Tidal Lagoon Power Generation Scheme in Swansea Bay

A report on behalf of the Department of Trade and Industry and the Welsh Development Agency

AEA TECHNOLOGY CONTRACT
NUMBERS: **14709570 and 14709574**

URN NUMBER: 06/1051

Contractors

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First published April 2006

Executive Summary

Tidal Electric Limited (TEL) has proposed the construction of a 60MW "tidal lagoon" power generation scheme in Swansea Bay.

TEL has estimated that the lagoon could be constructed for £81.5M and generate power at a cost of ~3.5p/kWh[1]. Renewable energy generated at this cost would be commercially very attractive and both the Department of Trade and Industry (DTI) and the Welsh Development Agency (WDA) have separately undertaken reviews to assess the claims made. The two reviews, undertaken independently, arrived at the same main conclusion. This was that the generation costs of the proposed tidal lagoon would be substantially higher than TEL's estimate.

The most significant differences between TEL's proposal and the Reviewers' assessment are as summarised in the following table:

Assessed Parameters	TEL estimate	This report	Reason for Difference
Cost of embankment	£48.5M	£137M	1. TEL assumed a design wave height of 4m. With the current lack of site data, the Review used a more prudent design wave height of 5m for this location. 2. TEL assumed 0.3m settlement of the embankment post-construction, which is the minimum they identified, which was between 0.3m and 2.3m settlement. TEL concluded that a settlement of 1m would increase construction costs by 10%. The Reviewers have assumed a 5% increase in construction costs to allow for a middle range settlement with the current lack of knowledge of ground conditions. 3. TEL assumed that the top of the water-retaining core of the embankment would be 7m above chart datum. This review assessed that the top of the core, after settlement, would have to be at least 10.5m above chart datum to prevent frequent overtopping. 4. TEL assumed an embankment slope of 1V:1.5H for the inner face and sheltered parts of the outer face. The Reviewers concluded that a shallower slope of at least 1V:2.5H would be required to ensure stability of the embankment's slopes on the soft sea bed. 5. TEL assumed the embankment's crest width to be 3m, whereas the Reviewers consider that a crest width of at least 5m would be necessary for safe access, to survive wave damage and to allow for a reasonable core crest width. 6. TEL used a median weight of stone armour of 4te. The Reviewers concluded that a median weight of stone armour of between 11te and 15te would be necessary, dependent upon wave period. Their analysis uses a mid-range value of 12te.

[1] Tidal Electric Ltd., Financial Analysis.

Assessed Parameters	TEL estimate	This report	Reason for Difference
Cost of Power House	£12.7M	£46M	1.TEL's estimate is based upon an all-in cost of reinforced concrete of £100/m^3. The Reviewers have taken a figure of £600/m^3 as a mid range value determined from the cost of concrete used for previously studied tidal barrage schemes, updated using the Government's All New Construction Output Price Index, and benchmarked with results from the Carbon Trust's Marine Energy Challenge. 2.The Reviewers concluded that for two way generation the water passage in the power house would need to be 10% longer than that assumed by TEL.
Predicted annual energy output	187,000 MWh/yr	124,000 MWh/yr	1.The Reviewers were unable to validate the Output model calculations used by TEL due to insufficient information provided, 2. The Reviewers therefore made their own calculations based on the same tide data used by TEL and using performance data for turbines provided during the Severn Barrage studies. 3. The Reviewer's model assumed a lower efficiency in reverse flow for two-way generation than that used by TEL.
Decommissioning	nil	£200M+	1. The Reviewers are concerned that TEL have not taken due account of the implications of decommissioning the project at the end of its life and for insuring against early removal of the structures should the project fail to be completed. 2 Typically, the developer would have to deposit a bond against these eventualities. The cost of this could be significant. 3. The cost of decommissioning could be at least as much as the cost of construction and possibly much more.
Contingency allowance	£1.15M	£20.4	1. The Reviewers are concerned that TEL have made little allowance for normal project risks. 2. A structured risk assessment would help TEL and their backers to get a better understanding of the likely project risks and the sensitivity of their estimates to potential scheme variations. 3. At this pre-feasibility stage, it would be reasonable to assume a contingency allowance of at least 10% of the capital cost i.e. around £20M.
Un-costed items	£0	£0	1.The estimates omit a number of work items such as:- ▪ Isolation gates to the lagoon side of the turbines, ▪ Trash screens to both sides of the turbines, ▪ Fish screens both sides of the turbines, ▪ Protection to the sewage outfall pipeline, ▪ Standby generation, duplicate power cable.

Thus, the total construction cost for the proposed tidal lagoon scheme is likely to be around £234M, compared with the TEL estimate of £81.5M (i.e. an increase by a factor of 3.6), and the lagoon is only likely to generate around 66% of the energy projected by TEL.

The cost of energy from the proposed lagoon is therefore estimated to be more than 4 times greater than that presented by TEL.

On this basis the cost of energy from the proposed lagoon would be at least 17p/kWh at 8% discount rate which conforms with results from previous studies of tidal lagoons undertaken by others.

The Reviewers see little prospect for reducing the cost of energy from this concept through replication, innovation or experience as it would uses standard engineering principles and mature technologies. The cost of the lagoon is dominated by the materials cost where there is little prospect for cost reduction and much scope for cost increase.

There are also proposals to construct tidal lagoons in other locations, such as off the coast of North Wales. Whilst this review has not studied these other proposed schemes, the issues surrounding the Swansea Bay scheme are sufficient to cast doubt on the economic viability of the tidal lagoon concept for the foreseeable future. The few possible locations with a higher tidal range offer a greater annual power output, and larger lagoons may offer some economy of scale. Studies of tidal barrages, however, have shown that the economies of scale are relatively minor whereas the potential for unacceptable impacts tends to increase with size.

Should TEL's engineering solutions prove deliverable, then the economics of all the potential tidal barrage schemes around the UK would also be significantly improved.

Contents

1 Introduction

1.1 Background

Tidal Electric Limited (TEL) has proposed the construction of a "tidal lagoon" in Swansea Bay. A description of the TEL single lagoon proposal is summarised in Appendix 1.

Supported by work by WS Atkins (WSA) and Montgomery Watson Harza (MWH), TEL[2] estimate that the lagoon could be constructed at a cost of £81.5M[3] and generate power at a cost of ~3.5p/kWh.

If this cost were achieved, the tidal lagoon, which would use standard engineering principles, and existing mature technology, would be very economically attractive within the current market for renewable energy power created by the Renewables Obligation. It would be competitive with onshore wind, and substantially cheaper than offshore wind.

The Department of Trade and Industry (DTI) and the Welsh Development Agency (WDA) have both, over a number of years and independently of each other, held discussions with TEL regarding the economics for the proposed lagoon.

These discussions led the DTI and WDA separately commissioning consultants to independently evaluate the economics for the lagoon. TEL provided details of their Swansea Bay proposal and related technical reports in confidence to the DTI and the WDA. The Reviewers, in turn, reported in confidence to the DTI and WDA. Both consultants agreed that the generation costs of the proposed tidal lagoon would be substantially higher than assessed by WSA and MWH.

In June 2005, the Government agreed to a House of Lords Science and Technology Committee request that they [the Government] should "*…. either to publish the report they have commissioned on tidal lagoons, or a summary of that report, with a view to promoting greater public debate on the advantages and disadvantages of such schemes.*[4]*…...*'

The DTI and WDA, through AEA Technology's Future Energy Solutions (FES) group, therefore contracted the same two independent consultants to produce this single report that synthesised and summarised their results, focussing on areas of the analysis that were most significant in giving such a different cost of energy to that determined by TEL.

The consultants both have many years of practical experience in large scale tidal, hydropower and commercial infrastructure projects, which they have drawn upon to

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[2] Where reference is made to TEL, this may include the results of work by WSA and MWH offered in support of the scheme by TEL.

[3] An earlier report undertaken in 2002 by AEA Technology, although heavily qualified, had indicated a construction cost of just under £41M.

[4] House of Lords Science and Technology Committee Fourth Report 2003-04, *Renewable Energy: Practicalities* www.publications.parliament.uk/pa/ld200304/ldselect/ldsctech/126/126.pdf

[4] Government Response page 20 67-69 www.parliament.uk/documents/upload/GovtRespRenewablesRevised.pdf

inform their assessments and to provide comparative results for key engineering criteria. Comparisons refer in large part to the results of previous detailed studies of tidal power schemes.

These studies include the Severn Barrage[5], and barrages on the Mersey [6], Wyre [7], Conwy [8] and Duddon [9] estuaries ranging in size from 700MW_e down to 33MW_e capacity. Relevantly, an earlier Severn Barrage study[10] also evaluated tidal lagoon-type schemes.

