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Part 2: Capital Cost 82-10

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by

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ABSTRACT

A generic methodology is devised for estimating the capital costs of small scale tidal power plants (1 - 100 MW rated power). In addition to the general dimensions determining the size of the tidal pond resource (surface area and tidal range) two site-specific dimensions (depth and length of closure structure) are required for this estimate. Dimensionless parameters and variables describing the power plant performance (Fay and Smachlo 1982) are used in the cost analysis to specify the relative sizes of the power plant components (turbine-generator, power house, sluice gates, cofferdam and barrage). The generic cost estimates are compared with those used in several site-specific studies. Unit total capital cost (cost per unit of average power produced) is calculated as a function of the size of the tidal pond resource, the latter being measured in terms of the ideal tidal pond power. A range of closure depths and lengths were used in these generic cost estimates. The minimum unit capital cost is shown to depend upon the size of the tidal pond as well as the site-specific dimensions. An optimum turbo-generator size can be determined so as to minimize the capital cost.

PREFACE

This study was initiated because of current interest in the possibility of small scale tidal power projects which might be located in the Gulf of Maine, especially the Bay of Fundy. While there is a continuing study of a large scale facility to be located in the Minas Basin (Nova Scotia) of the Bay of Fundy, recent studies of much smaller sites in Cobscook Bay (Maine) have raised the question of whether a number of small facilities might be preferable to a "megaproject". A pilot project at Annapolis Royal (Nova Scotia), soon to be completed, typifies a small scale tidal power plant.

Without prejudice to the large vs. small argument, this and an accompanying study develop a generic approach to the preliminary design and costing of small scale tidal power projects. They provide quantitative estimates of the technical performance and capital costs of such facilities as well as the hydrodynamic parameters of the tidal pond which will influence some environmental effects. A more definitive and precise characterization of hydrodynamic, environmental and economic factors would require a site-specific study.

We hope that the results of these analyses will be useful in the assessment of the advantages and disadvantages, both economic and environmental, of small scale tidal power and will provide a basis for screening of candidate sites and proposed projects.

1. Introduction

The growth of interest in renewable energy resources, particularly in regions such as New England which are heavily dependent upon fossil fuel imports, has resulted in the detailed site-specific investigations of a number of moderate to large scale (100 MWe - 1000 MWe) tidal power projects. The technology of such tidal power systems has been proven and demonstration of economic feasibility is awaited. Naturally, economic feasibility of tidal power as an alternative to burning fuel oil is very dependent on the fuel cost escalation rate, cost of capital, setting of the revenue rates, investment incentives and the time frame in which the analysis is undertaken as well as the physical and design characteristics of each particular system. The physical characteristics of a site along with the specification of system design determine the performance characteristics of a system. Knowledge of the design and performance characteristics of a system provides enough information for a preliminary estimate of the capital cost requirements for the five major components of a tidal power system, which are the turbo-generating equipment, power house, sluice gates, barrage and cofferdam (if utilized in the construction of the tidal power system).

In this analysis we develop a set of cost functions, dependent on the physical and design characteristics of a system, which provide a means for the preliminary estimation of capital cost requirements for each of the system components mentioned. Then, utilizing the predicted performance characteristics associated with the physical and design characteristic of the system (Fay and Smachlo 1982), selection of 'optimal' system designs for varying sizes of the available resource are made on the basis of minimizing the cost per unit of average power generated.

Dimensionless parameters which describe the physical characteristics of any site being investigated are incorporated in the development of this analysis. This generalizes the nature and applicability of the results to power plants of any size. Moreover, examination of the returns to scale available for different values of the parameters can be undertaken readily.

Only the capital cost requirements of the system components are examined. No attempt is made to account for the variation of financing expenses associated with projects of differing scale requiring differing planning and construction horizons. A more complete economic analysis, taking into account the uncertain financial factors mentioned, could be undertaken utilizing the capital cost estimates of this paper.

The methodology of the analysis could also be employed in a screening process of potential tidal power generation sites. Other costs of development not examined in this analysis are the additional construction costs associated with locks or service facilities, relocations, transmission lines, real estate and service equipment. These costs are generally not significant in comparison to the costs of the system components examined in this analysis (U.S. Army Engineer Division 1980 and Chas. T. Main, Inc. 1980).

In this analysis of single basin tidal power plant operation a single effect ebb-tide operating scheme is assumed. Double effect schemes have been estimated to be more expensive in their unit cost of power output due primarily to their more expensive turbo-generator units and the associated powerhouse structural requirements.

In subsequent sections (2-7) of this report we develop methods for estimating the cost per unit of rated turbine power for each of the principal components (turbine-generator, power house, sluiceway, barrage and cofferdam). These estimates are based on the size of each component and the unit cost of material (in the cases of the civil works). Two site specific parameters are introduced (total length and maximum depth of civil works) in addition to those implied in the system performance analysis (Fay and Smachlo 1982). For typical values of these parameters we then determine the total capital cost per unit of average power generated (section 8) as a function of resource size, which is measured by the ideal tidal power available in the tidal pond, and then show how the minimum unit cost may be determined by selection of the optimum size of the turbine.

