

DEVELOPMENT OF THE EFFICIENT AND ENVIRONMENTALLY FRIENDLY TIDAL POWER PLANT FOR SEVERN ESTUARY

1. Introduction

The tidal power plants with barrages are the second best after the conventional hydro-power plants clean energy power plants from economical point of view.

However, there are not very many feasible sites for the construction of these plants in the world. The tidal power plants require either the bay or the river estuary with sufficiently high tide amplitude and volume capacity. A very positive feature of tidal power plants is that they can generate practically the same amount of energy every day during two tide cycles what favorably distinguish them from solar plants and wind turbines.

Great Britain does not have many sites for the construction of the conventional hydro-power plants using the energy of the river flow, however it has the best in the world site for the tidal power plant with barrage. This site is Severn Estuary.

In January 2009 the British Department of Energy and Climate Change (DECC) prepared a short list of five Severn Tidal Power options for farther evaluation and using the results of this evaluation for public consultation in the second half of 2010 with goal to recommend selected schemes for further feasibility study. One of these options was Cardiff-Weston Barrage ebb generation power plant with power capacity of 8.64GW and a construction cost of £20.9bn providing 17,000 GWH per year what constitutes up to 5% of Great Britain yearly energy consumption [1]. However, there were two problems. One is the economical, since the time for the return of the capital for the plant construction at present prices is very high. It is equal to 39.4 years. The second problem is the negative effect on the environment, because this plant could use less than the half of the water in the plant basin what leads to two environmental problems: the change of the physico-chemical properties of the water in the basin and change of the tide prism at the Bristol Channel shore line.

Fortunately my work on the efficient and environmentally friendly tidal power plant conducted revealed in March 2010 that Cardiff-Weston Barrage option prepared by DECC for public consultation uses the power equipment (turbines and generators) that is providing only 17,000 GWH per year what is almost two times less than Canadian version of the power equipment providing 32,665 GWH per year with smaller (or at least the same) cost for the construction as DECC version. In addition to that I came up with my own version of Cardiff-Weston Barrage ebb generation power plant that produces 41,505 MWH per year, what is 27% higher than Canadian version with increase of cost for construction no more than 20% and has close to zero negative impact on the environment. I informed Mr. Ed Miliband, previous Secretary of State for Energy about the Canadian and about my version for Cardiff-Weston Barrage generation power plant with an offer to give to DECC all my materials for verification of my results and in the case positive verification to replace DECC version with one of suggested by me and I met negative reaction. After the change of DECC administration on May 21 I wrote a letter to Mr. Chris Huhne, the new Secretary of State for Energy, in which I was asking for cooperation. To my surprise a response to my letter arrived from Mr. Owen Jones at the Department for Environment, Food and Rural Affairs. So I still do not know what DECC new administration is going to do with my information.

Accepted by DECC Cardiff-Weston Barrage conceptual design was prepared in 2007 by Black & Veatch [1]. However, I do not blame Black & Veatch for not using the Canadian version of power equipment in their conceptual design, because the information about this version was never published and I found about it in 2007 using my personal contacts with former Manager at CANMET, Canadian Federal Department of Natural Resources, Mr. Tony Tung, and Mr. George Baker, former Vice President of Tidal Power Corp. Nova Scotia for whom it was prepared by Tidal Power Consultants Ltd in 1984 (see also section 2.2). I blame DECC previous administration for not contacting the key persons involved in conceptual design of The Bay of Fundy tidal power plant and not cooperating with me when in April 2010 I informed them about my findings.

2. Power Generation at Tidal Power Plants

2.1 Grid Requirements

A power plant must ultimately supply the electrical grid with alternating current of standard frequency. As a result, until recently, to satisfy this requirement all hydro plants had turbines powering synchronous generators with speed of rotation set to produce standard frequency called synchronous speed. The need to maintain synchronous speed renders low head generation economically inferior. Indeed, there hasn't been much development in power equipment for effective generation for low heads.

The situation drastically changed at the end of the last century with the introduction of effective frequency converters. For example, Itaipu — one of the biggest hydro plant in the world — feeds electricity to both Paraguay and Brazil, who have different frequency standards, using this technology.

