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Energy

A model of the costs for tidal range power generation schemes

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Tidal range power is gaining recognition as a globally important power source, replacing unsustainable fossil fuels and helping mitigate the climate change emergency. Great Britain is ideally situated to exploit tidal power but currently has no operational schemes. Schemes are large and expensive to construct, assessment of their costs is usually examined under conditions of commercial confidentiality. A national strategy for delivery needs a more open system that allows cost estimates to be compared between schemes; a model that evaluates the capital cost of major components has been developed. In 1983, Massachusetts Institute of Technology published a simple additive model of the costs of tidal range schemes on the east coast of the United States. Their model has been updated and benchmarked against recent schemes with published costs; the Sihwa Lake Tidal Power Station (South Korea, completed in 2011) was used along with the published costs for the Swansea Bay Tidal Lagoon proposal in South Wales to benchmark the model. There are developments in civil and mechanical engineering that may influence both the costs and speed of deployment. These are discussed along with methods for their inclusion into the model.

Keywords: economics & finance/power stations (non-fossil fuel)/renewable energy/UN SDG 7: Affordable and clean energy/UN SDG 9: Industry, innovation and infrastructure/UN SDG 13: Climate action

Notation

A_b	cross-sectional area of bund (m^2)
A_g	area of sluice elevation (m^2)
C_b	cost/m of bund (m^2)
C_c	cost/m of cofferdam (US\$ or Great Britain (GB)£)
C_p	cost of powerhouse section per turnine unit
C_s	cost of single sluice structure
C_{t+g}	cost of each turbo-generator unit, including electrical, control and instrumentation
D_o	diameter of turbine runners (m)
H_b	height of bund from crest to sea bed (m)
H_o	rated head of turbine (m)
L_b	length of bund (km)
L_c	length of cofferdam measured as total width of powerhouses plus sluices (m)
N_s	number of sluices
N_{t+g}	number of turbines and powerhouses
Pe	rated power of each generator (MW – power in megawatts)
R_1	rate for turbo-generator (\$m$^{-1.5}$/MW)
R_2	rate for powerhouse (\$/m^3)
R_3	rate for sluice (\$/m^3)
R_4	rate for cofferdam (\$/m^3)
R_5	rate for bund (\$/m^3)
R_a	tidal range (m)
s	slope ratio as in *1* vertically to *s* horizontally
W_c	width of embankment crest (m)
W_g	width of sluice (m)
W_p	width of powerhouse unit (m)

1. Introduction

Tidal range schemes are large and expensive pieces of infrastructure that over time pay for themselves through the reliable generation of sustainable power. The decision to invest in such schemes is complex, but basically underpinned by two components:

(*a*) the costs associated with construction, deployment and commissioning
(*b*) the rate of return of energy and its estimated value.

This paper concentrates on the first component, a subsequent paper, in preparation, covers the rate of return. In 1983, Massachusetts Institute of Technology (MIT), published a model of the costs of tidal range schemes in the United States (Fay and Smachlo, 1983). The structure of that model has been examined and employed to create an up-to-date version that will reflect the costs for schemes in Great Britain (GB).

To calibrate the updated model, it has been benchmarked to the largest and most recently commissioned scheme, the Sihwa Lake Tidal Power Station in South Korea (Bae *et al.*, 2010). The benchmarked costs have been applied to the Swansea Bay Tidal Lagoon Proposal in South Wales for further validation. It is argued that the rates used are sufficient for pre-feasibility cost estimates. Additionally, they allow a general comparison to be made between schemes and the number of turbines and sluices to be optimised within each. The discussion covers areas such as the recent advances in precast concrete construction techniques and describes how they can be included in the model.

There are factors beyond the two major components described above that will influence and may determine the success of a proposal. Although not discussed here, the environmental impact of a tidal range scheme is important in determining its approval to proceed. The precautionary principle has been a major factor in the failure of proposals progressing to completion over the last 100 years. The authors' previous paper (Vandercruyssen *et al.*, 2022) demonstrates how a barrage with two-way generation and pumping can maintain the full tidal range and protect intertidal areas. While environmental impacts must be externalised as costs to a project and consequently mitigated or compensated for, climate change is posing new challenges. The acceptance of sea level rise commits governments to act, meeting their international obligations, to protect existing environmentally designated intertidal areas. A failure to act will lead to a major loss of habitats and species on a global scale. A subsequent paper will cover the costs and implications of protecting existing intertidal areas from rising sea levels.

2. Five major components

Fay and Smachlo (1983) developed formulae for preliminary capital cost estimates for the five main components of tidal range power scheme. By summing the components, the overall capital cost can be estimated (Equation 1). These are the turbo-generating equipment (C_{t+g}), powerhouse (C_p), sluice gates (C_s), cofferdam (C_c), if utilised and bund (C_b). For the powerhouse, sluice gates, cofferdam and bund, Fay and Smachlo calculated the gross volumes of the structures and found the net volume of materials – that is, reinforced concrete and ballast.