2. Turbine-Generator Costs

2.1 Turbine selection

Comparison of the performance, direct costs and associated civil construction costs for vertical and horizontal shaft propeller turbines reveals a clear superiority of the horizontal shaft turbines for application in tidal power plants (Chas. T. Main, Inc. 1980). Presently three types of horizontal shaft turbines may be considered for such applications: bulb, tube and straight flow (rim mounted generator) turbine designs. Of these, only the bulb turbine has the combination of successful operating experience, required size availability, adjustable wicket gates, and more than one experienced supplying manufacturer. For this reason use of bulb turbines, presently considered to be the most economical design (U.S. Army Engineer Division 1980) for tidal power plant applications, will be assumed in this analysis. A straight flow ("Straflow") turbine is slated for installation at the Annapolis Royal tidal power plant, scheduled to begin power generation in 1983. Depending upon its operating experience, the Straflow design may supplant the bulb turbine as the most economical, but this remains to be seen.

2.2 Turbine-generator costs

The cost of turbo-generating equipment C_t is expected to increase with the rated power P_e. The unit cost, C_t/P_e, would be larger at lower heads because the turbine flow area must be increased(for a given power) necessitating a larger runner diameter and hence more turbine material. Based upon flow similarity (Fay and Smachlo 1982), the turbine flow area should increase as $H_o^{-3/2}$ (where H_o is the rated turbine head) for a fixed P_e.

Utilizing a study of the cost of bulb turbo-generator machinery (Verplanck and Wayne 1978) as a function of design head, the estimated unit cost can be well represented by:

$$C_t/P_e = (6900\ \$\ m^{3/2}/kW)/H_o^{3/2} \qquad (2.1)$$

over a range of head from 11 ft. (3.4m) to 35 ft. (10.7m), which is appropriate for tidal power plants. Eq. (2.1) implies that the unit cost increases in proportion to the turbine flow area.

For tidal power systems, a 10% increase in cost to cover cathodic protection and other preparations necessary for use of the equipment in a marine environment has been suggested. Also, a 10% installation charge is assessed as the cost of installation for the machinery. Hence, the cost of the in-place turbo-generating equipment for use in tidal power systems is estimated as:

$$C_t/P_e = (8270\ \$\ m^{3/2}/kW)H_o^{3/2} \qquad (2.2)$$

A comparison of Eq. (2.2) with a specific site study of turbogenerating costs is shown in Table 1. The close agreement with this and other cases not shown substantiates the use of Eq. (2.2) for preliminary cost estimation of turbo-generating equipment for small tidal power plants.

3. Power House Costs

3.1 Methodology of cost estimation

Estimation of the cost of the power house structure containing the turbo-generating equipment is made by first estimating the total in-place material volume of the power house. An estimate of the average in-place cost per unit volume of the materials comprising the power house can then be applied to the volume estimate of the power house to get a total cost estimate.

3.2 Estimate of the total in-place material volume and cost of the power house

To estimate the in-place material volume of the power house, we begin by assuming that the power house occupies a rectangular volume of length L_p (in the flow direction), width W_p and height H_p. We expect that the length L_p and height H_p will be proportional to the tidal range R and that the product W_pH_p will be proportional to the turbine flow area (or D_o^2, where D_o is the runner diameter). Thus the power house gross volume should be proportional to RD_o^2. Next we assume that the in-place volume V_p of material is a fixed fraction of the gross volume. In this manner, using the corresponding values of these quantities based on representative values taken from the Cobscook, Fundy and La Rance projects, we evaluated the proportionality constant to find:

$$V_p = 42\ RD_o^2 \tag{3.1}$$

The cost C_p of the power house is obtained by multiplying V_p by the unit cost $B_p(\$/m^3)$ of composite material put in place. To determine the unit cost C_p/P_e of the power house, we first relate D_o^2 to the rated power P_e through the empirical relation:

$$P_e = 0.8\ \rho\ D_o^2\ (gH_o)^{3/2} \tag{3.2}$$

in which ρ is the mass density of sea water and g is the acceleration of gravity. The constant 0.8 in Eq. (3.2) differs from the value given by Fay and Smachlo (1982) as the average for over a hundred turbines of all types. The former is an average value for current and proposed tidal plant turbines.

Substituting Eq. (3.2) in (3.1), we find the unit cost of the power house:

$$C_p/P_e = 52.6\ RB_p/\rho(gH_o)^{3/2} \tag{3.3}$$

Using a value of $B_p = \$264/m^3$ based on the Half Moon Cove study, we have calculated C_p/P_e and $(C_t+C_p)/P_e$ for several projects shown in Table 1. The agreement with the site-specific values is quite acceptable. The underestimate for the Birch Island site appears to be related to an underestimate of the volume of the power house, which is longer than would be expected for the tidal range at the site.

In subsequent calculations, a separate estimate of width W_p is needed. A suitable average of several projects is:

$$W_p = 2D_o^2/R \tag{3.4}$$

4. Sluice Gate Costs

4.1 Methodology of cost estimation

As for the cost estimation of the powerhouse structure, an in-place material cost analysis will be employed in estimating the cost of sluice gates. The venturi-type sluice gates will be modeled as hollow, rectangular structures whose material volume will be assumed to be proportional to the gross volume of the structure. As before, an average in-place material volume cost can then be applied to the estimated volume of the sluice structure to arrive at the cost of the sluice gate(s).

4.2 Structural dimensions, material volume and costs of the sluice gate.

As was done for the power house structure, we assume that the length and height of the sluice gate structure are proportional to the tidal range while the frontal area is proportional to the sluice gate area A_g, thus deducing that the volume of the structure is proportional to A_gR. The material volume V_g then becomes:

$$V_g = 18\ RA_g \tag{4.1}$$

in which we have used the design values of several tidal projects to evaluate the proportionality constant. (Note the similarity to Eq. 3.1).