The experience of the following other schemes have also been into consideration:

- The 240MW_e La Rance barrage in France, operational since the mid-1960s,
- The construction of a trial impoundment built offshore in the Wash in 1975 [11] as a potential precursor to large offshore water storage reservoirs, and
- The recently constructed Cardiff Bay barrage.

1.2 Basis of Review

The Reviewers have sought to focus on the key factors that affect capital cost, energy output and the resulting unit cost of energy generation highlighting where there were significant differences between their analysis and those of TEL.

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[5] THE SEVERN TIDAL POWER GROUP for Den: ‘Severn Barrage Project, Detailed Report Vol. IIIA: Civil Engineering, Including Site Investigations’. ETSU TID 4060-P3A. 1989

[6] MERSEY BARRAGE COMPANY for DTI: ‘Tidal Power from the River Mersey, a Feasibility Study: Stage III and IIIA report’. ETSU T/03/00140/REP.1993.

[7] TH TECHNOLOGY Ltd for Lancashire County Council, DEN et al: ‘River Wyre – Preliminary Feasibility Study – Tidal Energy Barrage & Road Crossing, Final Report’. 1991

[8] TH TECHNOLOGY Ltd for DEN: ‘Conwy Estuary Feasibility Study of Tidal Power’. ETSU TID 4075. 1990.

[9] SIR ROBERT MCALPINE Ltd & BALFOUR BEATTY PROJECTS & ENGINEERING Ltd for DTI: ‘Duddon Estuary Tidal Energy Barrage: Preliminary Feasibility Study’. ETSU T/06/00144/REP. 1994.

[10] SEVERN BARRAGE COMMITTEE: ‘Tidal Power from the Severn Estuary (Vol. 2)’. HMSO Energy Paper No. 46. 1981.

[11] BINNIE & PARTNERS for Central Water Planning Unit of DoE: ‘The Wash Water Storage Scheme: Feasibility Study: Vol. 10: Trial Banks’. 1976.

The following areas were reviewed:

- The engineering design of the embankment forming the impoundment,
    - the steepness of the sloping faces for stability,
    - the design wave height,
    - the maximum water level for design,
    - the height of the water retaining 'core',
    - the size and thickness of wave armouring,
    - the height of the impoundment and its crest width,
    - the factors of safety against failure,
    - the assumed degree of settlement,
- The resulting cost of the impoundment structure,
- The design of the powerhouse and its inlet structures.
- The all-in unit cost of reinforced concrete for the powerhouse
- The predicted average annual energy output.
- The cost and timescale for construction,
- The additional costs for a fully scoped scheme,
- The project risks and cost contingency,
- The implications of decommissioning,
- The cost and timescale of pre-consent works,
- The resulting discounted unit costs of energy generated (at 15%, 10% and 8% discount rates).

2 Design of embankment/impoundment structure

The dimensions of the proposed embankment/impoundment structure and the material for its construction would be governed by the site and condition of the seabed, tidal range and wave height in Swansea Bay, the lifetime required, the balance required between construction cost and its maintenance cost, the requirements for safe access for repairs and maintenance, and the area of the lagoon necessary to generate the power.

The Reviewers point to the key differences between the TEL and their own assessment which is based upon standard engineering practice for this type of structure.

2.1 Settlement of the impoundment/embankment

There are no specific geotechnical data available for the proposed site. TEL's design assumptions are based upon inferences drawn from a number of geotechnical sources around the site and are therefore subject to a significant degree of uncertainty.

Unconsolidated sediments found on shore, and during dredging of the port approach channels reveal that the seabed deposits in this area of Swansea Bay comprise a variety of sediment types including soft clays, peat, silts and sands, which can be expected to vary considerably over short distances[12].

TEL's geotechnical advisors concluded that settlement (consolidation of the seabed due to compression of sediments) could range from 0.3m to 2.3m over the route of the proposed embankment.

In costing the design, TEL has assumed a settlement of 0.3m which is the lowest and most optimistic value.

TEL concluded that if there were settlement of 1m, this would increase construction costs by ~10% due to the extra material that would be required to ensure that the final height of the embankment crest is at the desired level.

In the Reviewers' evaluation of the cost of constructing the embankment, they have allowed a 5% increase in cost due to settlement.

It is possible that a detailed geotechnical survey may enable the route of the embankment to be adjusted to minimise settlement, but this would either increase construction costs (longer embankment) while also increasing energy output somewhat, or reduce energy generated (smaller area of enclosure).

In any event, whatever engineering solution is adopted to counter high settlement there would be a high on-cost. This is a foreseeable risk for which a contingency allowance would be appropriate. TEL has made no such allowance.

A 9km embankment and a piled 8,000m^2 power station structure will require an extensive geotechnical investigation to provide a robust basis for civil engineering

[12] ATKINS: Preliminary Report on Rapid Geotechnical Desk Study, 19 December 2003.

design. For structures of this size, a geophysical survey correlated by marine boreholes is likely to cost around £1million. This cost would have to be incurred before consent was secured and therefore would be 'at risk'.

2.2 Crest height of impoundment/embankment

Extensive tidal range data are available for Swansea Bay[13].

Table 2.1 Tidal range data for Swansea Bay

	Above Chart Datum (Lowest Astronomical Tide)	Above Ordnance Datum (Newlyn)
Mean High Water Springs (MHWS)	9.5m	4.5m
Mean High Water Neaps	7.2m	2.2m
Mean Low Water Neaps	3.1m	-1.9m
Mean Low Water Springs (MLWS)	1.0m	-4.0m

This gives a mean spring tide range of 8.5m and a mean neap tide range of 4.1m.

The highest astronomical tide for the site is +10.4m above Chart Datum (CD)[14].

Water levels could exceed these levels in periods of storms, causing storm surges, and as a result of possible climate change. Modelling of sea levels by HR Wallingford and Proudman Oceanographic Laboratory [16] has shown that the predicted 100-year extreme water level for the site is +10.6m CD for present conditions, and +11.1m CD allowing for possible future rises in sea-level over the next 75 years.

The design of the embankment has a relatively impermeable core, protected by layers of rock armour increasing in particle size from the innermost layer outwards.

TEL proposes an embankment crest set at +10mCD. This is only 0.5m above Mean High Water Spring Tides. For the 4te rock armour size proposed, the water retaining core would therefore have to be set at around +7m CD.

The crest level would therefore be below the present highest astronomical tides (+10.4m CD) and extreme water levels due to surge tides, which could exceed +10.5m CD in rare events. During periods of high water and relatively frequent sea states, waves would break over the crest at this level. In addition, there will be significant flows through the rock armour layers above the inner core whenever the tide level exceeds +7m CD, which is below almost all high tide levels, i.e. the core would be overtopped every day.

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[13] ABPMer: Environmental Inception Study for a Proposed Tidal Impoundment Scheme, Swansea Bay.

[14] Chart datum is approximately the lowest astronomical tide level.

[16] HR WALLINGFORD, SR 590, 2002.

TEL accepts that the embankment crest will be over-topped. By its own analysis this would occur once every four months at present, rising to possibly as many as 40 times per year in the long term.

The Reviewers consider that the design of the safety critical embankment should minimise overtopping and that the height of the core should be high enough for it to retain water at all states of the tide.

There are three important reasons for this.

1. Erosion of the inner face of the embankment would be greater if the embankment were overtopped, unless larger rock armour sizes were used.
2. Whereas overtopping may not be of particular concern for a breakwater, flows over or through a water retaining embankment should be minimised. The top of the inner core therefore, should be at least at +10.4m CD, with suitable rock armour protection above,
3. For safety reasons the crest should be at a safe height to protect the public and maintenance operatives.

The Reviewers have therefore assumed in their evaluation a **minimum** acceptable embankment crest height of 13m CD. This level is determined from the height of the highest astronomical tide (+10.4 CD) plus an additional 2.5m for protection against excessive overtopping by waves.

There is a strong possibility that, on more detailed consideration, the embankment would have to be set at a higher level and this should be reflected in a cost contingency allowance.

2.3 Crest width

TEL assume a crest width of 3m.

For the crest rock to be stable against wave attack, the CIRIA/CUR manual[15] recommends a minimum size of crest width of at least 3xD_{50} of the armour stone. (D_{50} is defined as the median sieve size). This is about 5m for the size of stone assessed by the Reviewers as necessary (see below).

This minimum crest width also allows for safe access for maintenance and repairs and for a practical inner core top width of around 3m rather than the ‘pointed’ top in the TEL design.