1. $$\text{Capital cost} = N_{t+g}C_{t+g} + N_{t+g}C_p + N_sC_s + L_cC_c + L_bC_b$$

Table 1. Rates in US$, 1983 per unit for the five-main components of tidal range schemes

Fay US$ 1983	Turbo-generator	Power house	Sluices	Cofferdam	Bund
Rates	R_1	R_2	R_3	R_4	R_5
Units	$\$.m^{1.5}/MW$	$\$/m^3$	$\$/m^3$	$\$/m^3$	$\$/m^3$
Value	8.27×10^6	264	290	48	12.3

where N_{t+g} is the number of turbo-generators and powerhouse sections; N_s is the number of sluice gates; L_c is the length of the cofferdam, calculated as the combined width of powerhouses and sluice gates measured along the line of the bund. L_b is the length of the bund. Where the depth varies along the line of the bund it is split into sections of similar depths and the cost calculated for each section.

To determine average rates, they looked at several schemes along the Maine coast of the United States. All had similar tidal ranges of 5.5 m and the turbines had a rated head of approximately 4.0 m. The units and initial rates are shown in Table 1.

2.1 Turbo-generating equipment

Fay and Smachlo (1983) postulated that the cost per MW (power in megawatts) of turbo-generating unit C_{t+g} increases as $H_0^{-1.5}$, where H_0 is the rated head in metres; the relationship is based on flow similarity. The exponent is intended to represent the increased efficiency of the generator as the rated head increases; the speed increases and size of the generator reduces (Equation 2). Fay and Smachlo's initial rate R_1 was for tidal flow in one direction using small hydro-turbines and included a 10% increase for cathodic protection and other measures necessary for a marine environment. The rate includes installation costs at 10%.

2. $$C_{t+g} = R_1 \times H_0^{-1.5} \times \text{Pe}$$

where Pe is the rated power in MW of each turbogenerator.

2.2 Powerhouse

Fay and Smachlo's initial estimate of cost of the powerhouse (C_p) is derived from the volume of construction materials. They calculated the gross volume of the powerhouse as the length (in the flow direction), the width (across the intake) and the height. They assumed the length and height would be proportional to the tidal range R_a. Also, that the product of the width and height is proportional to the turbine flow area. Based on quantities from schemes at Cobscook, Fundy and La Rance, Fay and Smachlo (1982) evaluated the cost of each powerhouse, as follows:

3. $$C_p = R_2 \times 42R_a \times D_0^2$$

where D_0 is the runner diameter and R_2 represents the cost/m^3 of reinforced concrete. The other equations relate the runner diameter to the turbine rating but as this study considers varying the generator rating for the same size turbine the simple volume equation is used.

There will be economies of scale for multiple machines in a powerhouse as there will remain only two end walls and a single overhead crane. Also, the high rate for materials R_2 reflects in situ concrete construction within cofferdams. With modern technology, the authors expect that many of the structural components can be precast and floated into position.

2.3 Sluices

As for the powerhouse, Fay and Smachlo (1983) derived the material volume from the gross volume of the structure that is proportional to the tidal range R_a. Using example sites, the cost of a sluice (C_g) is given by Equation 4 where A_g is the frontal area of the gate.

$$4.\quad C_s = R_3 \times 18R_a \times A_g$$

where R_3 is the material rate for reinforced concrete.

Fay and Smachlo optimise the size, or number, of gates from material costs per unit whereas in the model here, power returns are used after an examination of sluice/turbine ratios using a zero-dimensional (0D) model.

2.4 Cofferdam

Fay and Smachlo (1983: p. 536) stated that '… the 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'. They went on to develop a cost based on interlocking cells 10 m wide, which are filled with granular material. The cofferdam is only employed for sluice gates and powerhouse structures. Its width (L_c) is proportional to the combined widths of all gates and powerhouses $W_g + W_p$. The height and thickness of the cofferdam are assumed to be proportional to a dimension H_b, which is the sum of the high-tide depth at the site of the powerhouse plus 3 m of freeboard (Equation 5).

$$5.\quad C_c \text{ per m} = R_4 \times 0.94H_b^2$$

$$6.\quad L_c = \sum W_g + W_p$$

2.5 Bund

The generic term 'bund' is used to describe either an embankment structure or a wall that provides the impoundment. Fay and Smachlo continued their volumetric cost estimate based on an embankment formed from hydraulic granular fill – for example, dredged sand and gravel. The gradient, or slope of the embankment can be defined as the ratio (s) of the change in horizontal distance for 1 m change in height; or more commonly 1:s, vertical: horizontal. For $s = 3$ the slope is better suited for hydraulic fill which has limited compaction. If rock-filled gabions or sand-filled geo-tubes are used to face the slope, then a $s = 2$ slope would be appropriate. The material rate R_5 is low to reflect the cost of sea-dredged aggregate that is placed without needing to bring the material ashore. In this case it is assumed that $s = 3$ for greater stability. The difference in volume is significant (2.25 times) and would increase dramatically if other than a minimum crest width (W_c) is considered (see Figure 1).