2.2 Power Generation at Tidal Power Plant Versus Low Head Conventional Hydro Plant

In order to generate the power a conventional low head hydro plant uses the river flow partially stored in the upper reservoir and the head formed by the dam. The upper reservoir enables this power plant to the planned changes in flow and head. The planing can be directed to maximum energy output per year or even per several years depending on the hydrology of the river it is built. Sometimes the planning is directed to the most efficient work of the plant in the grid. If the conventional plant is equipped with sufficient number of properly selected turbines the water stored in the upper reservoir is never lost excluding the case of catastrophic flood. The variation of the water surface elevation in the plant upper reservoir is easily planned and variation in elevation of the tail water is relatively small, excluding catastrophic flood. As the result the head variation, H/H_{max} , at low head conventional power plant usually do not exceed 35%. Evidently the best turbine for this type of plant either from the point of maximum energy output or from the point of the most efficient work in the grid is the Bulb turbine with Kaplan runner connected to the synchronous generator, because it works with high efficiency and acceptable pressure pulsations in draft tube at the sufficiently wide range of variations in the plant head and power output.

Tidal plant with barrage uses 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 the head at the tidal plant change drastically during each ebb/flood cycle of the tide. The head variation at tidal plant is 100%. The Kaplan runners can not work satisfactory at this head variation. Also Kaplan runners are complicated and not friendly to the environment. In addition to that large tidal plants like Fundy Bay or Severn Estuary require between 100 and 200 units and, because of Kaplan runner complicated design, it is almost impossible to maintain this large number of Bulb turbines with Kaplan runners.

The first significant step towards the development economically acceptable tidal plant was the acceptance of the Bulb turbine with axial propeller connected to generator of variable speed of rotation with converter to standard frequency. It was concluded in 1984 under Mr. George Baker, at that time Vice President of Tidal Power Corporation of Nova Scotia, in the updated feasibility study of 1976-1977 for the Bay of Fundy tidal power plant. I will call this version of power equipment for tidal plant in the rest of my paper as Canadian version of power equipment.

The Canadian version permits to turbine to work at heads, $0.2H_{max} \leq H \leq H_{max}$, at optimal operating regime and, therefore, significantly increases its yearly energy production. It also makes the turbine less expensive, much simpler and, therefore, acceptable for tidal plant with 100-200 units. However, Canadian version applied to Ebb generation tidal plant does not decrease the negative environmental impact.

Unfortunately Black & Veatch in its conceptual project of Cardiff-Weston Barrage for DECC has not accepted Canadian version of power equipment but its own version comprising Bulb turbine having stay ring with stay vanes instead of distributor with wicket gates and Kaplan runner (Toman Bulb turbine) connected to synchronous generator [1]. I will call it in the rest of my paper as DECC version of power equipment.

The next significant step was my invention of two-way generation tidal power plant with one way turbines and bypasses [2,3]. I will call it as Two-way tidal plant. Two-way tidal power plant utilizes the energy of ebb and flood using the Canadian version of power equipment. As it was mentioned in Introduction this plant produces 27% more energy per year than Ebb tidal plant if they both are equipped with commercially available axial propeller and has close to zero impact on the environment.

The most important fact is that in order to find the yearly energy production and the relative value of the available water volume of tide per cycle for: Ebb tidal plant with DECC version of power equipment, Ebb tidal plant with Canadian version of equipment, and Two-way tidal plant with Canadian version of equipment one does not need the experiments. It can be done by specially developed for these purposes program ENERGY briefly described in next section.

2.3 Equations Describing the Process of Power Generation at Tidal Power Plant and the Program Energy

2.3.1 Equations describing the process of power generation at tidal power plant

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

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

where:

T is the current time,
 $Z_b = Z_b(T)$ 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 Ebb tidal power plant $Q = Q_t$

The flow through the turbines:

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

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:

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

where:

$C_d = 0.60$ is the coefficient 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
 $g = 9.81 \text{ m/sec}^2$ is gravity acceleration.

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

$$P_c = 0.001 g \eta_c Q_t H \quad (6)$$

where:

η_c is current turbine value of efficiency corresponding to current values of (N_{11}) and (Q_{11}) .

2.3.2 The program ENERGY and its verification

The program ENERGY was developed by myself and Dr. Dmitry Gokhman (Department of Mathematics, the University of Texas at San Antonio) to perform highly accurate numerical integration of equations (1–5). As the result it computes the functions: $Z_b = Z_b(T)$, $H = H(T)$, $Q_t = Q_t(T)$, and $Q_b = Q_b(T)$. After that the function $P = P(T)$, is computed and, finally, the energy output E_{tc} and the water volume W_{tc} replaced from basin per one tide cycle using direct numerical integration of the functions $P(T)$ and $Q(T)$ by time, T .