The cost C_g of the sluice gate is then found by multiplying the material volume V_g by the unit cost B_g of material:

$$C_g = 18\ B_gRA_g \tag{4.2}$$

A performance parameter of the tidal power plant which specifies the amount of sluice gate area is (Fay and Smachlo 1982):

$$\gamma \equiv C_DA_g(gR)^{1/2}/Q_o \tag{4.3}$$

in which C_D is the discharge coefficient of the sluice gates and Q_o is the rated turbine volume flow rate. The latter may be found from the rated power P_e of the turbo-generator:

$$P_e = \eta_t \cdot \rho g H_o Q_o \qquad (4.4)$$

where η_t is the overall efficiency of the turbine and generator. Combining Eqs. (4.2) - (4.4) we find the unit cost of the sluice gates:

$$C_g/P_e = (18/\eta_t C_D) B_g R^{1/2} \gamma / \rho g^{3/2} H_o \qquad (4.5)$$

Using values of $\eta_t = 0.9$, $C_D = 1.7$ and $B_g = 290$ \$/m^3, the unit sluice gate costs were calculated for several tidal power plants and are compared with the values from the specific site studies in Table 1. The agreement is acceptable, although the costs given by Eq. (4.5) for the M3 and M4 sites are higher than the site-specific estimates.

In carrying out economic optimization studies, it was found desirable to allow γ to vary with the amount of the turbine capacity as defined by the dimensionless parameter β (Fay and Smachlo 1982):

$$\beta \equiv 2Q_o T / A_o R \qquad (4.6)$$

in which T is the tidal period and A_o the tidal pond surface area at mean sea level. Based on U.S. Army Engineer Division (1980), a mean empirical relationship exists between β and γ which defines a desirable amount of sluice capacity:

$$\gamma = 5.3 - 0.76\beta \qquad (4.7)$$

This relationship will be used in cost optimization studies.

In subsequent cost estimates, the width W_g of the sluice gate structure is needed. We use an empirical relation:

$$W_g = A_g/R \tag{4.8}$$

derived from several site-specific studies.

5 . Cofferdam Cost Estimation

5.1 Choice of cofferdam vs. float-in caisson construction

A choice must be made between the construction of a cofferdam or the use of the relatively new float-in powerhouse and sluice gate assembly technique. Since many uncertainties exist as to the applicability and cost of the float-in technique for use in regions such as Cobscook Bay (a primary site of interest for small scale applications), the use of cofferdams is assumed in this analysis.

5.2 Cofferdam cost estimation methodology.

A cellular cofferdam structure was selected as being the most suitable type for use in the Half Moon Cove feasibility report (Chas. T. Main 1980). Interlocking cells, thirty feet in width, are to be filled with a granular material. Estimation of the cost C_c of the cofferdam civil works consists of first estimating the total in-place material volume of the cofferdam V_c and then assessing the cost based on an in-place material cost per unit volume B_c as:

$$C_c = B_c V_c \tag{5.1}$$

Unless known to enclose the entire length of the structural barrier (as for the Half Moon Cove project design), the cofferdam is assumed to enclose only the sluice gate and powerhouse structures in a circular fashion. In this case the perimeter of the cofferdam structure would be proportional to the combined widths W_g and W_p of the sluice gates and the power house, as given by Eqs. (4.8) and (3.4). The height and thickness of the cofferdam structure is assumed to be proportional to a dimension D_b which is the sum of the high tide depth of the tidal channel at the site of the power house plus ten feet of freeboard. Thus the volume V_c of cofferdam material becomes:

$$V_c = 0.94(W_s + W_p) \quad D_b^2 \qquad (5.2)$$

where we have used site values for the Half Moon Cove project to evaluate the proportionality constant.

The unit cost of the cofferdam civil works can be found by combining Eqs. (5.2) and (5.1) and dividing by P_e. Noting that D_b is a site-specific variable we calculated C_c/P_e by this method using $B_c = \$48/m^3$ (Chas. T. Main 1980) and compared these values with site-specific estimates for several tidal power plants as shown in Table 1. The agreement is reasonable.

6. Barrage Cost Estimation

6.1 Methodology of estimation.

The cost of the barrage is assumed to be proportional to the length L_b and cross-sectional area A_b of the barrage. An estimate of the total material volume of the barrage is to be developed. An average in-place cost per unit volume of the barrage construction materals B_b can then be used to estimate the total cost of the barrage.

6.2 Development of the barrage cost estimation equation

The cross-sectional area of the barrage at its midlength will be approximated by an isosceles triangle of altitude D_b and base length $2mD_b$ where m is the average slope of the sea and basin sides of the barrage. Thus the crossectional area would be mD_b^2 at midlength and, we assume, half of that value when averaged over the length L_b of the barrage, giving a material volume V_b of the barrage equal to:

$$V_b = m\, D_b^2 \;\; L_b/2 \qquad (6.1)$$

If the opening to the tidal basin spans a distance L_c, then the length of the barrage is less than L_c by the widths W_s and W_p of the sluiceway and power house:

$$L_b = L_c - W_s - W_p \qquad (6.2)$$

If the average in-place cost per unit volume of barrage material is B_b, then the unit cost of the barrage can be found from Eqs. (6.1) and (6.2) to be:

$$C_b/P_e = B_b\, m\, D_b^2\, (L_c - W_p - W_s)/2P_e \qquad (6.3)$$

In Eq. (6.3) there are two dimensions which are specific to each site, L_c and D_b. For geometrically similar tidal ponds of differing surface area A_o, L_c would be proportional to $A_o^{1/2}$. To keep barrage costs to a minimum, better sites would have a lower value of $L_c/A_o^{1/2}$. For the sites listed in Table 1, $L_c/A_o^{1/2}$ lies in the range 0.15 - 0.25, which probably characterizes the most attractive sites. On the other hand, D_b might be expected to be approximately proportional to the tidal range R. As Table 1 shows, however, the range of D_b/R among the sites studied is about 3 to 8. In subsequent cost optimization studies, there-for, we will select values of $L_c/A_o^{1/2}$ and D_b/R which lie within these ranges as typifying the better sites.