2.4 Stability of embankment slopes

The slopes to the faces of the embankment require carefully evaluated to ensure that the structure remains stable both during and after construction and in the long term. Embankments built on soft, unconsolidated sediments will compact the underlying strata. Consequently, the design criteria of the embankment must consider slope

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[15] CONSTRUCTION INDUSTRY RESEARCH & INFORMATION CENTRE AND CENTRE FOR CIVIL ENGINEERING CONSTRUCTION & CODES: Manual of the use of Rock in Coastal & Shoreline Engineering. CIRIA (London) Special Publication 83; CUR (Gouda) Report 154. 1991.

stability immediately after construction before the foundation materials have gained strength and then again once the underlying sediments have compacted.

For the purpose of feasibility assessment two conditions are normally assessed as described in Appendix 2. It is possible that other construction or operational conditions may be identified during detailed scoping of the scheme that would present a more safety critical condition necessitating shallower slopes. The analyses are then viewed with respect to Factors of Safety (FoS) selected to allow for the natural unpredictability of soil properties and other construction uncertainties once detailed geotechnical investigations have been undertaken.

TEL's embankment design proposal has a slope of 1V:2.5H for the seaward face, and 1V:1.5H (34^o) for the internal (basin) face of the embankment and for the seaward face where suitably sheltered.

The TEL proposal includes the results of stability analyses. The results for the 1V:1.5H slope show a lowest Factor of Safety (FoS) of 1.0 for the long-term case.

For a water retaining embankment the normal **minimum** acceptable FoS for long-term conditions is 1.5[16], and for end-of-construction conditions 1.3 to 1.5.

An analysis carried for this Review [17] considered the ground conditions at the end of construction. The results for a 1V:2.5H slope are summarised on Figure A2.1 of Appendix 2 and show a minimum FOS of 0.912, with the failure surface going some depth into the seabed.

The FoS conditions for the TEL embankment profiles are inadequate for this structure.

The embankment could be strengthened by flattening the slopes, dredging to provide a suitable foundation, or including a strong geotextile as reinforcement of the foundation and/or fill.

Adding 1000kN/m tensile capacity in the base of the embankment, however, only raises the factor of safety for a 1V:2H slope from 0.87 to 1.13 and is still considered by the Reviewers to be inadequate. In addition, placing geotextiles in exposed marine conditions with strong tidal currents on the scale intended is difficult.

Whatever means are adopted to strengthen the embankment to provide adequate factors of safety would increase the cost of the embankment.

For this Review the cost of the embankment has been based upon **minimum** slopes of 1V:2.5H for both internal and external faces of the structure. However, the Reviewers consider that it may be expected that flatter slopes would be required on further analysis once detailed geotechnical data has been obtained. This should be reflected in a contingency allowance.

For comparison, the equivalent slopes for the embankments for the Severn barrage and the Duddon barrage were 1V:4H or flatter.

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[16] An engineering guide to the stability of embankment dams in the United Kingdom, BRE, DETR 2nd edition, 1999.

[17] Dr H J Walbanke; personal communication.

The results of this analysis show that building an embankment on potentially very soft foundations would not be easy and could not be contemplated without a detailed geotechnical investigation to verify foundation conditions.

2.5 Wave height and rock armour size

The rock armour chosen should be able to withstand, with repairable damage but without failure, the impact of the maximum wave that could occur during the life of the scheme. The choice of wave height that the embankment has to withstand greatly affects the size and cost of armour stone required.

The Reviewers' evaluation is based on the probability of 1 in 100 for such an event in any single year, the so-called 100-year storm.

Based on studies for the Swansea Bay Shoreline Management Plan[18], ABPmer suggest using a mean of the wave heights derived for Mumbles Head +2m CD contour and Port Talbot +5m CD contour. This value is 5.73m for a 1:100 year storm.

The Reviewers have therefore chosen a design wave height of 5m for the seaward face of the embankment as an intermediate value between TEL's figure of 4m and ABPmer's figure of 5.73m. This is a prudent assumption for pre-feasibility assessment before a site specific wave survey has been undertaken.

The TEL design and cost estimate are based upon a 4m design wave height and a wave period of 10s. They then propose a primary rock armour weight of 4te for the seaward-facing perimeter derived from the Hudson formula[19].

Much further work has been carried out in determining rock armour size since the Hudson formula was developed and a standard reference at present is the CIRIA/CUR Report 154[20]. The overall design process is complex and Figure A2.2 Appendix 2 illustrates the relationship between rock armour weight, wave height, wave period and damage level.

Where the design wave period is assumed to be 10s, Report 154 states that the significant period can range between 11.3s and 13.3s. The resulting extra wave energy requires larger rock than predicted by the Hudson formula.

The Reviewers have therefore assumed a mean (M_{50}) rock armour weight of 12te in their analysis. This is an intermediate value between the lowest assessed for a 10s wave period, and the highest for a 12s wave period. The rock armour layer thickness, normally twice the median rock size[19], will increase from about 2.3m for 4te rock to 3.3m for 12te rock.

As the height of the core is set for hydraulic reasons (as previously explained in Section 2.2), larger rock armour also increases the embankment crest height and cross sectional area. This results in a significant increase in the quantity of rock

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[18] Swansea Bay Shoreline Management Plan

[19] Shore Protection Manual, 1984.

[20] CONSTRUCTION INDUSTRY RESEARCH & INFORMATION CENTRE AND CENTRE FOR CIVIL ENGINEERING CONSTRUCTION & CODES: Manual of the use of Rock in Coastal & Shoreline Engineering. CIRIA (London) Special Publication 83; CUR (Gouda) Report 154. 1991.

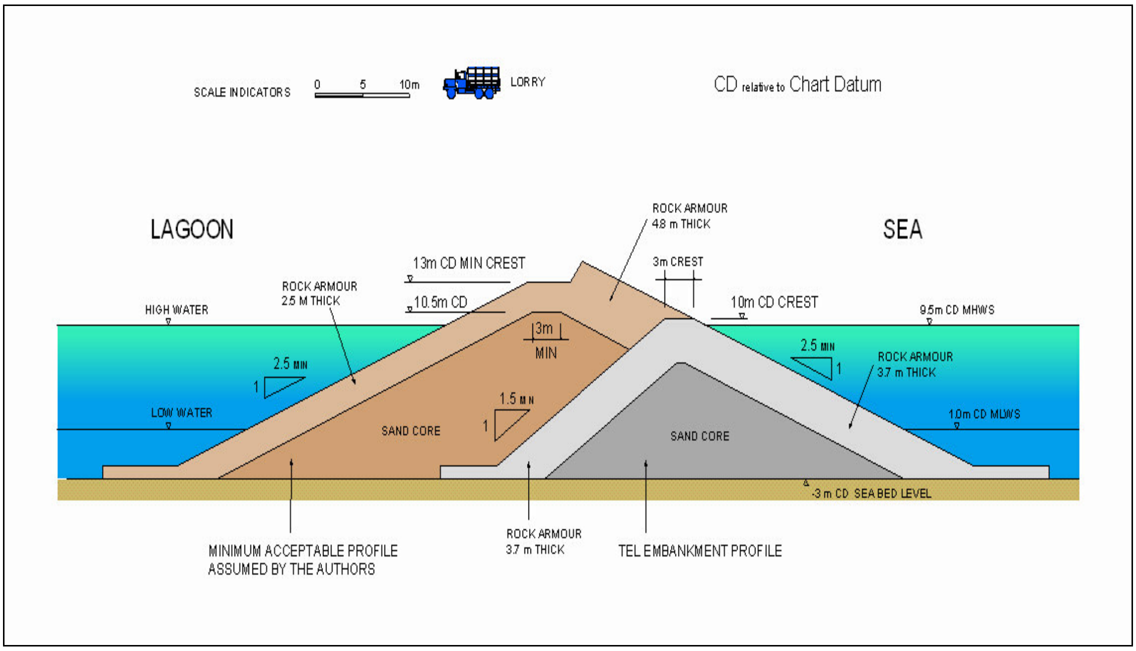
required and a higher unit cost for the larger rock due to the increased difficulty of production and handling.

This additional unit cost of larger rock armour has not been assessed by the Reviewers. It is reasonable to assume a contingency allowance to cover this additional cost.

2.6 Comparison of embankment profiles

Figure 2.1 illustrates the difference in cross-sectional profile between the TEL embankment and the **minimum** profile likely to be acceptable for a seaward embankment at a sea-bed level of –3mCD.

Figure 2.1 Comparison of embankment profiles – TEL and Review



2.7 Capital cost of embankment/impoundment

For the Reviewers' estimate of the cost of the embankment, they prepared two cross sections including the points raised above. One for the seaward-facing embankment founded at –3.0m CD representing about 50% of the circumference and a second for the landward-facing embankment founded at 0m CD.

The resulting quantities of materials are shown in Table 2.2 below. The unit costs the Reviewers have used for each material are the same as those used by TEL except for a new item, "quarry-run rock". This additional item is considered necessary in the Reviewers' design to provide temporary protection to the core material during construction. The unit cost for this item has been taken as half that of armour under-layers, to reflect its relatively easier production.

