverse effect (C_{avw} = 0.868).
- Two-way concept with mixed-flow runner and exit stay apparatus – insignificant adverse effect (C_{avw} = 0.906).

Adverse effect on the beaches in Bristol Chanel caused by the smaller than one value of available volume usage ratio, C_{avw}.

- DECC concept – extremely high adverse effect (C_{avw} < 0.281).
- Canadian concept with Voith runner – strong adverse effect (C_{avw} = 0.539).
- Canadian concept with mixed-flow runner and apparatus – significant adverse effect (C_{avw} = 0.801).
- Two-way concept with Voith runner – mild adverse effect (C_{avw} = 0.868).
- Two-way concept with mixed-flow runner and exit stay apparatus – insignificant adverse effect (C_{avw} = 0.906).

Adverse effect on the beaches in the basin caused by the dfference in the shape of the functions $Z_t = Z_t$ (T) (the basin level before the barrage is built) and $Z_b = Z_b$ (T) (the basin level after the barrage is built).

- DECC concept – extremely high adverse effect (the shapes of $Z_t = Z_t$ (*T*) and $Z_b = Z_b$ (*T*) do not have anything in common, see Figure 4).
- Canadian concept with Voith runner – strong adverse effect (the shapes of $Z_t = Z_t$ (*T*) and $Z_b = Z_b$ (*T*) are very different, see Figure 9).
- Canadian concept with mixed-flow runner and Exit Stay Apparatus – significant adverse effect (the shapes of $Z_t = Z_t$ (*T*) and $Z_b = Z_b$ (*T*) are significantly different, see Figure 12).
- Two-way concept with Voith runner – mild adverse effect (the shapes of $Z_t = Z_t$ (*T*) and $Z_b = Z_b$ (*T* – 3) are not very different, see Figure 9).
- Two-way concept with mixed-flow runner and exit stay apparatus – insignificant adverse effect (the shapes of $Z_t = Z_t$ (*T*) and $Z_b = Z_b$ (*T* – 3) are very close, see Figure 12).

Comment

It was recently suggested by Dr. David Prandle, Professor, University of Bangor, UK, that it is possible to decrease the adverse effects on the environment caused by ebb generation tidal power plant by sluicing the water from the basin after the end of generation [8]. It is clear that in the case of Canadian concept at the end of generation the head is so small (see Figure 9) that it is not possible to pass a suffcient amount of the water from the basin to significantly decrease the adverse effect on the environment via sluices which are used for filling the basin during the flood. However, one can install and use the bypasses at the final stage of generation as would be in the case of a two-way concept. Of course in this case the Canadian concept will produce less energy than without bypassing. In order to get the feeling of the size of this decrease in energy output one , it has been shown that the Canadian concept in order to have the same value of C_{avw} = 0.868 as the two-way concept must produce per deim 76,735.22MWhr instead of 94,130.12MWhr, or 18% less. The author is planning to include in the capabilities of the ENERGY program the computation of optimized energy output of the Canadian concept with the same value of C_{avw} as for Two-way concept.

Conclusion and recommendations

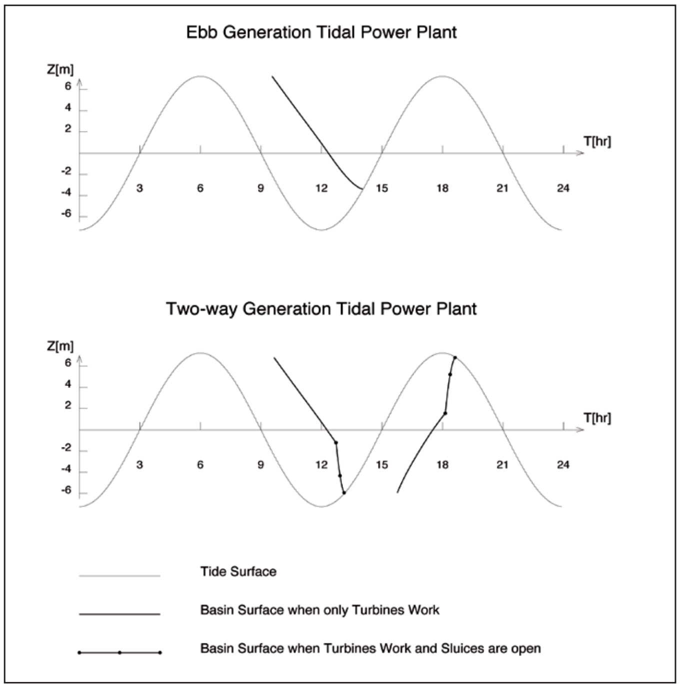
The Severn Estuary is unique with its natural beauty and located in the highly populated area of the UK. The preservation of its natural beauty is very important for the people, wildlife, and business community. So no compromise can be taken with respect to adverse effects of future Severn Estuary tidal power plant.