It follows from Eq. (6.3) that the unit cost of the barrage will decrease with increasing tidal pond size A_o since L_c will increase as $A_o^{1/2}$ while P_e will vary in proportion to A_o. On the other hand, the unit costs of the turbogenerator,power house and sluice gates will be little affected by the size of the installation. Thus barrage costs will become a very small part of the total cost as the pond size increases.

Using a value of $B_b = \$12.3/m^3$, the unit cost of the barrage was determined from Eq. (6.3) and compared with specific site studies as shown in Table 1. Very close comparison is observed for each site examined. For the Half Moon Cove project, the average wall slope m is lower than that for the other projects. This reflects the differences in construction techniques to be employed. The Half Moon Cove project is fully enclosed by a cofferdam allowing for dry placement and construction of the barrage. The other projects would be built by dumping techniques as outlined by U.S. Army Engineer Division (1980). Our subsequent economic analysis assumes construction of the barrage by dumping methods and a value of $m = 3$ will be employed in general barrage cost predictions as a 'standard' value of m based on the recommendation of U.S. Army Engineer Division (1980).

7. Total Capital Costs

The last lines of Table 1 list the totals of the component costs, both as determined from the site-specific studies and from our cost equations. For all cases the agreement between the site-specific and generic cost estimates is quite acceptable, some of the discrepancies for the component figures having been averaged out in the process of summation.

Of the total capital costs, those of "active" components (turbine, power house and sluice gates) constitute between 70% to 80%. This reflects the choice of sites which do not require extensive barrage construction. Although complete figures are not available, the cost of the turbine-generator itself is nearly half of the total cost. On the other hand, the cofferdam cost is quite small, about 10% of the total, which does not provide much of a margin for cost reduction by use of float-in units for the power house and sluice gates.

As was noted in section 2.2, the unit cost of turbine-generator units increases as the rated head is lowered, about in proportion to the turbine flow area. This increase reflects the greater amount of turbine material needed to pass the larger volume flow of water at lower head, assuming a fixed power generated. Because material stresses are also reduced at lower heads, it may be possible to reduce turbine costs below the values given in Eq. (2.1) by suitable design changes which take into account the low heads at which tidal power plants will operate.

The sites listed in Table 1 experience substantially the same tidal range, 5.5m, typical of that near the entrance to the Bay of Fundy. Unit capital costs will vary inversely with the tidal range, the turbo-generator costs being most sensitive since they will vary as $R^{-3/2}$. Thus for lesser tidal ranges, such as might be experienced along the Maine coast, unit costs will be higher and the costs of the "active" components will constitute an even greater percentage of the total capital costs.

8. Capital Cost Optimization

8.1 Methodology of capital cost determination

The cost methodology of the preceding sections permits the determination of the total capital cost of a projected facility if the site and plant characteristics are specified. Although the properties of a particular site are given, the size of turbine and sluice gates and their operating parameters are to be chosen by the plant designers. In this section we consider a method for selecting the plant design variables so as to minimize the unit capital cost of power produced.

The principal site variables which determine the potential for tidal power are the tidal pond surface area A_o at mean sea level and the tidal range R. An additional variable of much lesser importance is the rate of increase of tidal pond surface area with tidal level. (Fay and Smachlo 1982 define a dimensionless representation, λ, of this variable). The ideal tidal power I is the maximum power which can be developed from a given site (Fay and Smachlo 1982):

$$I = \rho g A_o R^2/T \tag{8.1}$$

In addition, for the purpose of determining the capital costs, the depth dimension D_b and the total length L_c of structure (barrage, power house and sluice gates) closing off the tidal pond must be specified.

Turbine flow can be characterized by the rated volume flow rate Q_o and head H_o, which together define the rated ideal turbine power P_o (Fay and Smachlo 1982):

$$P_o = \rho g Q_o H_o \tag{8.2}$$

But the turbine flow rate and head can be defined respectively in terms of two dimensionless parameters β (Eq. 4.6) and ψ (Fay and Smachlo 1982):

$$\psi \equiv R/2H_o \tag{8.3}$$

the latter having a value of 0.8 when the plant is operated to maximize energy production. The sluice gate size can also be defined in terms of a dimensionless parameter γ (Eq. 4.3). For the purposes of our cost optimization, however, we will assume the approximate relationship, Eq. (4.7), between γ and β. Thus, in effect, only one dimensionless variable parameter, β, will be needed to specify the characteristics of the turbine and sluice gates

Fay and Smachlo (1982) define two performance variables, η (ratio of average to rated ideal turbine power) and ε (ratio of average ideal turbine power to ideal tidal power). The relationships among the powers and the dimensionless parameters and variables can be succinctly given by:

$$P_o/I = \beta/4\psi = \varepsilon/\eta \tag{8.4}$$

The dependent performance variables ε and η are functions of the plant and site parameters β, γ, ψ and λ (Smachlo 1982). Obviously, ε and η are related explicitly by Eq. (8.4).