Table 2.2 Embankment quantities and costs

Seaward Section (foundation at –3mCD)					Landward Section (foundation at 0mCD)				Overall total cost (£M)
Item	Quantity (m^3/m)	Total quantity (m^3x1000)	Unit cost (£/m^3)	Cost (£M)	Quantity (m^3/m)	Total quantity (m^3x1000)	Unit cost (£/m^3)	Cost (£M)	
Sand fill	290	1305	5.5	7.18	163	734	5.5	4.03	11.21
Quarry run	220	990	15	14.85	155	698	15	10.47	25.32
Armour underlayers	139	625	30	18.75	82.5	371	30	11.13	29.88
Primary armour	127	572	35	20.02	0	0	35	0	20.02
Secondary armour	66	297	35	10.40	110	495	35	17.33	27.73
Totals				71.20				42.96	114.16

Thus, the cost of the materials for the embankment would be about £114M compared to the £48.5M estimated by TEL.

The quantities in Table 2.2 and in TEL's estimate do not include allowances for the following items:-

- Contractor's preliminary costs for mobilisation, overheads, etc. (say 15%),
- Design risk contingency (cl. 2.1, 2.4 and 2.5) (say 5%) for:
  - Extra fill quantities due to settlement of the seabed,
  - The use of flatter slopes, geotextiles or other method to strengthen the structure,
  - Weaker foundations found,
  - Larger rock armour material cost,
- Construction risk contingencies, from storm damage etc. (10%)

Including 30% on-costs raises the total from £114M to around £150M.

3 Power house design and cost

In this Section the Reviewers consider the design and cost of the power house focussing on:-

- the draught tube section of the structure for bi-directional flow,
- the unit 'all-in' cost of reinforced concrete, and
- the cost of the power generation equipment.

The TEL proposal provides little detail of how the power station structure would be connected to the embankment. This is a critical element of the design requiring additional caisson units or other works. This is an additional cost that does not appear to have been addressed in the TEL scheme.

The Reviewers also consider that the TEL design does not provide sufficiently robust concrete sections to withstand loads during float-out and when dewatered. There is a significant risk therefore that the concrete quantities assumed would have to increase following detailed design. This risk is assumed to be the 10% contingency allowance in the Reviewers' estimate.

3.1 Design of structure for bi-directional flow

The structure must provide suitable hydraulic conditions for bi-directional generation.

The draught tube section of the structure is important for slowing down the water leaving the runner and recovering part of the kinetic energy in the flow. This improves the efficiency of the turbine and also helps reduce the destabilising effects of waves.

Previous studies of tidal power barrages have all converged on similar designs for the arrangement of the powerhouse and the dimensions, relative to the size of the turbine runner diameter.

For the UK estuary barrage schemes, the overall length of the water passage varies from 7.38x turbine runner diameter for the Mersey barrage to 8.72x runner diameter for the Duddon barrage. This compares with a 9.1x runner diameter for the proposed Swansea Bay lagoon.

However, Mersey and Duddon were both proposed as uni-directional schemes, generating power only on the outflow of water from these barrages. The Swansea Bay lagoon is proposed as a bi-directional scheme, generating on both the filling and emptying of the lagoon.

At La Rance, the water passage length is 10x runner diameter. The scheme was originally designed for two-way generation. (See Figure 10.1 later).

Thus the Reviewers have based their assessment on a water passage length for the proposed lagoon of 10 times the runner diameter, i.e. an increase of 10% above that used by TEL. This is reflected in their cost estimate.

3.2 Cost of concrete for the power house

In the absence of detailed drawings for the concrete structures, it is not possible to carry out a normal itemised cost estimate.

The Reviewers have therefore based their assessment of cost on 'all-in' unit rate for reinforced concrete, including formwork, reinforcement, finishes, small built-in parts, scaffolding etc.

With the aim of comparing like with like, the all-in unit rates for reinforced concrete have been extracted from published reports for the following barrage schemes and the costs updated to the present time. Using the government's All New Construction Output Price Index [21], costs rose by 47% between 1995 and 2005 or about 4%/year. The costs below are based on a lower annual rate of cost increase of 2% to allow for possible improvements in productivity.

Table 3.1 All-in unit costs of reinforced concrete

Scheme	Base date	All-in concrete cost (£/m^3)	Approx. updated cost (£/m^3)
Conwy	1990	586	788
Duddon	1993	576	730
Severn	1988	440	616

These results show the economies of scale that would arise when moving from the smallest barrage (Conwy) to the largest (Severn). Reinforced concrete for the smaller scheme with fewer caissons is more expensive than for large scheme.

The proposed Swansea Bay lagoon is somewhere in size between Conwy and Duddon, and this suggests that concrete would cost in the region of £750/m^3 for Swansea.

For comparison, within the Carbon Trust's Marine Energy Challenge, the study teams have normalised the unit costs being used when studying concrete structures for wave energy devices. The Arup report[22] on the oscillating water column has the following unit rates.

- Concrete supply and place £79/m^3
- Formwork to base slabs £30/m^2
- Formwork to walls £50/m^2
- Reinforcement, supply and fix £750-800/te in base and walls, £2000/te in roof.

[21] Web site: http.//www.acenet.co.uk/index.

[22] Web site: http://www.thecarbontrust.co.uk/ctmarine2/res/owc1.pdf Appendix C.

Therefore, an approximate basic all-in cost is £330/m^3, assuming concrete averages 0.5m thickness and 1te of reinforcement to 4m^3 of concrete (the Severn Barrage figure is 1te per 5.4m^3; the Duddon figure is 1te per 2.6m^3). The following additional percentages in the Arup report [22] are then applicable to obtain an all-in rate.

- Management and supervision: 20%
- Plant and equipment: 15%
- Craneage: 15%
- Small tools 1.8%
- Indirect labour 10%
- Profit and overheads 15%

Total extras 76.8%

The resultant cost of reinforced concrete is £580/m^3, which is less than but comparable with the figures for tidal barrages above.

Taking all the above into account the Reviewers have used a unit cost of reinforced concrete of £600/m^3 for the Swansea Bay lagoon powerhouse.

For comparison, TEL uses a figure of £100/m^3 for the cost of reinforced concrete. If this cost can be delivered, then the costs of tidal power barrages studied in the UK would be greatly reduced.

3.3 Cost of power house

TEL's estimated cost of the power house and associated items such as installation is £12.7M, of which £6.1M is for the reinforced concrete and £1.15M is a 10% contingency allowance.

With a unit cost of concrete of £600/m^3 and using TEL's estimated volume of concrete for the power house of 61,000m^3, this structure would cost £42M.

The Reviewers' estimate also includes a 10% allowance for the following items discussed above:-

- A 10% increase in the length of the water passage giving say 2% additional cost,
- More robust concrete sections – say 5%,
- Caisson structures to connect the power station to the embankment – say 3%.

The resulting total is £46.2M.

With a further allowance of 10% for normal design and construction contingencies, the overall cost of the Power Station structure is likely to be in the order of £50M.

3.4 Cost of power generation equipment

Hydro projects with bulb turbines of similar diameter and rating to those proposed for Swansea Bay are rare, and so reliance for cost data has to be placed on other proposals for tidal power development. Table 3.2 below summarises the costs of turbines and generators adopted for other tidal power schemes, with costs updated at 2%/year since the studies were undertaken.

Table 3.2 Costs of turbines and generators

Item	Conwy	Duddon	Wyre
Turbines + generators cost (£M)	15.53	49.52	22.50
Installed capacity (MW)	33	100	54.4
No. x diameter of turbines	6 x 4.0m	10 x 5.5m	4 x 6.2m
Cost/kW installed (£)	471	495	414
Base date	1990	1993	1991
Updated cost (£/kW)	646	628	546

These results show that costs per kW installed reduce as the turbine size increases, which is to be expected. For a like-for-like comparison, the Reviewers would suggest a unit cost of about £650/kW for the Swansea turbines and generators.

TEL has used a unit cost of £223/kW, based on budget prices from China. The Reviewers have been unable to validate this figure.

For a 60MW scheme, the cost of the turbines and generators, based on other tidal power studies, is ~£40M, whereas TEL's is £13.4M plus about £0.7M for miscellaneous equipment. However, for the assessment of the cost of energy, the much lower TEL figure has been assumed.

If this figure can be delivered it would greatly reduce the costs of other tidal power schemes.

4 Overall scheme capital cost

This section summarises the Reviewers' assessment of the capital cost of the proposed Swansea Bay lagoon in comparison with the TEL figures.