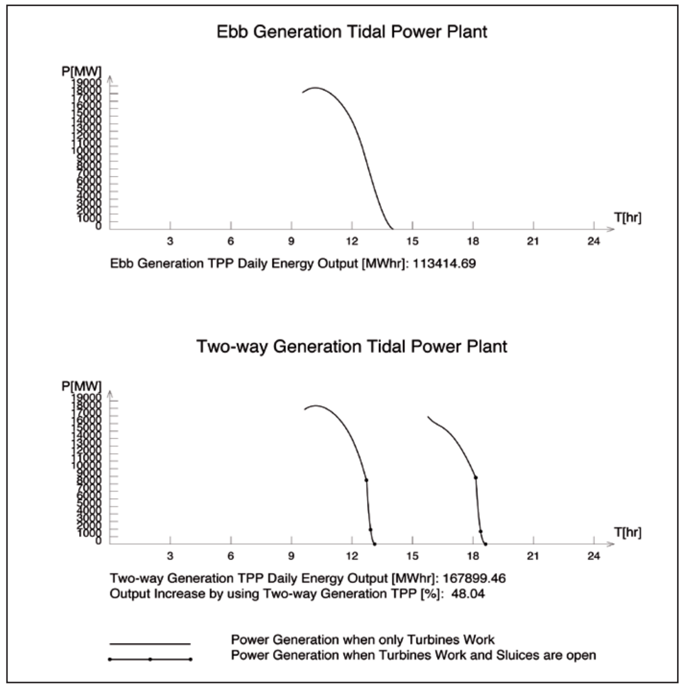
This paper presents the comparison of DECC, Canadian, and Two-way concepts based on computations done via the ENERGY program. Unfortunately these computations were done using the capacity curve $A_b = A_b$ (Z_b) for The Bay of Fundy basin, because the capacity curve for Severn Estuary basin was not supplied. The author strongly believes that the use of the capacity curve for Severn Estuary basin will not substantially change the results obtained using the capacity curve for the Bay of Fundy basin. The paper has shown that there is a reasonable prospect of improving the Canadian and Two-way concepts with respect to the environmental issues and increasing their energy outputs using the Bulb turbine with mixed-flow runner and exit stay apparatus. However, this requires experimental verification.

The Two-way concept with Voith Bulb turbine has hardly any adverse effects on the environment. It is superior in environmental aspects to the Canadian concept with the same turbine and produces more energy per year, however it is more expensive. Thus in order to compare the Two-way concept to Canadian concept it is necessary: to establish the price of Two-way concept as the result of the conceptual project of this concept and to make the adverse effects on the environment of Canadian concept equal to the two-way concept by adding to the Canadian concept the capability to use the bypasses during the final stage of generation.

Recommendations

- Independently verify the program ENERGY. The author believes that ENERGY computes all necessary parameters of tidal power plant operation with very high accuracy, but the price of Severn tidal power plant is so high, that the author considers this verification as





Above, left to right; **Figure 12. Plots of $Z_t = Z_t$ (T), $Z_b = Z_b$ (T), for Canadian and Two-way concepts equipped with Bulb turbine having mixed-flow runner and Exit Stay Apparatus; Figure 13. Plot of P = P (T) for Canadian and Two-way concepts equipped with Bulb turbine having mixed-flow runner and Exit Stay Apparatus**

an unavoidable step (the author is ready to give the source of the program ENERGY together with User's Manual). In the author's opinion it will not take more than two weeks.

- Recompute all results for Canadian and Two-way concept with commercially available Voith Bulb turbine using the capacity curve, $A_b = A_b$ (C_b), for the Severn Estuary basin. In author's opinion it will not take more than three or four weeks.
- Encourage one of recognized hydraulic laboratories to test the Bulb turbine with mixed flow runner without and with Exit Stay Apparatus. On author's assessment the tests will not take more than half a year and will cost no more than $500,000. The author has the programs for the design of the mixed-flow runner and Exit Stay Apparatus to be incorporated in any selected Bulb turbine. The computations by the author's program INNA which was verified by numerous experiments will not take more than one month. The fabrication of the mixed flow runner and Exit Stay Apparatus will cost no more than $150,000 in the authors opinion and will not take more than one month. The author expects that fabricated runner and exit stay apparatus will be tested in already existing model turbine, however some other alterations in the model turbine may be needed. The experiments would be short. Mixed-flow runner without Exit Stay Apparatus has to be tested only at optimal operating regime. For that one have to experimentally find the optimum testing the operating regimes close to predicted by INNA optimum. Mixed-flow runner with Exit Stay Apparatus has to be tested only at several operating regimes: $N_{11} = (N_{11})$opt and $(Q_{11})_{opt} \le Q_{11}$ $(Q_{11})_{max}$, where $(Q_{11})_{max}$ is Q_{11} corresponding to maximum available power.
- Test the turbine with Exit Stay Apparatus for fish mortality.
- Develop conceptual projects of Canadian and two-way concepts of Cardiff-Weston barrage tidal plant with the same value of C_{avw}. IWP&DC

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Dedicated to author's wife, Inna Gokhman

References

1. Tidal Power in UK, Research Report 3 - Severn barrage proposals, Black & Veatch, October 2007.
2. Alexander Gokhman, Two-way generation tidal power plant with one-way turbines, UK Patent GB 2 436 857 B, 20.02.2008.
3. Alexander Gokhman, Two-way generation tidal power plant with bypasses, UK Patent Application GB1003836.2, 12.03.2010.
4. Alexander Gokhman, Hydraulic Turbine and Exit Stay Apparatus therefor, US Patent No. 6,918,744 B2, July 19, 2005.
5. Richard Fraser, Alexander Gokhman, et al., Development of an Exit Stay Apparatus for Francis Turbine, HydroVision 2008.
6. Alexander Gokhman, Hydraulic bulb turbine with mixed-flow propeller runner, UK Patent Application GB1003849.5, 15.03.2010.
7. Alexander Gokhman, Tony Tung, New Bulb Turbine with Mixed-Flow Propeller Runner, HydroVision 2010.
8. David Prandle, Design of tidal barrage power schemes, Marine Engineering 162, December 2009 Issue MA4.