The scheme of calculating unit costs is straightforward. Assuming that A_o, R, D_b, L_c and λ are determined for a site, H_o is found from Eq. (8.3) for $\psi = 0.8$. A trial value of β is chosen, for which Q_o is calculated from Eq. (4.6), P_o from Eq. (8.2) and γ from Eq. (4.3). Multiplying P_o by an assumed turbo-generator efficiency η_t gives the rated electric power P_e (Eq. 4.4). Thus all the information is at hand to determine the component and total capital costs per unit of rated electric power by the methods given in sections 2-6 above. Finally, from the performance analysis (Fay and Smachlo 1982), the capacity factor η can be determined (since β, γ, ψ and λ are known). Dividing the cost per unit of rated electric power by η will give the capital cost per unit of average electric power produced.

8.2 Dependance of capital cost on plant and site parameters

Typical calculations of this type are shown in Fig. 1 for $R = 5.5$m, $\bar{D}_b/R = 3, L_c/A_o^{1/2} = 0.2$, and $\lambda = 0.4$. (In this and other figures, $\psi = 0.8$ and $\eta_t = 0.9$). As independent variable we have chosen the ideal tidal power I as specifying the range of tidal pond sizes of interest, namely 10^3 to 10^6 kW of power. For any given β, the decrease in unit cost with increasing tidal pond size (I) is the result of the decreased relative cost of the barrage. For large enough I, the unit cost approaches the sum of the turbo-generator, power house and sluice gates costs which are independent of size. But in this limit the unit cost increases as β is increased because, as shown by Fay and Smachlo (1982), the capacity factor η begins to fall as β increases giving rise to an increase in the capital cost per unit of power generated. On the other hand, at low values of I, the declining relative cost of the barrage with increasing β overbalances the effect of a small decline in the capacity factor η, so that larger values of β produce lower unit costs.

In the interesting range of I between 10^4 and 10^6 kW, the optimum value of β decreases from 2 to 1 with a 10^3 factor increase in power, or about as the -0.1 power of I. It is very interesting to note that the values of β in Table 1 for the five sites correspond very closely to the optimum (or minimum capital cost) values of Fig. 1. We also note that the large scale projects studied for the Bay of Fundy, listed in Table 1 of Fay and Smachlo (1982), use values of β between 2 and 3.

A second general conclusion can be drawn from Fig. 1. For the values of the site parameters used, the minimum unit capital cost does not decline significantly with I increasing beyond a megawatt. While it would be imprudent to extrapolate blindly our cost equations to the megaproject range ($I \sim 10^7$kW), there do not seem to be substantial economies of scale beyond about one megawatt of ideal tidal pond power.

In Fig. 1 we have used ideal tidal power to characterize the size of the facility. It is of more direct interest to determine the rated electric power P_e which can be determined from Eq. (8.4) to be:

$$P_e/I = \beta \eta_t / 4\psi \qquad (8.5)$$

Since $\psi = 0.8$ and $\eta_t = 0.9$, for example, P_e would vary between 0.56 and 0.28 times I over the range of $10^3\text{kW} < I < 10^6\text{kW}$, for the minimum capital cost design.

The depth D_b of the pond closure structure has an important influence on the cost since deeper channels will require more material for both active structures as well as the barrage. In Fig. 2 we show the unit capital costs when D_b/R is 8, rather than 3 as in Fig. 1. It is immediately apparent that the capital cost is somewhat higher because of the greater depth and that barrage costs are relatively greater for any given value of I. For minimum cost, the corresponding values of β are in the range of 2 to 3. This supports the intuitive notion that sites with shallow entrance channels are to be preferred.

The other site-related parameter is the length L_c of the closure to the tidal pond. In Fig. 3 we show the unit cost for $L_c/A_o^{1/2} = 0.1$ which is half as great as the value used in Fig. 1. The principal effect is a reduction in barrage costs, which lowers the minimum cost at smaller values of I without any change at higher values. The range of optimum values of β is slightly reduced.

Finally, we note in every case that if the ideal tidal power is sufficiently great for barrage costs to be negligible then the unit cost is not a strong function of the parameter β. Although there is a minimum cost at an optimum value of β, it is a shallow minimum and larger values of β than the optimum would result in noticeably greater power at not significantly greater unit cost. It is possible that, when other factors are considered, higher than optimum values of β might be chosen.

9. Conclusions

A generalized method of estimating capital costs for small scale tidal power plants has been found to give good agreement with costs estimated in five site-specific studies. The generic method uses two site-specific dimensions (length of tidal pond closure and depth of closure structure) in addition to the general dimensions defining the tidal pond power potential (surface area and tidal range). The method provides estimates for the capital costs of the major components of a tidal power plant: turbine-generator, power house, sluice gate, barrage and cofferdam used during the construction phase.

For typical tidal power plant designs, the turbine-generator and power house comprise more than half of the total capital cost and the sluice gates another one quarter. Cofferdam costs are only about ten percent of the total.

The minimum unit capital cost (cost per unit of average power produced) decreases with increasing size of tidal pond chiefly because the relative cost of the barrage becomes smaller. This decline of minimum unit cost with increasing size is not significant beyond a tidal pond size of about one megawatt of ideal power for typical conditions. (For a 5.5m tidal range, one megawatt corresponds to a pond area of 15 hectares). Thus there do not appear to be significant economies of scale for large tidal power projects.

For a given tidal pond, there is an optimum turbine size which minimizes the unit capital cost. Typically, the rated electric power of the optimum turbo-generator is a substantial fraction of the ideal tidal pond power. But the unit cost possesses a shallow minimum so that substantially larger power than the optimum could be installed with only a slight penalty of higher unit capital cost.