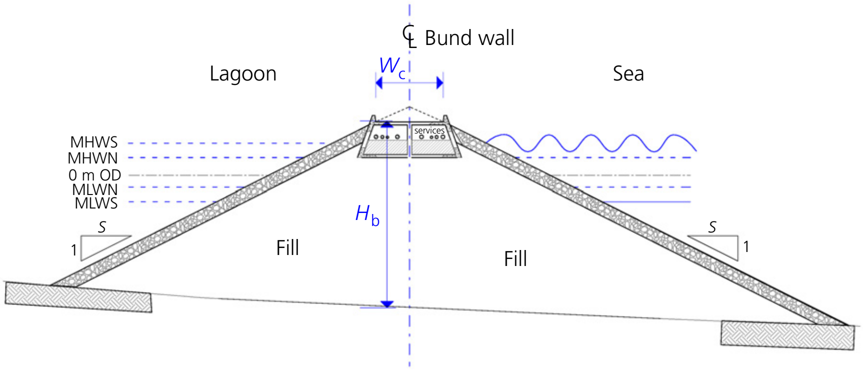

Figure 1. Typical embankment section. MHWS, mean high water spring; MHWN, mean high water neap; MLWN, mean low water neap; MLWS, mean low water spring

In Figure 1 the area of the cross-section is given by

$$7.\quad A_b = H_b(sH_b + W_c)$$

where W_c is the width of the embankment crest. W_c is approximately 8 m for a simple service road but would increase significantly for a wider public carriageway. It is prudent to add the cost of a rock-filled gabion blanket 1 m thick or Bioblocks (Firth *et al.*, 2014) to the batters. Assume the cost for this is $5 \times R_5/\text{m}^3$ and then the cost per m of bund is given by

$$8.\quad C_b \text{ per m} = R_5(H_b(sH_b + W_c) + 10sH_b)$$

The crest is the top of the bund, protruding above the highest tide. Its minimum level should be 3 m above the highest tide, allowing 2 m for storm surge plus 1 m for waves and sea level rise for the first 50 years. The crest is to minimise over-topping and does not assist generation. Thus, H_b is the distance between the seabed and the level of the crest. The height of the bund will vary along its length; ideal schemes will have some deep water for the turbines and less deep water in other areas to reduce the cost of the bund.

3. Benchmarking

Sadly, only limited data are available for the largest and most recently commissioned scheme, Sihwa completed in 2011. Also considered is the proposed Swansea Bay scheme which has been proposed by Tidal Lagoon Power (2022) but so far has not gained financial or environmental approval.

Other schemes have been considered but dismissed due to lack of technical or financial details. The La Rance scheme is a beacon of longevity, completed in 1967 (Waters and Aggidis, 2016a). It uses 24, 10 MW Kaplan bulb turbines. The technical details are particularly relevant as it was designed to operate in two-way generation mode with pumping. The financial information on this project is dated (commissioned 55 years ago) so any form of cost indexing over such a long period would be unreliable. The Annapolis project, sited in the Bay of Fundy, Canada was constructed in 1984 and consists of a single 20 MW straflo turbine. It was operational for 35 years until 2019 when it was closed after equipment failure (Tethys, 2022). This type of turbine is not currently being considered for use in GB but nevertheless may be suitable. Other small projects in China and Russia have been discounted from this study.

3.1 Sihwa lake tidal power station

At Sihwa power is generated on the flood tide only as the scheme was designed to reduce stagnation in the impoundment. Sluices are included but not sized to optimise flow for generation. The bund was pre-existing, so the total capital cost represents electro-mechanical equipment, powerhouse, sluices and cofferdam. Some details of the design and sketches are given by Bae *et al.* (2010).

- There are 10, 25.4 MW generators, which operate in flood mode only. Runners are 7.5 m in diameter and the design speed is 64.29 r/min.
- Mean spring tidal range is 7.8 m. The rated head is 5.82 m, which is 75% of the maximum tidal range.
- Turbine intakes and outfalls are ~16 m square.
- There are eight sluice gates, 12.0 m high × 15.3 m wide.
- The circular cell cofferdam consists of 29 primary cells and 28 spandrel walls. Stability was provided solely by gravity with the cell filling. The height was up to 31.5 m due to the water depth and ground conditions.