ENERGY optimizes the input parameters defining the process of power generation at tidal power plant maximizing the value of E_{tc} using the following approach.

In the case of Ebb tidal plant only the time for the beginning of generation, T_{gb} must be optimized. This is done by accepting in the input upper and lower boundaries, $(T_{gb})_{up}$ and $(T_{gb})_{lo}$, for T_{gb} and computation of E_{tc} for 11 evenly spaced values of T_{gb} along the segment $(T_{gb})_{lo} \leq T_{gb} \leq (T_{gb})_{up}$ and so on until maximum value of E_{tc} is found.

In the case of Two-way tidal plant the program optimized the following parameters:

- $(T_{gb})_e$ - time for the beginning of generation for the ebb.
- $(T_{bp})_e$ - time for the bypasses participation at the ebb final phase.
- $(H_{bo})_e$ - the value of the hight of the bypasses opening for the ebb final phase
- $(T_{gb})_f$ - time for the beginning of generation for the flood.
- $(T_{bp})_f$ - time for the bypasses participation at the flood final phase.
- $(H_{bo})_f$ - the value of the hight of the bypasses opening for the flood final phase

In the case the optimization for all six parameters was done using the same approach as in the case of Ebb tidal plant for T_{gb} .

The program ENERGY was verified using the following approach.

The function $\frac{dZ_b}{dT} = \frac{dZ_b}{dT}(T)$ was computed by numerical differentiation of $Z_b = Z_b(T)$ for all values T of output from ENERGY and compared to right part of equation (1) at these values of T . The relative difference between left and right parts of (1) never exceeded 0.5%.

It is evident that the numerical results obtained by the program ENERGY do need the experimental verification, because the equations (1–6) without any doubt adequately represent the process of power generation at tidal power plant.

3. Comparison of DECC, Canadian, and Two-way Versions of Cardiff-Weston Barrage Severn Power Plant

3.1 Introduction

The following analysis was conducted by me using the program ENERGY for the comparison of DECC, Canadian, and Two-way versions by yearly energy outputs, E_{year} , and the water volume, W_{tc} , replaced from basin per one tide cycle. The comparison was conducted for Severn Estuary tide amplitude, $A_t=7.25$ m and accepted by DECC $D_t=9.0$ m and $K_t=216$ using the capacity curve, $A_b = A_b(Z_b)$, for the Bay of Fundy basin. The reason for this is that DECC refused to provide me with the capacity curve for Severn basin despite my several requests.

3.2 Commercially Available Bulb Turbine Offered by Voith

One year ago on June 21, 2009 I (being the Senior Technical Specialist in Turbine Equipment of Gareth Woodham Company "Severn Lake Tidal Power Group") requested the information from Voith head quarters at Heidenheim and on June 26 have received the requested data for the Bulb turbine with Kaplan runner for Severn tidal power plant conditions accompanied with elevation and plan views of the turbine (see Figure 1). In my request I specified the diameter of the turbine, $D_t=7.5$ m and the maximum head, $H_{max}=12.0$ m instead of $D_t=9.0$ m and $H_{max}=14.5$ m. The reason for this was that Gareth Woodham was not able to get for me the capacity curve for Severn Estuary and the parameters on the DECC turbine. So I had to work on my development of the efficient and environmentally friendly tidal power plant for Severn plant using the Bay of Fundy capacity curve, $H_{max}=12.0$ m, and $D_t=7.5$ m. The other parameters specified by Voith were:

Maximum efficiency, $\eta_{max}=0.95$

Optimal unit flow, $(Q_{11})_{opt} = 2.031 \text{ m}^3/\text{sec}$

Optimal unit rotation, $(N_{11})_{opt} = 148.510 \text{ rpm}$.

Cavitation coefficient at optimum, $\sigma_{opt} \approx 1.2$

As can be seen in Figure 1 for the turbine with $D_t=7.5$ m draft tube height, $H_{dt}=12.838$ m and draft tube bottom, $H_{dtb}=2.474$ m, therefore, draft tube upper part, $H_{dtu}=10.364$ m. So for the turbine with $D_t=9.0$ m $H_{dtu}=12.437$ m and, therefore, this turbine with $H_s \geq -12.437$ will not be more expensive than the turbine in Figure 1 (the upper edge of the draft tube cannot be below minimal tail water level, TWL_{min}).