The minimum unit capital cost will increase with increased depth of the closure structure and decreased tidal range. The unit turbine cost is especially sensitive to the tidal range because larger turbine flow area is required at the lower head which accompanies a smaller tidal range.

10. References

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11. Nomenclature

A_b	Crossectional area of the barrage (m^2)
A_g	Flow area of sluice gates (m^2)
A_o	Surface area of tidal pond at mean sea level (m^2)
B_b	Unit cost of barrage material ($\$/m^3$)
B_c	Unit cost of cofferdam material ($\$/m^3$)
B_p	Unit cost of power house material ($\$/m^3$)
C_c	Capital cost of cofferdam ($)
C_D	Discharge coefficient of sluice gates
C_g	Capital cost of sluice gates ($)
C_p	Capital cost of power house ($)
C_t	Capital cost of turbine-generator ($)
D_b	Depth of barrage structure (m)
D_o	Turbine runner diameter (m)
g	Acceleration of gravity (m/s)
H_o	Rated head of turbine (m)
H_p	height of power house (m)
I	Ideal power of tidal pond (W)

L_b	Length of barrage (m)
L_c	Length of tidal pond closure (m)
L_p	Length of power house (m)
m	Slope of barrage walls
P_e	Rated electric power of turbine-generator (W)
P_o	Rated ideal power of turbine (W)
Q_o	Rated turbine volume flow rate (m^3/s)
R	Tidal range (m)
T	Tidal period (s)
V_c	Volume of cofferdam material (m^3)
V_g	Volume of sluice gate material (m^3)
V_p	Volume of power house material (m^3)
W_g	Width of sluice gates (m)
W_p	Width of power house (m)
β	Turbine flow parameter, Eq. (4.6)
γ	Sluice gate flow parameter, Eq. (4.3)
ε	Ratio of average ideal turbine power to ideal tidal pond power
η	Ratio of average ideal turbine power to rated ideal turbine power

η_t	Turbine-generator efficiency
λ	Parameter defining shape of tidal pond volume (Fay and Smachlo 1982)
ψ	Ratio of tidal half-amplitude to rated turbine head
ρ	Mass density of sea water (kg/m^3)

Table 1

COMPARISON OF ESTIMATES OF TIDAL POWER PLANT COMPONENT UNIT COSTS

	Half Moon Cove[1]	Goose Bay[2]	Birch I.[2]	Treat I.[3] (M3)	Cooper I.[3] (M4)
P_e (MW_e)	12	195	165	180	180
H_o (m)	4.3	4.0	4.0	4.0	4.0
R (m)	5.55	5.55	5.5	5.5	5.5
A_o (10^6 m^2)	2.2	78.7	65	80.1	68.8
D_b (m)	18.3	43	40	30.5, 12	53.3
L_c (m)	370	2470	1550		
L_b (m)	310	1770	1220	1040, 1100	805
m	2	3	3	3	3
β	2.1	1.0	1.0	0.9	1.0
γ	3.0	6.3	6.5	5.7	5.7
C_t/P_e (\$/kW)	917				
(Eq. 2.2)	(939)				
C_p/P_e (\$/kW)	238				
(Eq. 3.3)	(282)				
$(C_p+C_t)/P_e$ (\$/kW)	1155	1405	1735	1350	1320
(Eq. 2.2 + Eq. 3.3)	(1219)	(1340)	(1340)	(1340)	(1340)

Table 1 (Continued)

	Half Moon Cove[1]	Goose Bay[2]	Birch I.[2]	Treat I.[3] (M3)	Cooper I.[3] (M4)
C_g/P_e (\$/kW)	209	422	426	289	206
(Eq. 4.5)	(183)	(412)	(425)	(372)	(373)
C_c/P_e (\$/kW)	454[4]	288	251		
(Eqs. 5.1, 5.2)	(465)[4]	(367)	(324)		
C_b/P_e (\$/kW)	108	308	219	100	
(Eq. 6.3)[5]	(106)	(309)	(218)	(115)	
Total (\$/kW)	1926	2423	2631	1739[6]	
(Total)	(1973)	(2428)	(2307)	(1827)[6]	

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[1] Stone and Webster (1980)

[2] U.S. Army Engineer Division (1980)

[3] Stone and Webster (1978)

[4] Cofferdam encloses the barrage also.

[5] Based on L_b, row 7.