The equation for the turbo-generator (Equation 2) was applied with a rated head (H_o) of 5.82 m, gives the cost of a unit as

$$9.\quad C_{t+g} = 8.27 \times 10^6 \times 5.82^{-1.5} \times 25.4 = \$15.0\,\text{M}$$

For the powerhouse, Equation 3 was parameterised with a 7.5 m turbine and a 7.8 m tidal range as shown below

$$10.\quad C_p = 264 \times 42 \times 7.8 \times 7.5^2 = \$4.9\,\text{M}$$

For the sluice gates Equation 4 with dimensions of 12×15.3 m gates and a 7.8 m tidal range; the cost for one gate is given by

$$11.\quad C_s = 290 \times 18 \times 7.8 \times 12 \times 15.3 = \$7.5\,\text{M}$$

The cost of the cofferdam is calculated using Equation 5 with the width of the powerhouses $W_p = 10 \times 16$ m, and the width of the sluice $W_s = 8 \times 15.3$ m. In this case take the depth $D_b = 31.5$ m as reported by Bae *et al.* (2010).

$$12.\quad C_c \text{ per m} = 48 \times 0.94 \times 31.5^2 = \$44.8\text{k}$$

The bund was pre-existing for Sihwa so it is excluded from the total capital cost.

Since the costs of large-scale projects are commercially sensitive, it is difficult/impossible to locate a detailed cost breakdown of the project. Bae *et al.* (2010) and *Power Technology* (2014) list the cost as $355 million (US, 2011). The authors

Table 2. Benchmarking 1983 rates with Sihwa reported capital cost to update rates to millions of dollars (\$m), 2011

Sihwa Lake	Turbo-generator		Power house	Sluices		Cofferdam		Capital cost (\$m, 2011)	
Rates	R_1		R_2	R_3		R_4			
Units	$\$.\text{m}^{1.5}/\text{MW}$		$\$/\text{m}^3$	$\$/\text{m}^3$		$\$/\text{m}^3$		Estimate	Actual
Initial values from Table 1	8.27×10^6		264	290		48			
Input	N_{t+g}	C_{t+g} (\$m)	C_p (\$m)	N_s	C_s (\$m)	L_c (m)	C_c (\$k)		
	10	15.0	4.9	8	7.5	18 × 16	44.8		
Estimated cost	150		49	60		12.9		271.9	355
% estimated cost	55%		18%	22%		5%			
Sihwa rates at 1.31	10.80×10^6		346	380		63			

use this information to benchmark the updated figures from Fay and Smachlo (1983), as shown in Table 2.

The benchmark factor of 1.31 in Table 2 is the ratio between the actual and estimated cost. It is somewhat less than inflation between 1983 and 2011. This may be due to:

- the size and number of turbines used for Sihwa
- advances in turbine design since 1983
- advances in civil construction technologies and equipment
- lower construction costs in South Korea.

The benchmarked cost of a turbogenerator set based on Equation 2, is now given as

13. $$C_{t+g} = 10.80 \times 10^6 \times \ 5.82^{-1.5} \times 25.4 = \$19.5\text{m, } 2011$$

Schmid (2005), announced that VA Tech Hydro were awarded a contract of \$93 million for the delivery of the electro-mechanical equipment (turbine runner, shaft seals, stator cores etc.). This accounts for 47% of the \$195 million total for the turbo-generators. Thus, the generators, transformers, balance of mechanical, electrical and control and instrumentation systems account for 53%.

3.2 Other predictions for the cost of turbogenerators

Fay and Smachlo's (1983) formulae were based on a range of runner diameters and generator ratings. The US east coast tidal ranges were distributed around 5.5 m, which is lower than the 7.4–9.6 m (mean high water spring) seen along the west coast of GB (Vandercruyssen *et al.*, 2022). For GB the most efficient bulb turbines will be the largest that can be manufactured, currently this is with 7.5–8.0 m diameter runners. The generator ratings are likely to be in the range of 15–30 MW. The exponent (−1.5) used in Equation 2 sets the cost for a 30 MW machine with an operating head of 7.4 m, only just above that of a 20 MW machine with an operating head of 9.6 m. This contrasts with the often-quoted flat rate of £1 million/MW.

3.2.1 Swane (2007)

Swane (2007) proposed a different formula based on prices for double-regulated bulb turbine units from Alstom. His graphs showed that costs depend on the rated head and the diameter of the turbines. The graphs showed diameters of 4.5, 6.0 and 7.5 m, and heads of 5, 10 and 15 m. Swane estimated costs in millions of Euros (€m) at 2007 prices to be given by Equation 14, where H_o is the turbine's rated head, and D_o is the diameter of the runners. Note that the exponent on rated head is now a small positive number. Instead of the power rating in MW the D_o^2 term is used; this represents the area of flow and reference (Vandercruyssen *et al.*, 2022) indicates that there is an optimum power output for any particular site and tidal range.

14. $$C_{t+g} = 5.5 + 0.1185 \times H_o^{0.18} \times D_o^2$$

Substituting H_o and D_o for Sihwa, gives the estimated cost of a turbo-generator unit as in Equation 15

15. $$C_{t+g} = 5.5 + 0.1185 \times 5.82^{0.18} \times 7.5^2 = €14.65\,\text{million}$$

Using the Historical Currency Converter (2021) the factors for 2007 are €1 = US\$1.32 = £0.67. This is equivalent to \$19.4 million or £9.8 million at 2007 prices.