Table 4.1 Cost comparison

	TEL Cost (£M)	**Review Cost Assessment (£M)**
Capital cost		
Impoundment	48.5	114
- additional costs – Section 2 above	0	23
Powerhouse structure	11.55	42
- additional costs – Section 3 above	1.15	4
Turbine plant & equipment	14.1	14.1*
- additional costs – Sections 9.1,2 & 3 below	0	3
Connection to grid and other costs not assessed	3.7	3.7
Sub-total	**79**	**203.8**
Contingencies allowance 10%	-	20.4
Sub-total		224.2
Other costs		
Consent, detailed design, supervision of construction	2.5	10.1**
Relocation or extension of the Water Utility's long sea outfall.	0	0***
Total cost	**81.5**	**234**

Notes: * TEL's cost estimate. See Section 4.4.

**The Reviewers have based this item on 4.5% of scheme cost. Approximate equivalents are 2.5% for the Duddon barrage, 10.4% for the Conwy barrage and 5.6% for the Mersey barrage.

*** Detailed study would be required of the need to relocate or extend the existing outfall.

5 Operation and Maintenance

TEL has assumed costs of 0.5% per year of the capital cost of the scheme for operation and maintenance (O&M), plus an allowance of £4M for a major overhaul of the M&E equipment every 20 years. These are comparable with assumptions for tidal power barrages studied in the UK. TEL has also allowed for payment of £250k/year for the lease of the seabed from the Crown Estate.

An important consideration for both routine O&M and replacement of large items such as turbines is access to an 'island' structure in shallow coastal waters with a high tidal range. Movement to and from the key landing point on any offshore structure must take account of weather and tidal conditions in order to facilitate safe access of personnel and equipment. Consequently O&M costs may well prove to be higher than for land-connected tidal barrages. The Reviewers also consider that there is a significant likelihood of high in-lagoon dredging maintenance costs.

In their financial analysis however, the Reviewers have used the same percentage allowance for O&M costs as TEL as the annual cost is significantly increased due to a much higher capital cost estimate.

The Crown Estate has advised that they have not yet devised a formula for the commercial rent for wave and tidal projects. The off-shore wind farm rental formula is based on a fixed fee linked to the price of electricity in 2001 multiplied by output. In the absence of any detailed guidance, the Review has taken the £250k/year figure assumed by TEL. It should be noted however, that, as the structure lies substantially within the Swansea Harbour boundary, an additional lease may be payable.

6 Decommissioning

TEL proposes that the impoundment structure should be left in place at the end of its useful life with the removal of the turbine/generator equipment and the concrete power station structure. The embankment therefore would be allowed to become an artificial reef or, if the lagoon progressively silted up, an island.

Any legacy structure would pose a residual hazard. Any breach of the embankment would lead to its rapid disintegration of the structure through tidal and wave action. This has implications for navigation and public safety and the redistribution of materials on the sea bed would have environmental implications, particularly if contaminated by geotextiles, etc.

The Reviewers are concerned that TEL may not fully appreciate the implications of decommissioning in consenting their project and for the cost of compliance. Any consent application will have to be supported by a detailed decommissioning proposal. To leave any part of the structure as a permanent feature would have residual liability to third parties for harm caused by works which are not removed and for the cost to The Crown Estate of removing works in order to avoid that liability.

Thus, in leasing areas of seabed for off-shore engineering projects, the Crown Estate requires developers to submit proposals that would:

> a) detail how the developer would ensure that the cost of complete removal and reinstatement is covered should he fail to complete or later abandon the Works, such as the provision of a performance Bond;
>
> b) provide a detailed and realistic method statement for removal and reinstatement including an assessment of potential environmental impacts.

The cost of decommissioning, removal and reinstatement is likely to be similar to that of construction if not greater. The plant and equipment required would be similar and the care required to remove the embankment material without significant loss would be great. The cost of disposal of this quantity of waste material could be significant.

In terms of the net present cost of decommissioning in 125 years time this end of life cost would be small. Of more significance will be the implication for insuring against complete removal and reinstatement due to a failure to complete, to irreparable structural failure or to financial failure during the life of the project. To secure a bond to cover these eventualities will require evidence of a robust design and may prove costly.

7 Predicted Annual Average Energy Output

In this section, the Reviewers compare TEL's projection of the annual average energy output from the proposed Swansea Bay tidal lagoon with their own and make comparisons for validation with other proposed and actual tidal barrage schemes.

7.1 TEL estimate of annual energy output

The TEL proposal estimates an average annual energy output for the Swansea Bay scheme of 187,000MWh/year.

TEL has not provided details of their power output model and therefore the validity of the Swansea Bay output projection has not been verified.

7.2 The Reviewers' estimate of annual energy output

For comparison therefore, a spreadsheet model was developed for the review to simulate the operation of the scheme through a mean spring tide, a mean tide and a mean neap tide, using turbine performance data from the studies of the Severn barrage.

This model was used to simulate a turbine runner diameter of 3.3m, as for the TEL proposal. However, the Reviewers have made some different operational and efficiency assumptions that affect the calculation of energy generated. These are:-

- TEL assumes a reduced turbine efficiency of 4% when operating in the reverse flow direction TEL[23]. The Review has assumed an efficiency reduction of 15%[24]. The effect of this can be seen in the reduced power output during the flood tide in Figure 7.1 below. This reduces the overall scheme efficiency by 15/2 = 7.5% to compare with 2% by TEL.
- TEL assumes a turbine efficiency of 92% for all heads of 2.74m or more varying linearly down to 80% at 1.52m. Based on actual manufacturer's turbine performance data, the Reviewers' equivalent figures were 89.4 to 93.4% for heads of 3.66m or more, reducing to 72.9% at 1.52m head.

A weir shown at the seaward end of the turbine inlet chambers on the TEL outline design drawing has its crest only 1.5m below Chart Datum. This is high enough to restrict flows and cause a significant loss of head across the turbines when sea levels are low. It has been assumed that this feature would be 'designed out' and therefore this loss has not been included in the Reviewers' model.

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[23] This reduction is due to a set of guide vanes upstream of the turbine runner, which imparts a swirl to the flow as it approaches the runner blades and maximises efficiency. In reverse operation the guide vanes are downstream of the runner. Therefore not only are the runner blades operating inefficiently, but the guide vanes are now counter-productive as they obstruct the flow leaving the turbine.

[24] TEL state the range to be 10-20% (Atkins Consultants Ltd: Feasibility Study for a Tidal Lagoon in Swansea Bay).

Submergence limitations, to avoid the risk of cavitation damage, have also been taken into account. The best output at the design point of 9ft (2.74m) head is about 1.75MW with a flow of 77.9m^3/s and a turbine speed of 111.11 rpm. The rated power of 2.5MW would be reached at a head of 3.66m.

Operation has been simulated for a mean spring tide, a mean tide and a neap tide. This allows the relationship between tidal range and energy output to be established. It is noted that optimum energy output during mean and neap tides is achieved with fewer than 24 turbines operating, a feature noted in the Duddon barrage studies.

The calculated annual average energy output is based upon all the 705 tides in 2003, a year when the total energy would be close to the long-term average. The tidal range will vary by ~8% over an 18.6 year cycle because of cyclical astronomical variations, therefore taking a value close to the long-term average will give the best approximation for any given scheme. 2003 is also the year used by TEL.