[6] Not including cofferdam cost

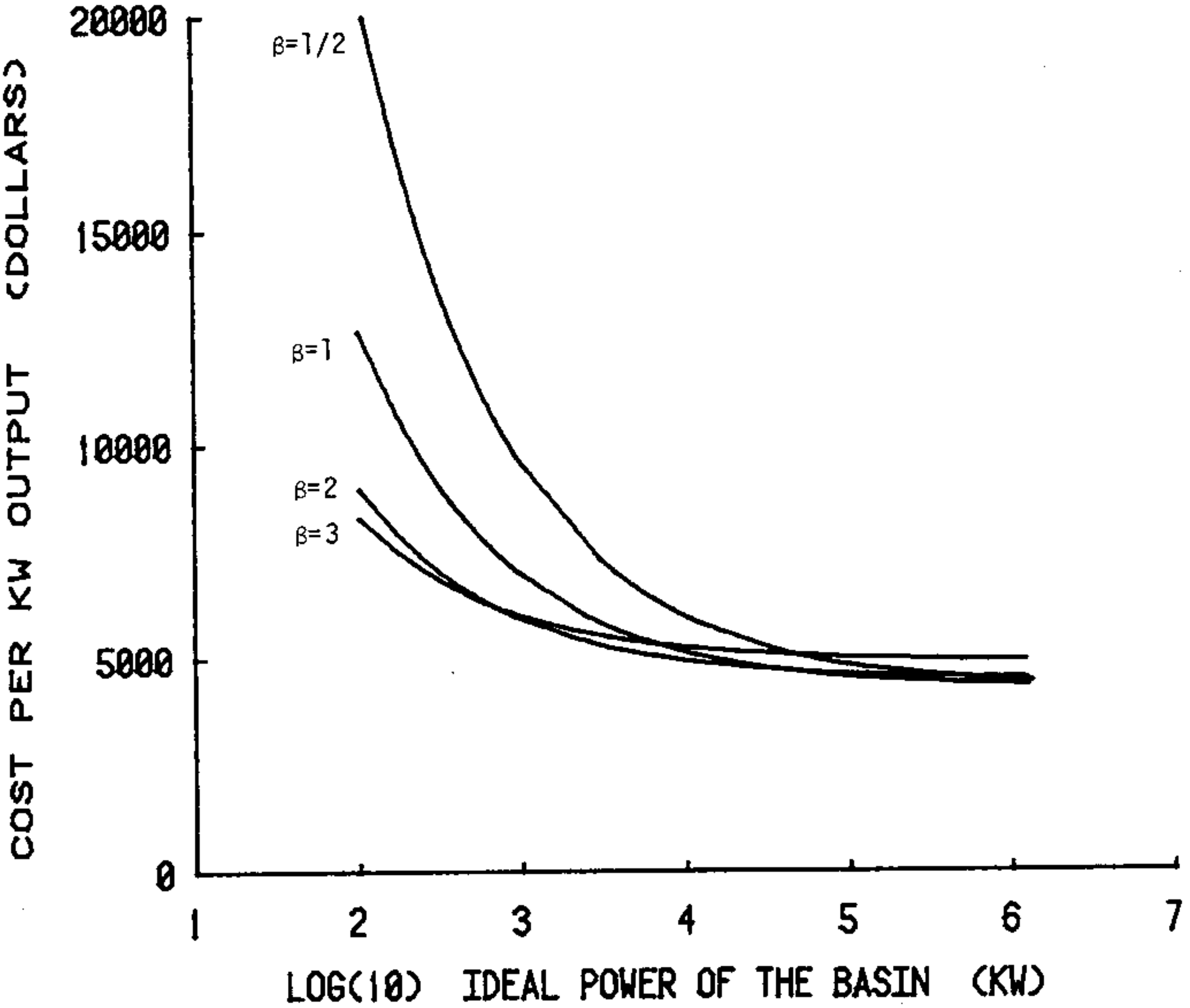

Fig. 1 Capital cost of a tidal power plant per unit of average power produced plotted as a function of the ideal tidal power of the tidal basin for various relative turbine sizes as measured by the parameter β (Eq. 4.6). The tidal range R is 5.5m. The power plant parameters are $\psi = 0.8$ and $\eta_t = 0.9$; the tidal pond is characterized by $D_b/R = 3$, $L_c/A_o^{1/2} = 0.2$ and $\lambda = 0.4$