3.2.2 Parsons Brinckerhoff (2009)

In their options study for the Severn Estuary report, Parsons Brinckerhoff Ltd (2009) used rates based on the power rating and turbine diameter as shown in Table 3. The figures in italics have been added by interpolation.

For fully reversible bulb turbines, they estimated an additional cost of 12.5% compared to ebb only bulb turbines.

3.2.3 Proposed formula

Swane's equation 14 is useful as it includes rated head and diameter of the runners. However, the model must account for

Table 3. Bulb turbine cost estimates used for Severn Estuary report, November 2008 rates

Turbo-generator		Cost rate: £m/MW		Cost £m, November 2008	
Rating: MW	Diameter: m	Ebb only	Two-way	Ebb only	Two-way
10	5.25		1.166	*10.4*	11.7
12.5	4.80	0.917	*1.032*	11.5	12.9
24	7.85		0.721	*15.4*	17.3
25	6.60	0.627	*0.705*	15.7	17.6
25	8.30		0.705	*15.7*	17.6
30	9.00		0.638	*17.0*	19.1

various generator ratings. Following analysis of these alternative methods of estimating the turbo-generator costs, the authors propose the empirical equation that links cost to the rated head and generator rating equation 16 is proposed. This relates to Table 3 over the more limited ranges of generator rating and runner diameters currently being considered for GB. The formula has been updated from 2011 to 2016 by an index factor of 1.39. In the 2009 study of the River Severn schemes, Parsons Brinckerhoff (Parsons Brinckerhoff Ltd, 2009) increased the rate for the turbogenerator by 20% to allow for dual flow and triple regulation. The authors propose to apply this to all GB schemes. Also applying the 1.16 factor for UK inflation from 2011 to 2016 yields

$$C_{\mathrm{t+g}} = 3.36 \times H_{\mathrm{o}}^{-0.5} \times P_{\mathrm{e}}^{0.9}\ \mathrm{m},\ 2016 \tag{16}$$

The −0.5 exponent on rated head gives an 11% cost reduction over the range of rated head relevant to Sihwa and the schemes in GB. The 0.9 exponent on the power rating gives a slight reduction in cost per MW where the runner diameters are within the range of 7.5–8.0 m relevant to Sihwa and the schemes in GB. Equation 16 was used to create Table 4.

Updated turbo-generator costs in GB£ at 2016 rates using a rated head H_{o} for Swansea Bay of 5.8 m and 20 MW generator rating is £22.5 million each. Note that the mean spring tides for Sihwa and Swansea Bay are similar at around 7.8 m. The mean spring tidal range for the river Severn is 9.6 m, which is similar to that of Morecambe Bay.

To benchmark against other rates for the Swansea Bay scheme, converting the $US to GB£ using a historic currency converter (Historical Currency Converter, 2021) and change the year from 2011 to 2016 using the UK construction price index for new infrastructure construction (BEIS, 2021). The factors are 0.64 and 1.16, respectively (see Table 5).

Table 4. Estimated turbo-generator costs based on generator rating and rated head, in millions of pounds (£m), 2016

Mean spring tide range: m	Rated head, H_{o}: m	Generator rating: MW				
		10	15	20	25	30
7.8	5.8	12.1	17.4	22.5	27.5	32.4
9.6	7.2	10.8	15.6	20.2	24.7	29.1

Table 5. Conversion from US$, 2011 to GB£, 2016

Sihwa Lake	Power house	Sluices	Cofferdam	Bund
Rates	R_2	R_3	R_4	R_5
Values US$, 2011	346	380	63	12.3 × 1.32
Values £, 2016	258	283	47	16.2

Rates R_2 and R_3 look reasonable for the cost of in situ reinforced concrete. Rate R_4 represents sheet piling with dredged sand infill, also appears reasonable. R_5 for dredged sand appears to be low; the 2008 *Interim Options Analysis Report* (Parsons Brinckerhoff Ltd, 2008) for the Severn Estuary used £15/m^3. Applying a 20% inflation increase gives $R_5 = £18/\mathrm{m}^3$.

3.3 Swansea Bay tidal lagoon

In the absence of the deployment of any new tidal range scheme since Sihwa, the model has been used to estimate the cost of the proposed tidal lagoon at Swansea Bay in South Wales, UK. Despite the development being the most advanced in the UK, the UK government declined funding support, so this scheme is not actively progressing. Waters and Aggidis (2016b) state there are 16 × 20 MW units with 9.5 km of bund costing £850 million (BBC, 2014). Approximate water depths and the bund location are given in figures in the paper by Petley and Aggidis (2016). No other published technical data have been found.