The Voith Bulb turbine with $D_t=9.0$ m under $H_{max}=14.5$ m cavitation free work at optimum operating regime (according to Canadian power equipment version) requires:

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

It is clear the maximal value of cavitation coefficient at optimum providing cavitation free work for Voith Bulb turbine:

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

So there is still room for the increase of $(Q_{11})_{opt}$ without increase of capital expenses for the construction if one uses Canadian power equipment version.

3.3 Performance of DECC Version for Cardiff-Weston Barrage Severn Power Plant

The main parameters of DECC version are in the their report [1]:

Number of units, $K_u=216$

Turbine runner diameter $D_t=9.0\text{m}$

Operating speed of turbines, $N_{op}=50\text{rpm}$

Total power, $P_{tot}=8,640\text{MW}$

Energy production per year, $E_{year}=17,000\text{GWhr}$

The value of H_{max} is not specified in Black & Veatch report [1]. So I had to get this value by the method of iterations by analyzing Severn plant with Canadian version of power equipment and having the same other parameters of DECC version with resulting maximum head, $H_{max}=12.69\text{m}$.

Now combining the formulae (4) and (6) one can get:

$$\eta_{op}(Q_{11})_{op} = \frac{P_{tot}}{0.001gK_t H_{max}^{1.5} D_t^2} \quad (7)$$

The equation (7) gives for DECC data $\eta_{max}(Q_{11})_{max}=1.139\text{m}^3/\text{sec}$. So accepting Voith value of maximum efficiency, $\eta_{max}=0.95$ one gets for DECC version $(Q_{11})_{max}=1.199\text{m}^3/\text{sec}$.

3.3 Performance of Canadian Version for Cardiff-Weston Barrage Severn Power Plant with Voith Bulb Turbine

The main parameters of power equipment:

Number of units, $K_u=216$

Turbine runner diameter $D_t=9.0\text{m}$

Synchronous speed, $N_{syn}=41.66667\text{rpm}$

Maximum efficiency, $\eta_{max}=0.95$

Optimal unit flow, $(Q_{11})_{opt} = 2.031\text{m}^3/\text{sec}$

Optimal unit rotation, $(N_{11})_{opt} = 148.510\text{rpm}$.

Frequency converter is working for turbine rotation, $0.6N_{syn} \leq N_t \leq 1.4N_{syn}$.

The results of computations by ENERGY are shown in Figures 2 and 3 $E_{day}=93,628.39\text{MWhr}$, $E_{year}=34174.36\text{GWhr}$. As can be seen from Figure 3 there is the energy loss caused by the limitation of frequency converter shown above, $(E_{lost})_{day}$. This value of $(E_{lost})_{day}$ can be found by comparison with presented in Figure 9 ENERGY output showing the results of computation of the ebb generation plant with two-way generation plant for Severn with identical power equipment, but without Frequency converter limitation ($0.6N_{syn} \leq N_t \leq 1.4N_{syn}$). As can be seen from Figure 3 and Figure 9, $(E_{lost})_{day}=94,174.53\text{MWhr} - 93,628.39\text{MWhr}=546.14\text{MWhr}$, or only 0.58% of energy without Frequency converter limitation.

So the yearly energy output of 34174.36GWhr for this version is 2 times higher than DECC energy output of 17,000GWhr. What is interesting that the yearly energy output of 25,239.36GWhr for Severn with Canadian version of power equipment having DECC value of $(Q_{11})_{opt} = 1.199\text{m}^3/\text{sec}$ (see Figures 4 and 5) is also 49.5% higher than DECC energy output of 17,000GWhr.

It is clear that DECC version has two deficiencies in accepting its own version of power equipment for Severn instead of known at that time Canadian version of power equipment with commercially available Voith Bulb turbine.

* The first deficiency was caused by the acceptance of Toman bulb turbine with synchronous generator instead of Canadian version that led to much smaller energy output even with the same value of $(Q_{11})_{opt} = 1.199\text{m}^3/\text{sec}$. It also led to the increase at least for 40% in the cost of the turbine runners and the cost of 216 turbine runners is the predominate part of all the capital cost for Severn plant construction. It also would lead to environmental disaster, because it is close to the impossible to maintain working every day 216 Kaplan runners without the oil leaking into the basin.

* The second deficiency was caused by the acceptance of $(Q_{11})_{opt} = 1.199\text{m}^3/\text{sec}$ what was not required by the value of submergence, H_s . As can be seen from Figure 1 the maximum absolute value of submergence, $|H_s|$, must be smaller than the upper part of the draft tube exit, $H_{so} = 12.838\text{m} - 2.474\text{m} = 10.364\text{m}$. It is easy to see that for the homologous turbine with $D_t = 9.0\text{m}$ $H_{so} = 12.44\text{m}$. So with Voith value of $H_s = -7.73\text{m}$ there is the large safety margin for the turbine even with larger discharge capacity than $(Q_{11})_{opt} = 2.031\text{m}^3/\text{sec}$.