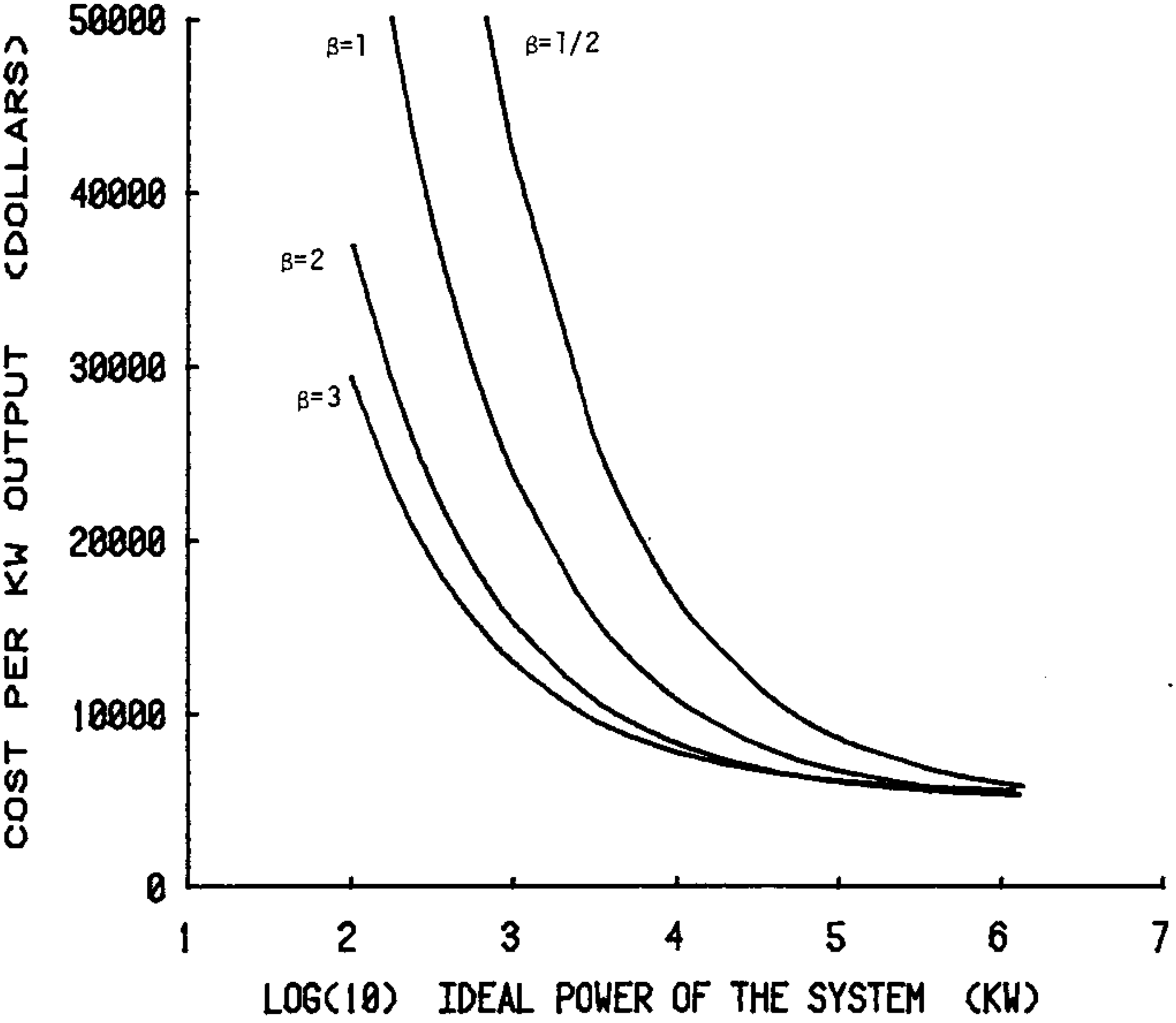

Fig. 2 Same as Fig. 1 except $D_b/R = 8$.

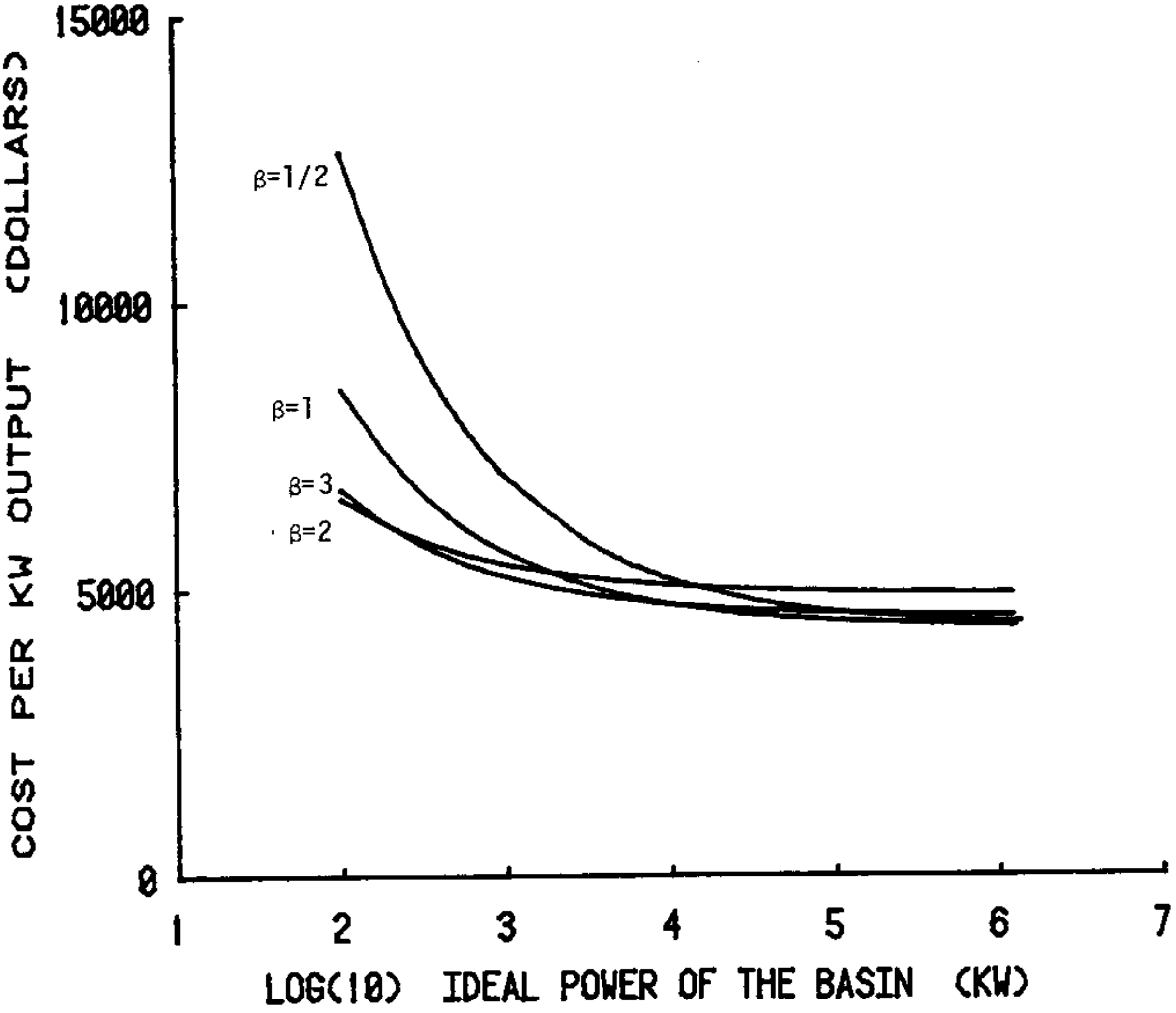

Fig. 3 Same as Fig. 1 except $L_c/A_o^{1/2} = 0.1$