The water within the impoundment is too shallow for efficient bulb turbine operation (Figure 2). A rule of thumb is that the centreline of the turbine should be at least the diameter of the runners below the lowest water levels, to avoid cavitation. The ideal invert level of the turbine caisson for a 7–8 m dia. turbine would be about −18 to −20 m outer diameter (OD). The scheme may be designed with significant dredging and or modified turbine intake and outfall structures; this would affect the accuracy of a cost estimation. To estimate the depths and volumes of the bund materials used in Table 6, an average depth of 5 m below sea level from Figure 2 and assume the crest of the bund is at 7 m OD, this gives $H_{\mathrm{b}} = 12$ m in Equation 8.

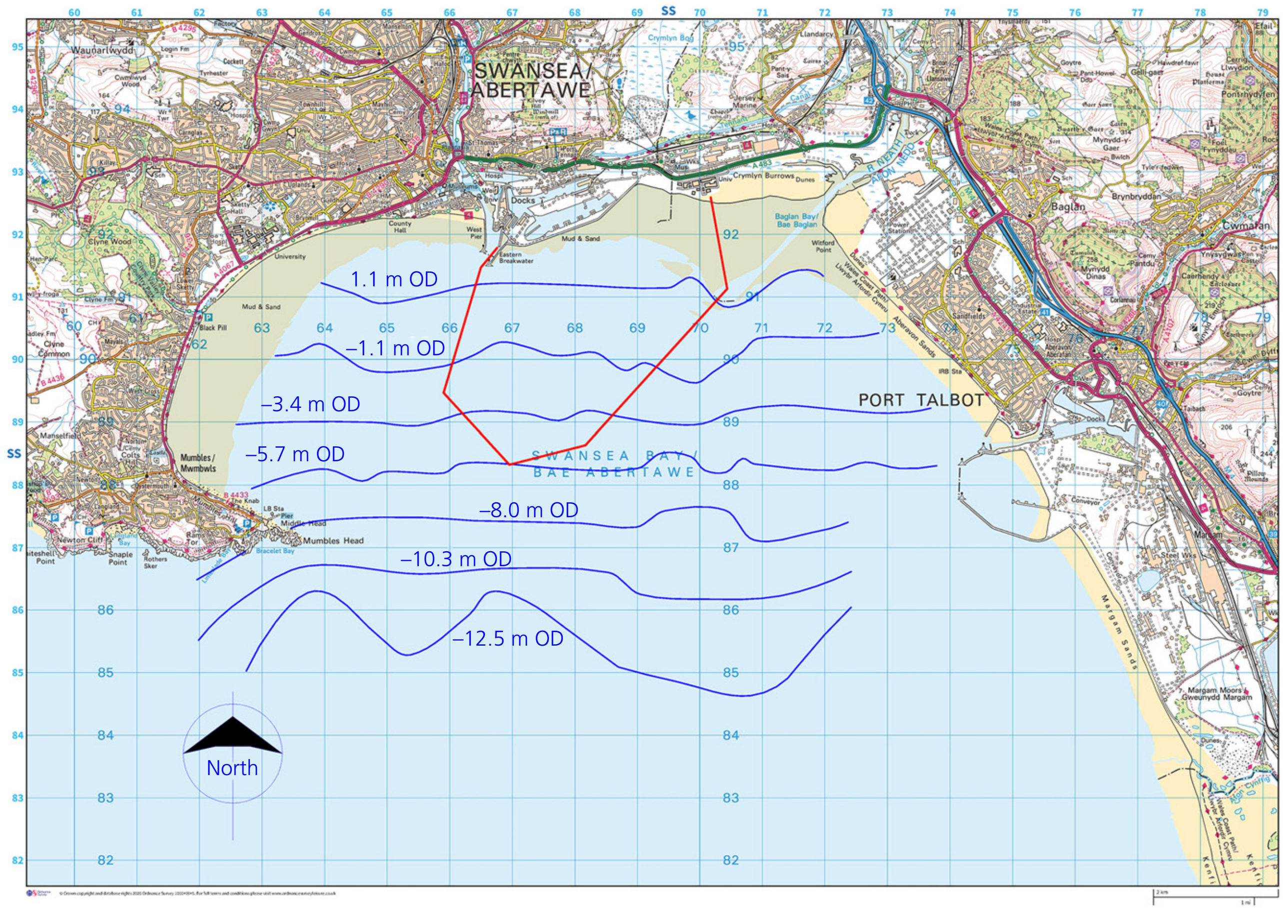

Figure 2. Water depths below mean sea level around the Swansea Bay by Petley. ©Crown copyright 2022 Ordnance Survey. Media 014/22

Table 6. Swansea Bay benchmarking capital cost, in millions of pounds (£m), 2016 rates

Swansea Bay	Turbo-generator		Power house	Sluice gates		Cofferdam		Bund		Prelims and site overheads	Capital cost (£m, 2016)	
Rates	R_1		R_2	R_3		R_4		R_5				
Units	$£.m^{1.5}$/MW		£/m^3	£/m^3		£/m^3		£/m^3		At 30% of civil costs	Estimate	Published
Sihwa rates, 2016	See Table 4		264	290		48		18				
Input	N_{t+g}	C_{t+g} (£m)	C_p (£m)	N_s	C_s (£m)	L_c (m)	C_c (£k)	L_b (m)	C_b (£k)			
	16	22.5	5.55	7	9.17	361	27.6	9500	16			
Estimated cost	360		89	64		10		152		120	795	850

Applying these rates to the Swansea Bay scheme with the following inputs.