3.4 Two-way generation tidal power plant with bypasses for Cardiff-Weston Barrage Severn Power Plant

In 2008 I received the patent for "Two-way generation tidal power plant with one-way turbines" [2]. My invention permitted to use Canadian version of power equipment and utilize the energy of both ebb and flood. However, this version of two-way tidal power plant produced more energy than ebb generation plant only in the case of very large number of units. At Severn it required to have more than 350 units in order to produce more energy than using ebb generation plant. However, 350 units are not economically effective. In addition to that this plant used close to a half of available tide volume and, therefore, had the same negative effects on the environment as ebb generation plant with Canadian version of power equipment.

In 2009 after development of the program ENERGY I have tried to use sluices bypassing the water in parallel with power house during final phases of both ebb and flood generation. The results shown by ENERGY were very much encouraging. Two-way plant produced substantially more than ebb generation plant energy both having Canadian version of power equipment and 216 units

In addition to that two-way plant have used the water volume per cycle almost equal to the available tide volume and, therefore, had close to zero negative effects on the environment.

In 2009 I applied for the patent for "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 power house 6 with one-way turbines between the bay shores 1 and 2. The power house 6 is located at the shore 2. The head reservoir 8 is formed by the head barrage 10 located in the basin 5, the power house 6, a part of the main barrage 16 located between the power house 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 power house 6, and a part of the main barrage 15 located between the power house 6 and the tail barrage 9. There are the following sets of sluices:

- * 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 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 5 is passing via open sluices 14 to the head reservoir 8. After

passing through the turbines of power house 6 to the tail reservoir 7 the flow finally passes to the outer bay 4 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 5 to the outer bay 4 in parallel with the turbines of power house 6.

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 4 allocated for power house 6, generating flow, is passing via open sluices 13 to the head reservoir 8. After passing the turbines of power house 6 to the tail reservoir 7 it finally passes to the basin 5 via sluices 12. There is also flow from the outer bay 4 to the basin 5 via bypasses 17 in parallel to the flow passing via power house 6.

3.5 Performance of Two-way Generation Version for Cardiff-Weston Barrage Severn Power Plant with Voith Bulb Turbine

As it was shown in Section 3.3 the loss of energy output in Canadian version of Severn Power Plant caused by the limitation imposed by frequency converter on the operation is equal to 0.58%. It is clear that this limitation is irrelevant in relative comparison of Canadian version with Two-way generation version of Severn plant having Voith Bulb turbine in this section. So, since the results of computations by ENERGY presented in these sections do not include this loss, only relative increases in energy outputs will be used as the results of these comparisons.

As can be seen from Figures 9, 10, and 10 the energy output of two-way tidal plant with Canadian version of power equipment and $(Q_{11})_{opt} = 2.031 \text{ m}^3/\text{sec}$ is 28.5% higher than of the ebb plant with identical power equipment. So using $E_{year} = 34174.36 \text{ GWhr}$ for Ebb with same equipment but with Frequency converter limitation (see section 3.3) the yearly energy output for two-way plant, $E_{year} = 34174.36 \times 1.285 = 43,914.05 \text{ GWhr}$. It also can be seen in Output 1 that used basin volume, V_{use} , is 1.933 km^3 for ebb plant and 3.115 km^3 for two-way plant. So with available basin volume, $V_{ava} = 3.588 \text{ km}^3$, the volume usage ratio, $C_v = V_{use}/V_{ava}$, is 0.539 for ebb generation plant and 0.868 for two-way plant.

3.6 Summary

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

The unit energy cost for this comparison was accepted to be 0.031 £/kwh [1].

The capital required for DECC version of Cardiff-Weston Barrage Severn power plant is $\text{£}20.90 \text{ bn}$ (Letter from DECC, of 26 January 2009 signed by Sarah Rhodes). As was mentioned in Section 3.3 the turbine runners for DECC version can be assessed to be 40% more expensive than the propeller runners of Canadian version, however in DECC version the mechanism for the wicket gates is absent and instead of it there is some closing device at the turbine inlet. So it will be conservative to assume that Canadian version is at least 10% less expensive than DECC version, or $\text{£}18.81 \text{ bn}$. According to the preliminary assessment by Mr. Frank Hamill of Bechtel Two-way version will be 20% more expensive than Canadian version, or $\text{£}22.57 \text{ bn}$.