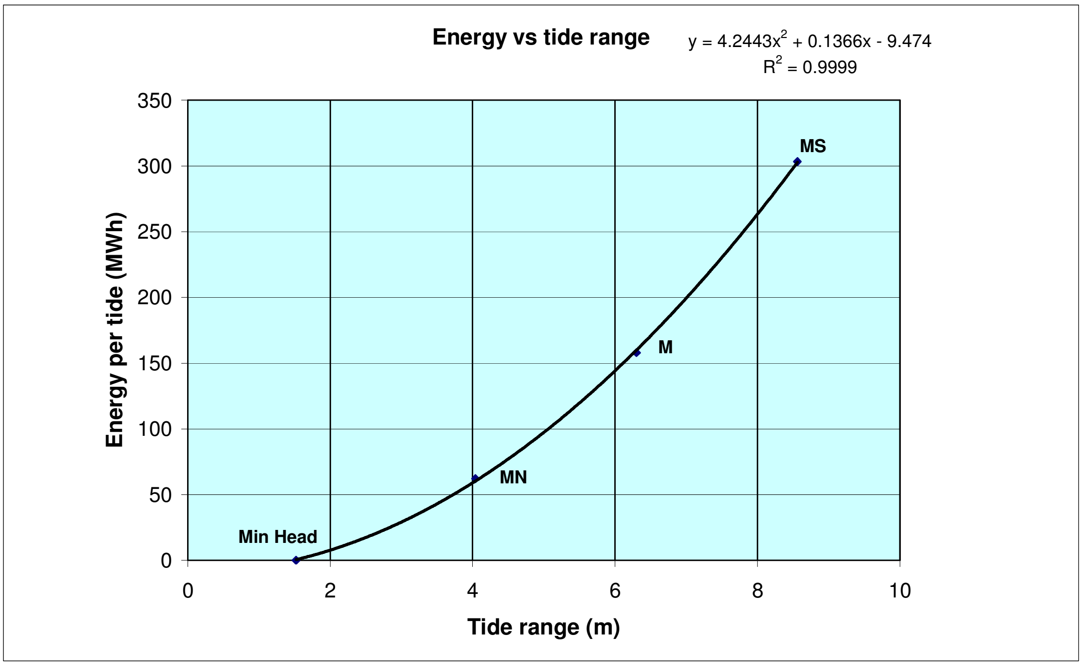
The tidal range for each day has been extracted from a spreadsheet supplied by TEL and allocated to one of 10 ranges in 0.47m steps. This gives 365 tidal ranges, converted into 705 tides as shown in Table 8.1 which shows the number of tides in each range. The calculated energy output for each of the three tidal ranges (spring, mean and neap), plus the output at a tidal range of 1.52m have been used as reference points to calculate the energy output relative to tidal range, expressed as a fitted curve for 2003 (Figure 7.1). The lowest value used represents the minimum operating head for the turbines. The energy output for each tidal range band was then calculated from the curve and multiplied by the number of times that tidal condition occurred during the year (see Table 7.1). The total energy for the year is the sum of total energy output from each tidal range. This gives 130,500MWh. The Reviewers have reduced this value by 5% to take account of water friction losses and turbine availability. This results in a rounded overall estimate of annual energy output of 124,000MWh.

Table 7.1: Summary of energy output from Swansea Bay lagoon

Mean of tide range	Number of tides	Energy (MWh)	Total energy (MWh/yr)
4.23	89	67.0	5,967
4.70	71	84.9	6,030
5.17	44	104.7	4,606
5.63	48	125.8	6,040
6.10	41	149.3	6,121
6.57	56	174.6	9,779
7.04	66	201.8	13,322
7.50	56	230.3	12,896
7.97	93	261.2	24,293
8.44	141	294.0	41,456
Total	705		
		Total gross	**130,510**
		95% Total	**123,984***

*Total taking account of friction losses and turbine availability

Figure 7.1: Energy output per tide v tidal range

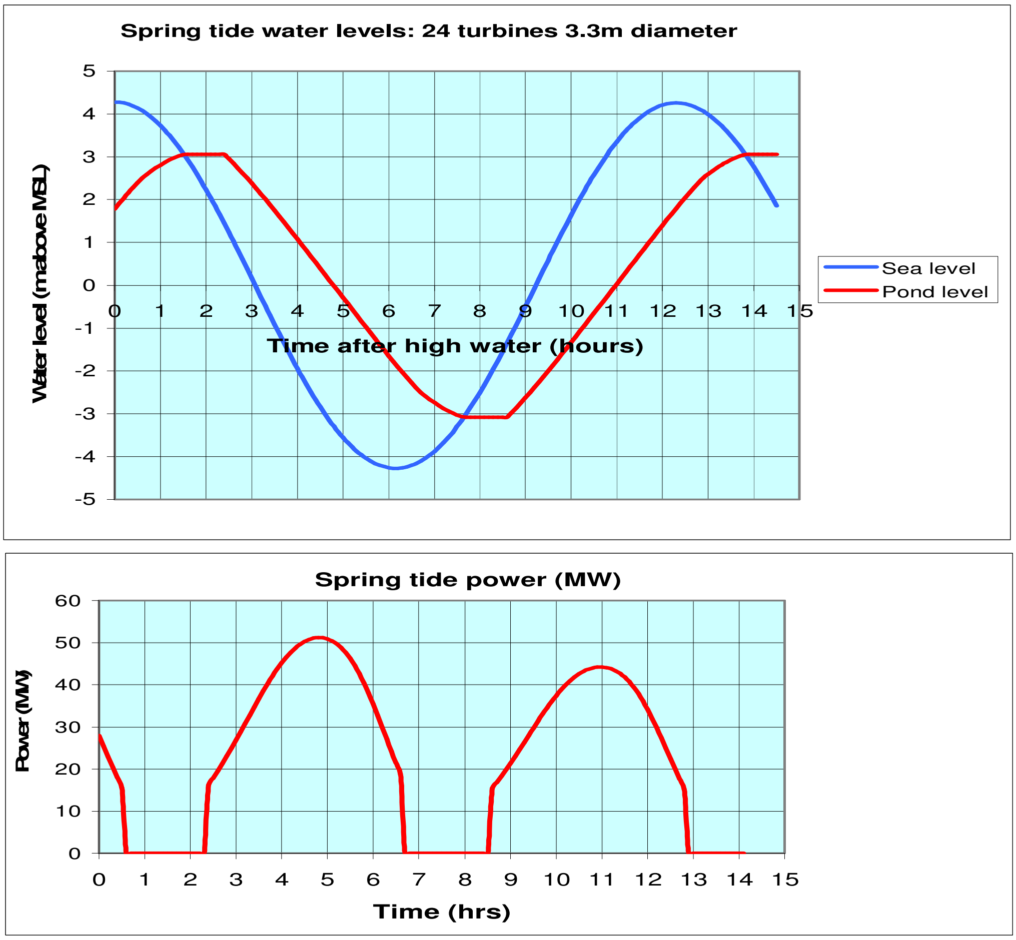


MS = Mean Spring tidal range, M = Mean tidal range, MN = Mean Neap tidal range

Min Head = Minimum operating head for turbines i.e. 1.52m plotted for purposes of generating a fitted curve.

Figure 7.2 shows typical operation during a mean spring tide (8.56m). The total energy generated during this tide would be about 303MWh. The figure clearly shows how energy output fluctuates through a complete tidal cycle. The energy generated is represented by the area defined by the lower graph and can be determined from the reference point for a mean spring tide on Figure 7.1.

Figure 7.2 Operation during mean spring tide



7.3 Comparison of estimated power output with other barrage schemes

The load factor is the overall average output of the turbine sets, expressed as a percentage of the installed power. An annual output of 124,000MWh represents a load factor of 24% for the Swansea Bay scheme. Unlike other tidal power schemes, the Swansea Bay scheme does not include gate-controlled openings, or 'sluices', to help maximise the water available for power generation. If say 200m^2 of sluice area were added, the total energy output would increase by about 10% to give a load factor of about 26.5%.

La Rance barrage when operating in two-way mode had a load factor of 26%. It has since been fitted with improved turbine blades and is operated mainly as a one-way (ebb generation) scheme with reverse pumping to raise water levels in the basin at the end of the flood tide. The resulting energy output has increased from 540 to about 600GWh/year, giving a load factor of 28.5% [25]. The UK barrages that have been studied all have load factors in the range 21-26%. All the tidal energy schemes investigated in the UK have concluded that ebb-generation, supported by flood pumping on some tides, is the preferred generation option as two-way generation is considered to be uneconomic.

The load factor *per se* is not a design aspect – it follows from the optimisation of the number of turbines and generators in terms of the resulting unit cost of energy. However, the load factor provides a quick check of overall performance. For comparison, based on an energy output of 187,000 MWh/year, TEL's load factor is 35.6%.

[25] http://www.edf.fr/html/en/decouvertes/voyage/usine/estuaire/usine_estuaire_d.html

8 Cost of Energy

In this section the Reviewers present their assessment of the cost of energy for the proposed tidal lagoon. In this context, cost of energy is taken to mean the price at which the power would have to be sold to give a Net Present Value of zero at each of the following discount rates, 8%, 10% and 15%, as is common practice.

Two analyses are presented to compare the costs, performance and assumptions from the TEL proposal with those determined by this Review.

8.1 Assumptions and data for discounted cash flow analyses

The table below shows the comparative data and assumptions. Bold text is used to highlight the differences between the two analyses.

Table 8.1 Comparison of Capital, Operation and Maintenance (O&M) costs and annual energy output.

	TEL	This Review
Capital construction cost, including design, consent, procurement and management	£81.5M	**£234M**
Phasing of costs prior to commissioning	3 years – 1 year for planning etc and two years for construction	**5 years – 3 years for planning etc and 2 years for construction**
Scheme lifetime	120 years	120 years
Average annual energy output	**187,000MW/h**	**124,000MW/h**
Crown Estate lease	£250k/year	£250k/year
M&E major overhauls	£4M every 20 years	£4M every 20 years
O&M costs	0.5% of construction cost per year. This is equivalent to **£0.41M** per year.	0.5% of construction cost per year. This is equivalent to **£1.15M** per year.
Decommissioning cost	£0	**£200M+**

8.2 Cost of energy results

Table 8.2 below gives the results of the calculations of the cost of energy.