- The cost of each turbogenerator is $C_{t+g} = £22.5$ million from Table 4 or Equation 16, where $H_o = 5.82$ m and involves 20 MW generators.
- The cost of the powerhouse was taken from Equation 3 with range $R_a = 8$ m mean spring tide. Runners are 8.0 m in diameter, and $R_2 = £258/\ m^3$ from Table 5, giving the cost $C_p = £5.55$ million.
- As the number and sizes of sluices was not known, a sluice ratio of 2 was assumed – that is, the area of sluices is twice the area of turbine runners. For 8 m dia. runners the area of flow is 50 m^2. Thus, for a sluice ratio of 2 with 15 m^2 sluice, there would be 0.44 sluices for every unit. There will be seven gates for 16 turbines. The cost of

a sluice gate is taken from Equation 4 with $R_a = 8$ m and $R_3 = £283/m^3$ from 0; $C_s = £9.17$ million.

- The cost of the cofferdams was taken from Equation 5 but using the height of the bund H_b as the ideal invert level of −18.0 m OD plus a high tide of 4 m OD, plus freeboard of 3 m to allow for storm surges and waves, gives $H_b = 25$ m. The cost/m of cofferdams is given by

$$C_c \text{ per m} = 47 \times 0.94 \times 25^2 \times 10^{-6} \cong £27.6\text{k} \quad (17)$$

The width of the sluice gates, $W_g = 7 \times 15 = 105$ m.
The width of the powerhouse, $W_p = 16 \times 16 = 256$ m.
$R_4 = £47/m^3$ from Table 5.

- The average level of seabed from Figure 2 and light detection and ranging (Lidar) data (Defra, 2022) or hydrographic charts (UKHO, 1984) is approximately −5 m OD. Add a maximum sea level of 4.0 m OD and a 3 m freeboard, give a bund height of 12 m. The bunds are formed with dredged granular fill with $s = 3$ batter, $R_5 = £18/m^3$. Assume the width of the bund crest is 8 m. The cost per metre length from Equation 8 is given by

$$C_b \text{ per m} = 18(12(3 \times 12 + 8) + 10 \times 3 \times 12) \cong £16\text{k} \quad (18)$$

The capital costs are increased by 30% of the civil engineering costs to allow for preliminaries, surveys, design, contingencies and profit as used in Appendix A of the government-sponsored study of options in the Severn Estuary (Parsons Brinckerhoff Ltd, 2008). The value is only an approximation but is used consistently to make schemes comparable. Higher contingencies may be necessary for the first scheme in the UK but should diminish for subsequent schemes.

Table 6 shows the calculated estimate is 94% of the published capital cost. This is good correlation given the lack of design information and the probable need for dredging which is not included.

Other factors that could influence the estimates include:

- the cost of construction in South Korea might be significantly less than in the UK or USA
- the turbines were made in Europe and have been benchmarked with the River Severn study so there is no change to Table 6.

None of the rates proposed will be accurate but it is suggested that they are sufficient for the optimisation of schemes and their overall ranking. These rates can be improved when feasibility designs have been completed for other future schemes.

4. Potential development of model

4.1 Precast concrete elements

In 1983, Fay and Smachlo (1983) highlighted cost implications of the choice between cofferdams and precast concrete construction of the civil works. By 1991, Baker (1990) was advocating precast concrete construction for all elements of tidal range schemes, including precast turbine halls. Precasting technology has developed significantly since then. Also, from a safety perspective the industry should not consider working up to 20 m below sea level if there is a viable alternative (HMG, 2015). Parson Brinckerhoff's study for the Severn Estuary (Parsons Brinckerhoff Ltd, 2009) used 'all up' rates for caisson construction, derived from the *Interim Options Analysis Report* (Parsons Brinckerhoff Ltd, 2008), between £215 and £322/m^3. It varies due to the cost of setting up the fabrication facilities. If semi-permanent facilities are created on the west coast of GB for several schemes, the likely cost will reduce to the lower end of the range. These rates span the rates R_2 and R_3 for in situ concrete but would avoid the need for cofferdams. It is believed that with today's technology all the concrete structures could be precast to a high degree.