Results of comparison of DECC, Canadian, and Two-way versions of Cardiff-Weston Barrage Severn Power Plant can be summarized as following:

Table 1 Comparison of DECC Version with Canadian and Two-way Versions Equipped with Voith Bulb Turbine

Version	DECC	Canadian	Two-way
Yearly Energy Generation	17,000GWhr	34,174.36GWhr	43,914.05GWhr
Yearly Revenues from Energy Production	£0.53 bn	£1.06 bn	£1.36 bn
Plant Construction Capital	£20.90bn	£18.81bn	£22.57bn
Return Time on Invested Capital	39.4 years	17.7 years	16.6 years
Water Replaced from Basin per Tide Cycle	<1.000km ³	1.933km ³	3.115km ³
Available Volume Usage Ratio	<0.281	0.539	0.868
Power Generation Time per deim	<10 hours	10.0 hours	15.0 hours

As can be seen from Table 1 DECC version is absolutely inferior to Canadian and and Two-way versions of Cardiff-Weston Barrage Severn Power Plant. The difference between Canadian and and Two-way versions in Return Time on Invested Capital is not that great and may change in favor of Canadian version with more accurate assessment of the plant construction capital for Two-way version. However, the difference in Available Volume Usage Ratio in favor of Two-way version is very large and makes this version to be the best for Severn. However, this conclusion is preliminary and requires recomputation of the Yearly Energy Generations and Available Volume Usage Ratios using verified by me program ENERGY with capacity curve, $A_b = A_b(Z_b)$, for Severn Estuary basin.

4. New Ideas for the Bulb Turbine in Canadian Version of Power Equipment

4.1 Introduction

The new ideas presented in this Section are based on my two inventions: "Hydraulic Turbine and Exit Stay Apparatus therefor" [4] and "Hydraulic bulb turbine with mixed-flow propeller runner" [6]. Conducted by me theoretical analysis shows that these two inventions are supposed independently improve the energy productions of the Canadian and Two-way versions of the tidal plant, however, this must be experimentally verified. So in this section I am only presenting two ways for improvement of the effectiveness of these tidal plant versions. Obtained by me using program ENERGY values of E_{year} and V_{use} are not the facts but only the definite indications of the possible improvements.

4.2 Exit Stay Apparatus

The use of Exit Stay Apparatus (ESA) in Hydraulic turbine 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 Exit Stay Apparatus 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.

Conducted by me in 2008-2009 analysis of these experiments in application to Bulb turbine with axial flow and mixed-flow propellers shows that in these turbines at the regimes with increase of Q_{11} and $N_{11} = (N_{11})_{opt}$ the efficiency will gradually decrease without unacceptable increase in pressure pulsations in draft tube and without changing σ comparing to the same turbine not having Exit Stay Apparatus

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. So predicted by me functions $\sigma = \sigma(Q_{11})$ and $\eta = \eta(Q_{11})$ are numerically inputted in the program ENERGY and the program increases the value of Q_{11} at the regimes according to the formula for H_s and finds corresponding value for η .

4.3 Hydraulic Bulb Turbine with Mixed-flow Propeller runner

The elevation view of Bulb turbine with mixed-flow propeller and Exit Stay Apparatus is shown in Figure 12. As can be seen in this figure the substitution in Bulb turbine of axial propeller with mixed flow propeller 6 and adding Exit Stay Apparatus 7 requires only changes in central part of the turbine following the bulb 4.

The substitution in Bulb turbine an axial flow propeller by a mixed-flow propeller with $(N_{11})_{opt} = 130$ rpm allows to increase the value of $(Q_{11})_{opt}$ without increasing draft tube upper part H_{dtu} (see Section 3.2). This was proved by design a Bulb turbine with $(Q_{11})_{opt} = 2.830$ m³/sec using the program INNA. Predicted by this program values of sigma at the optimum was very close to the one obtain by numerous laboratory experiments in different Hydraulic Laboratories of the world (LMZ, Russia, Allis-Chalmers, USA, Ganz, Hungary). Since in Canadian version of power equipment the turbine without ESA works only at optimum it is experimentally proved fact that the Bulb turbine with mixed-flow propeller can have $(Q_{11})_{opt} = 2.830$ m³/sec without the increasing the cost of construction. Conducted by me theoretical analysis of the losses at the peripheral runner profiles indicates the efficiency of such a turbine will have the same peak efficiency 0.95 as the commercially available Voith turbine. However, this value of peak efficiency is not the experimentally verified fact [6,7].