Table 8.2 Costs of energy for proposed Swansea Bay tidal lagoon (p/kWh)

	Using TEL data and assumptions (p/kWh)	Using the Reviewers' data and assumptions (p/kWh)
@ 8% discount rate	4.03	17.2
@ 10% discount rate	4.98	21.4
@ 15% discount	7.45	32.5

8.3 Comparisons with other schemes

Similar calculations have been carried out for the Conwy, Wyre and Duddon barrages. The results are as follows:

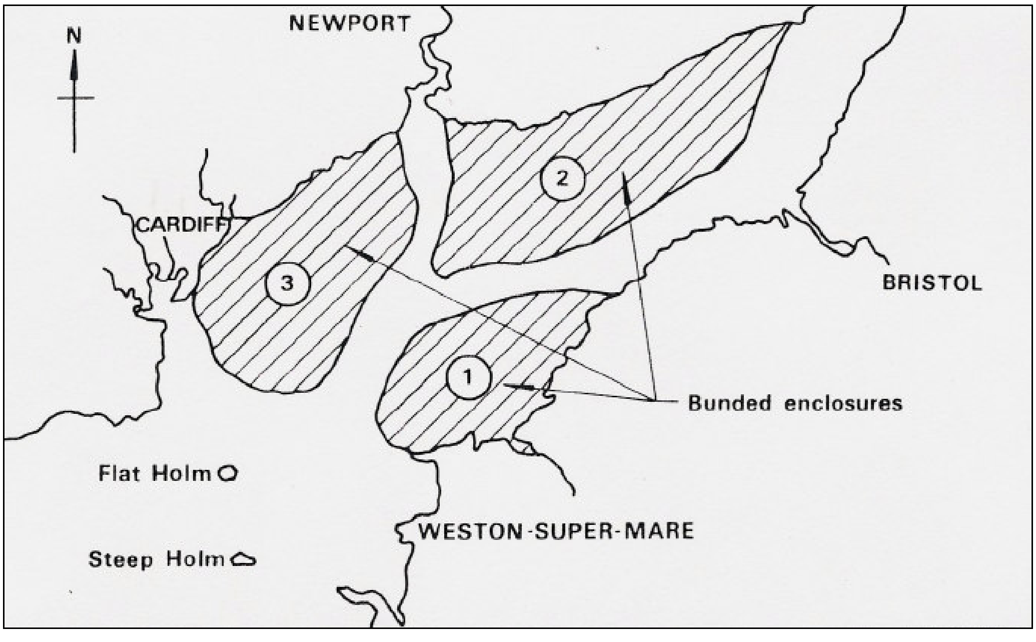
Table 8.3 Comparison of Capital Costs, annual energy output and unit cost of generation for small scale tidal energy schemes in UK and Swansea Bay scheme.

	Conwy	Wyre	Duddon	Swansea Bay (the Reviewers' assessment)
Cost (£M) (2005)	72	119	327	230
Annual energy (GWh)	60	131	220	124
@ 8% discount rate	11.5	9.1	14.9	17.2
@ 10% discount rate	14.1	11.3	18.7	21.4
@ 15% discount	21.0	17.3	28.9	32.5

Of the three barrages above, the Duddon is by far the longest, with about 4.5km of embankments. This is reflected in its high unit costs of energy.

During the studies of the Severn barrage reported in EP46 (Ref. 10), two proposals for tidal power lagoons located on the sides of the estuary were submitted and evaluated on a like-for-like basis to compare with the Severn barrage (Figure 8.1 shows one such proposal for multiple lagoons). Both had their powerhouses in relatively deep water to one side of the main channel, with their enclosing embankments connected to the shore in order to reduce their overall length and cost compared with a fully enclosed offshore 'lagoon'. Studies showed that the unit cost of energy would be about 40% higher than that from the Severn barrage, mainly on account of the cost of the embankments.

Figure 8.1 Tidal lagoons evaluated as part of the Severn Barrage Programme



For further comparison, the Cardiff Bay barrage, completed in 1999, cost £220M. The total barrage length is 1.1km compared to over 9km for the Swansea Bay scheme and contains similar concrete structures. Whilst having to contend with a higher tidal range, the Cardiff Bay barrage had the benefit of land access for construction and a more sheltered aspect.

9 Other factors to be considered

Other factors may be foreseen to have an adverse influence the economics of the proposed tidal lagoon. Should the scheme proceed, these would have to be included in a detailed project risk assessment. They are briefly described below with an indicative contingency allowance shown.

9.1 Switchgear and transmission

The proposed 11kV/132kV switchgear and transmission system would be near standard practice for this type of installation. Duplicate cables to the 132kV substation on shore would reduce the risk of interruption due to cable damage.

Other tidal barrage studies have included in their cost estimates for a standby generator and associated switchgear in case of blackout.

These costs do not appear to have been allowed for by TEL and a contingency allowance would be appropriate at this pre-feasibility stage.

9.2 Mechanical and Electrical plant layout

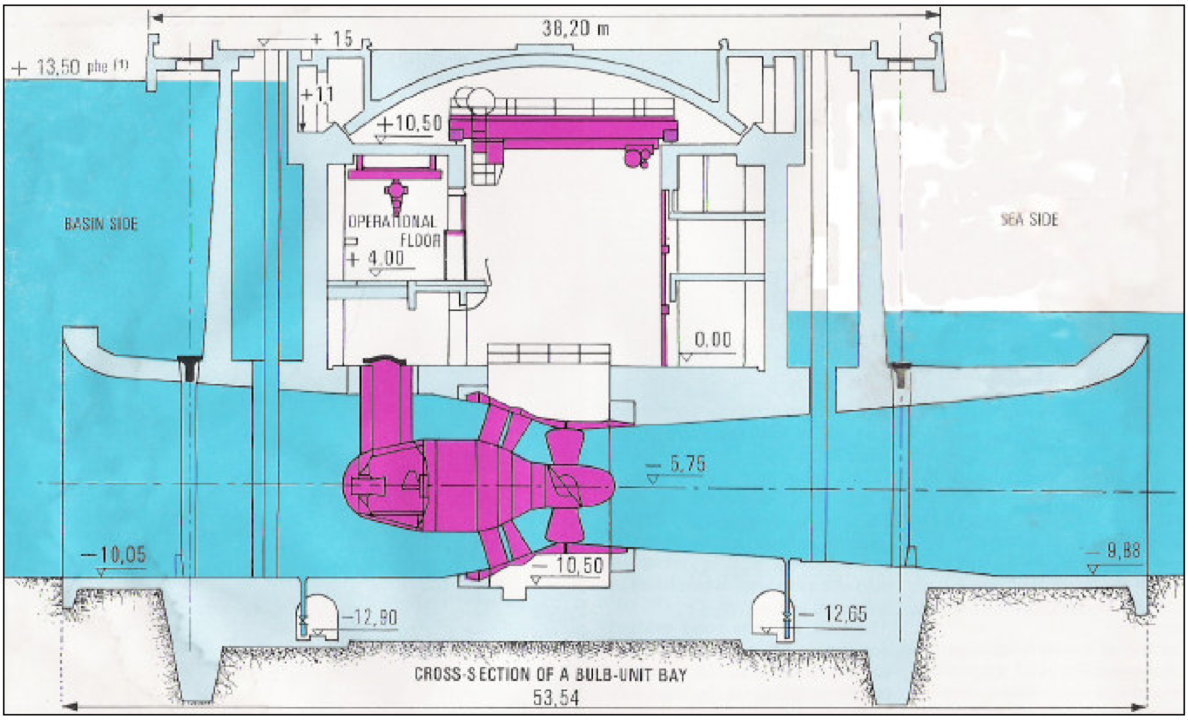
The configuration of the generation plant proposed by TEL would consist of 24 turbine sets, each of about 3.3m runner diameter driving a 2.5MW generator. The turbines would be designed to generate in each direction of flow (as at La Rance barrage). The turbines would be of Kaplan type – with 4-bladed runners. These turbines would have adjustable blades, and a set of adjustable guide vanes upstream of each turbine. The ability to vary the pitch of each turbine blade maximises its efficiency, as the head of water varies throughout each tidal cycle.

Each generator could be housed within a pressurised steel bulb or within a concrete pit forming part of the caisson structure. Emergency closure gates, and isolation stoplogs, would normally be required both upstream and downstream of each turbine to allow the water passages to be dewatered for safe maintenance, as at La Rance (Figure 9.1). TEL has allowed costs for gate valves on the seaward side and stoplogs on the pool side, but not both.

The TEL proposal makes no provision for trash screens or fish screens. For two way generation, these would be required on both sides of the turbine.