Navigation locks will be required in any tidal range scheme allowing passage by vessels. Since locks are essentially the same as sluice gates, they are not estimated separately here. At slack tides all the locks and sluices will be open for passage. All locks and sluices can be monitored and operated remotely. In 2009, The World Association for Waterborne Transport Infrastructure (PIANC) published report 106 (Rigo, 2009) that considered all aspects of lock design and construction, focusing on novel techniques and concepts. It included more than 50 project reviews of existing locks or projects in development. Notably they include several projects where locks have been precast and floated into position.

4.2 Immersed tunnels

Immersed tunnels are a good example of what can be achieved with current marine design and construction techniques. The first, and currently only, scheme in the UK was built under the Conwy Estuary in 1988 (Stone *et al.*, 1989). The current state of this technology can be seen on the Fehmarnbelt 18 km immersed tunnel (Femern A/S, 2011). Construction started in 2020. It will be the world's longest of its type for both road and rail connections between Denmark to Germany. The tunnel will comprise 79 precast elements and ten special elements. One standard element weighs 73 000 t, is 217 m long, 42 m wide and 10 m high. The tunnel's construction budget is €7.1 billion and construction is planned to take 7 years.

Both these projects involved temporary dry docks and casting facilities adjacent to the works. They demonstrate that large elements can be precast, floated into position and joined with watertight seals. Given the potential for tidal range along the west coast of GB it is likely that one or more semi-permanent casting facilities could be constructed, thus reducing the cost for individual schemes.

4.3 Vertical caissons

An alternative to embankment construction is provided by precast concrete caissons. The Spanish construction company Dragados has built several breakwaters and docks by forming precast vertical caissons using a specially developed floating barge. At Abra Exterior Port, Bilbao in Spain, they built a 2.4 km breakwater in water depths in excess of 33 m. Martinez and Rodriguez (1997) reported details from a project at the Port of Valencia, Spain. As well as a detailed description of the fabrication the following details of the caissons are given (Martinez and Rodriguez, 1997):

> Each floating caisson was 42 m long, 15.6 m width, 16.5 m height, its concrete volume was 2857 m^3, weighing approximately 6860 metric tons, including 116 metric tons of rebar. The ratio of the material volume to the gross volume is 0.26.

Once the gross size of the caisson is known, the net volume of precast concrete (rate R_6) will be approximately 26% of the gross volume. The other 74% will be dredged aggregate or waste stone at rate R_4.

5. Discussion

The decision to develop a tidal range power scheme proceeds through a cycle of increasingly detailed assessments. The initial analysis involves a generic desk-based approach. The output of such an analysis must provide robust information that allows the decision to proceed or not to be made in a timely manner at a reasonable price. The capital cost model described here provides such an initial assessment. The transparency of the approach and ability to modify for civil and mechanical engineering developments give confidence that schemes can be compared.

The analyses are not simply essential initial assessments to support developers' decisions but have value for national strategy. It is important that schemes can be compared on a 'level playing field' to help determine if and where national finances should support development; the analyses can be completed rapidly for multiple sites and can be ranked allowing those selected to undergo further study. For government, the outcomes are not intended to provide detailed future financial planning to cover the whole cost, as this is likely to be supported by venture capital from the private sector. However, their support and targeted funding of schemes is better justified through transparent analysis that replaces the current haphazard appearance and failure of proposals.

The simple structure of the model (Equation 1) makes it straightforward to modify for new technologies and techniques. As described, novel methods of marine construction may reduce the costs and even remove the need for a cofferdam; by setting $C_c = 0$. The rate for precast concrete and floating out can replace the rates R_2 and R_3 for the powerhouses and sluice gates. Other approaches need to be looked at from a costs perspective and assessed for suitability across a full range of coastal sites.

It is important to recognise that the work reported here does not indicate that the task is completed. There is important work to do exploiting the model, linking it to 0D estimates of tidal power at matched locations. The results would form the basis of a strategy to deploy tidal range power in the UK and will be the subject of another paper being prepared by the authors.

For the wider assessment of the costs and benefits a life-cycle analysis for carbon associated with the schemes (including habitat protection) would prove informative. As the changes to the environment due to climate change become more obvious, decisions on mitigation and adaptation must be urgently considered; the model presented is part of a suite that will inform those decisions.

6. Conclusion

The model is effective at producing an initial estimate of the capital costs of a tidal barrage as demonstrated by benchmarking against the Siwha Lake tidal power station and the Swansea Bay lagoon proposal. The estimates of cost are easy to produce, based on clearly identified components that can be modified for novel technologies. The output must be combined with data describing the rate at which power can be extracted from the tidal range at different times and other costs and benefits.

The model provides only an approximate capital cost but is proposed as a method of ranking schemes and optimising their components. The importance and ability will be demonstrated in a subsequent paper. The model can and should be refined when tidal range schemes are developed and better cost information becomes available.

Disclaimer

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