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

Table 2

Comparison of DECC Version with Canadian and Two-way Versions Equipped with Bulb Turbine Having Mixed-flow Propeller and Exit Stay Apparatus

Version	DECC	Canadian	Two-way
Yearly Energy Generation	17,000GWhr	41,396.85GWhr	61,283.30GWhr
Yearly Revenues from Energy Production	£0.53 bn	£1.28 bn	£1.90 bn
Plant Construction Capital	£20.90bn	£18.81bn	£22.57bn
Return Time on Invested Capital	39.4 years	14.7 years	11.9 years
Water Replaced from Basin per Tide Cycle	<1.000km ³	2.874km ³	3.249km ³
Available Volume Usage Ratio	<0.281	0.801	0.906
Power Generation Time per deim	<10 hours	10.2 hours	14.8 hours

As can be seen from Table 2 the use of Mixed-flow Propeller and Exit Stay Apparatus in Bulb turbine could lead to tremendous increase in Yearly Energy Generation, E_{year} , in comparison with DECC. For Canadian version in 2.43 times and for Two-way version 3.60 times and, because of it tremendous decrease in Return Time on Invested Capital. For Canadian version decrease in 2.28 times and for Two-way version in 3.31 times.

5. Comparison of all versions with respect to the adverse effects on the environment

1. Oil pollution of the shore of Bristol Chanel.

* DECC version — significant pollution caused by 216 units with Kaplan runners.

* All other versions — zero pollution. All these versions are using propeller runners.

2. Danger to fish passing from the basin to the Bristol channel via turbines caused by runners blades adjustments

* DECC version — significant danger caused by 216 units with Kaplan runners.

* All other versions — zero danger. All these versions are using propeller runners.

3. 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 version — extremely high adverse effect ($C_{avw} < 0.281$)
- * Canadian version with Voith runner — strong adverse effect ($C_{avw} = 0.539$)
- * Canadian version with mixed-flow runner and Exit Stay Apparatus — significant adverse effect ($C_{avw} = 0.801$)
- * Two-way version with Voith runner — mild adverse effect ($C_{avw} = 0.868$)
- * Two-way version with mixed-flow runner and Exit Stay Apparatus — insignificant adverse effect ($C_{avw} = 0.906$).

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

- * DECC version — extremely high adverse effect ($C_{avw} < 0.281$)
- * Canadian version with Voith runner — strong adverse effect ($C_{avw} = 0.539$)
- * Canadian version with mixed-flow runner and apparatus — significant adverse effect ($C_{avw} = 0.801$)
- * Two-way version with Voith runner — mild adverse effect ($C_{avw} = 0.868$)
- * Two-way version with mixed-flow runner and Exit Stay Apparatus — insignificant adverse effect ($C_{avw} = 0.906$).

5. Adverse effect on the beaches in the basin of caused by difference 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 version — 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 version with Voith runner — strong adverse effect (the shapes of $Z_t = Z_t(T)$ and $Z_b = Z_b(T)$ are very much different, see see Figure 6)
- * Canadian version 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 see Figure 8)
- * Two-way version with Voith runner — mild adverse effect (the shapes of $Z_t = Z_t(T)$ and $Z_b = Z_b(T)$ are not very much different, see see Figure 6)
- * Two-way version 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 see Figure 6)

Comment:

It was recently suggested by Dr.David Prandle, Professor, University of Bangor, UK, that it is possible to decrease the adverse effects on 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 version at the end of generation the head is so small (see Figure 4) that it is not possible to pass sufficient 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 like it is done at two-way tidal plant. Of course in this case the Canadian version will produce less energy than without bypassing. In order to get the feeling of the size of this decrease in energy output one can see from Output 1 (showing the results of computations for Canadian and two-way versions with Voith turbine) that the Canadian version in order to have the same value of $C_{avw} = 0.868$ as two-way version will produce per deim 76,735.22MWhr instead of 94,130.12MWhr, or 18% less. I am planning to include in the capabilities of program ENERGY the computation of optimized energy output of Canadian version with the same value of C_{avw} as for two-way version.

6. Conclusion of the paper and recommendations to DECC

6.1. Conclusion of the paper.

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

The paper presents the comparison of DECC, Canadian, and two-way versions based on computations using developed and verified by me program ENERGY. Unfortunately these computations were done using the capacity curve, $A_b = A_b(Z_b)$, for The Bay of Fundy basin, because previous DECC administration refused to give me the capacity curve for Severn Estuary basin. (I strongly believe that the use of the capacity curve for Severn Estuary basin will not substantially change the results obtained by me with capacity curve for the Bay of Fundy basin).

The present paper has shown without need in experimental verification, that developed in 2006 - 2010 DECC version of Cardiff-Weston barrage is drastically inferior to Canadian and two-way versions (both with commercially available Voith bulb turbine) not only in environmental aspects but also in economical aspects.

The paper have shown that there is a reasonable prospect of improving Canadian and two-way version with respect to the environmental issues and with respect to increasing their energy outputs by using instead of Voith Bulb turbine the Bulb turbine with mixed-flow runner and Exit Stay Apparatus. However, this requires the experimental verification.

The two-way version with Voith bulb turbine practically does not have an adverse effects on the environment. It is superior in environmental aspects to considered in the paper Canadian version with the same turbine and produces more energy per year than the last one, however it is more expensive. So in order to compare two-way version to Canadian version it is necessary:

- * To establish the price of two-way version as the result of the conceptual project of this version.
- * To make the adverse effects on the environment of Canadian version equal to two-way version by adding to Canadian version the capability to use the bypasses during the final stage of generation.

6.2. Recommendations to DECC .

DECC has to immediately:

1. Independently verify my program ENERGY. I am absolutely positive 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 I consider this verification as unavoidable step. I am ready to give the source of the program ENERGY together with Users Manual as I indicated in my letters to DECC Management. In my opinion it will not take more than 2 weeks.

2. Recompute all my results for Canadian and Two-way version with commercially available Voith Bulb turbine using the capacity curve, $A_b = A_b(Z_b)$, for the Severn Estuary basin. I strongly believe that the use of the capacity curve for Severn Estuary basin will not substantially change the results obtained by me with capacity curve for Bay of Fundy basin. In my opinion it will not take more than 3 - 4 weeks.

In a case of the results presented in this paper essentially repeated:

1. To abolish the DECC version of Cardiff-Weston Barrage as greatly inferior in all aspects to Canadian and two-way versions.
2. To solicit proposals from major hydro turbine manufacturers, hydro turbine testing laboratories, and hydro turbine research consortia to the tests of Bulb turbine with mixed flow runner without and with Exit Stay Apparatus. In the

case of positive results of these tests both Canadian and two-way versions will benefit. On my assessment the tests will not take more than half a year and will cost no more than \$ 500,000. I have the programs for the design of the mixed-flow runner and Exit Stay Apparatus to be incorporated in any selected Bulb turbine. My computations will not take more than one month. The fabrication of the mixed flow runner and and Exit Stay Apparatus will cost no more than \$ 150,000 and will not take more than one month. The fabricated runner and exit stay apparatus will be tested in already existing model turbine. The experiments will be very short. Mixed-flow runner without Exit Stay Apparatus has to be tested only at optimal operating regime. Mixed-flow runner with Exit Stay Apparatus has to be tested only at several operating regimes: $N_{11} = (N_{11})_{opt}$ and $(Q_{11})_{opt} \leq Q_{11} \leq (Q_{11})_{max}$, where $(Q_{11})_{max}$ is Q_{11} corresponding to maximum available power.

3. At the same time to order:

* The alterations in Black & Veatch a conceptual project in order to have the conceptual project of Cardiff-Weston with Canadian version of power equipment and bypasses capable to have the same value of C_{avw} as for two-way version.

* A conceptual project of two-way version.

4. To Select the best from economical point of view between Canadian and two-way versions with the same C_{avw} .

Acknowledgments

I would like to express my gratitude to the following persons:

Mr. Tony Tung, T. Tung Hydraulic Energy, Canada, for introducing me in 2006 the research in the field of tidal power plants, helping me in getting information about the conceptual project of tidal power plant for The Bay of Fundy, and giving to me several valuable suggestions after reviewing my paper;

Mr. Gareth Woodham, Founder of the Severn Lake Company, and Chair of the Severn Lake Tidal Power Group, whose mission is to build the Severn Lake Causeway and who has given unwavering support to my "two way generation tidal power plant with one way turbines;

Mr. Frank Hamill, Hydraulic Specialist at Bechtel Corporation, San Francisco, for being my consultant in hydraulic structures for my work on "Two-way generation tidal power plant".

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.