A contingency allowance would be appropriate at this pre-feasibility stage to cover these various omissions.

Figure 9.1 Cross section of powerhouse at La Rance



9.3 Caisson installation

The world's largest tidal power plant, La Rance, was built on rock, in the dry, behind temporary cofferdams. All the barrages proposed for the UK would be built by floating the various caissons into position. Only one scheme, proposed for the Duddon estuary, would have a significant length of embankment although the power house would be floated in as a caisson.

The same procedure is proposed for the power house section of the Swansea Bay scheme, except that each caisson would be floated out from the construction yard on a pontoon due to the shallow water location. This would then be sunk at site to allow the caisson to be floated off into its final position. If the draft for similar caissons as the Conwy barrage is used as a comparator, the pontoon would have a calculated lifting capacity of about 10,000te.

There is no allowance for the cost of this purpose built pontoon in the TEL estimates. An allowance of £1M is made in the Review estimate for this item.

A number of the features in the TEL outline design would create difficulties for this construction proposal. The upstream and downstream inlet structures proposed could not be floated into position without large and complex temporary blanking-off walls where they join with the turbine caissons and the asymmetrical arrangement proposed will require flotation tanks and/or ballast to make them float horizontally. It has been assumed by the Review that these features would be designed out in a more refined design proposal.

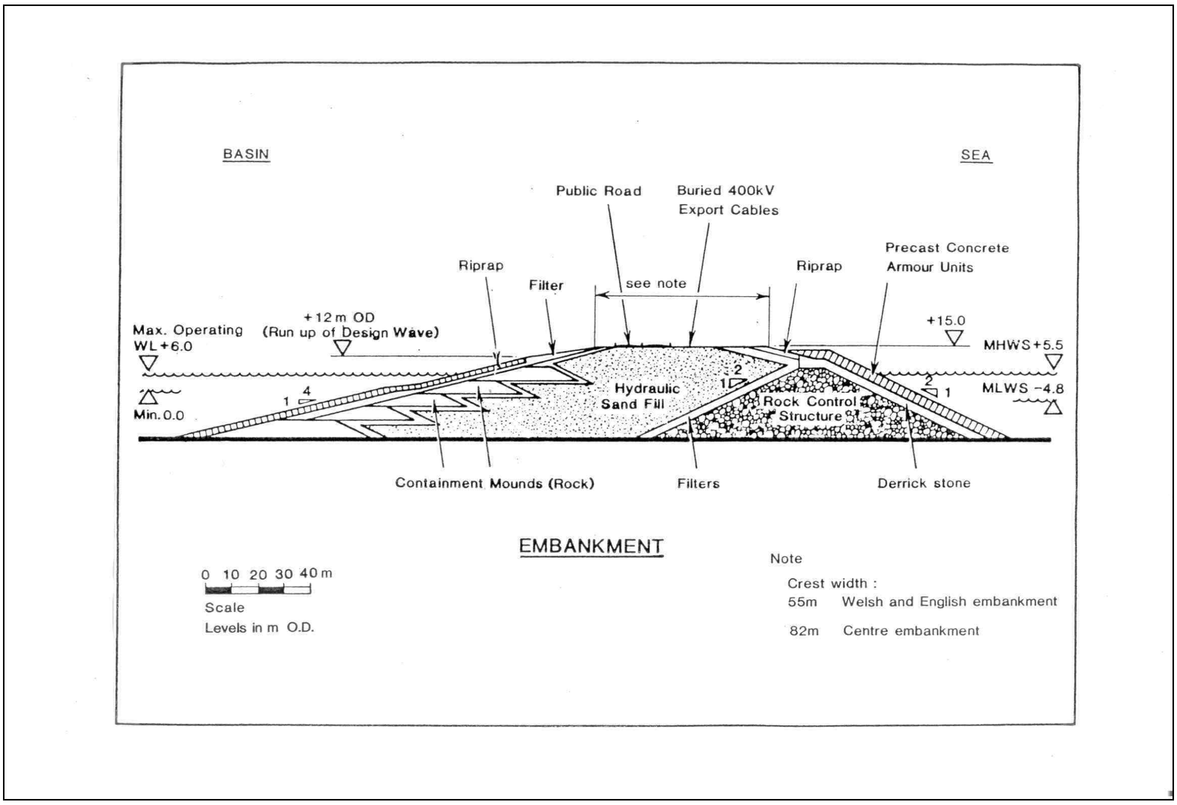
9.4 Construction methods and sequencing

The proposed scheme would be located in an area subject to a large tidal range and substantial waves. Waves with a significant height of 1m can be expected at least weekly, even daily. Therefore, the main problem during construction of the embankment will be in preventing damage to the sand core and armour under-layers until the main armour has been placed.

Studies of other tidal power schemes, and experience at the Offshore Trial Bank in the Wash, showed that it is essential to protect the core material against erosion by waves and currents until the armour layers have been placed.

One method, proposed for the Severn barrage and the Duddon barrage, is to provide containment bunds of quarry-run rock, with a wide grading, in stages, forming a 'Christmas tree' cross section. Figure 9.2 illustrates the type of rock protection to the sand core devised for the Severn barrage.

Figure 9.2 Cross section of the embankment for the Severn Barrage.



These bunds are designed to resist only small waves temporarily during the construction period and the layers of rock armour must follow close behind. These bunds and the open face of the advancing embankment will remain at risk of damage during this period. During a two to three year construction period there will be a significant risk of sea conditions that could threaten the structural integrity of the embankment. A robust construction methodology will have to be devised to protect the incomplete structure during these periods causing additional work and significant delays. A suitable risk allowance should be included in the cost estimates.

The inner face of the embankment may also be exposed to a more severe wave climate during construction than after completion, due to longer fetch lengths. This may require the armour size to be increased to suit the temporary conditions.

An overall contingency allowance of 10% has been made in the Review's estimate of construction cost in Section 3 above.

9.5 Project consent and environmental impact assessment

For the Swansea Bay scheme, where a private developer wishes to pursue a commercial development without Government support, the *Environmental Impact Directive*[26] ensures that all consenting authorities will require project specific EIAs addressing both the positive and negative impact of a development.

The developer will typically have to address such fundamental issues as whether the site chosen is the most appropriate, including evaluation of other potential sites, what provision is to be made for removal upon decommissioning and a detailed safety case assessment.

Before an EIA can be commenced the engineering works needs to be well defined. The Reviewers consider that the feasibility engineering work undertaken by TEL so far will be inadequate for this process. TEL's own Environmental Inception Study[27] for the Swansea Bay highlighted the need for a more defined design.

The planning and consenting processes are derived from democratic principles designed to allow all stakeholders to put their case for or against a particular development. The consent process is co-ordinated by the DTI and the Planning process by local Authorities.

For an un-contentious, well defined, well understood scheme consent may be achieved within 9 months from application. Other schemes, more open to contention may take up to 6 years or more if public enquiries are involved and further detailed investigative work is required.

For a scheme of this scale with no precedence to follow, the cost and timescale would be around £5M and, if successful, could take at least three years to get to consent. A public enquiry could add several years to the consenting process and a further £1M or more to the cost with no guarantee of success.

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[26] Directive 85/337/EEC as amended by 97/11/EC.

[27] ABPmer, "Environmental Inception Study for a proposed Tidal Impoundment Scheme, Swansea Bay", April 2004.

There are a number of issues to be addressed in an EIA that are likely to be highly contentious, difficult and/or expensive to investigate and are likely to have a significant impact on the consenting process. These are:-

- The impact of the construction phase including:
    - The winning and transport of suitable rock armour,
    - Dredging of sands for the sand core,
    - A robust construction methodology to prevent catastrophic loss of material in storm conditions,
    - On shore facilities such as the construction dry-dock, power-lines etc.
- The visual impact of most large scale projects has the potential to be very contentious. A large artificial structure in an established seascape could arouse some hostile reactions. Sophisticated visual impact techniques coupled with sensitive consultation will be necessary to gain public acceptability. The experiences of other near-shore renewable energy projects are indicative of the difficulties that may be encountered in this respect.
- Tidal lagoons have the potential for large scale and wide area disruption to coastal regimes. For Swansea Bay, constructing an obstruction spanning c50% of the mouth of the Bay will have an inevitable impact on the tidal flows and sediment movements in and around the Bay. These are unpredictable without extensive and expensive computer modelling backed by extensive site investigations to produce data on sediment concentrations, water velocities, waves, etc.
- The Swansea Bay scheme would lie between two navigation channels serving the Port of Neath and the larger docks at Swansea. Vessels up to 30,000dwt and a ferry service to Cork, Republic of Ireland use the Swansea Docks and the Bay is a popular area for sailing and has a rapidly expanding marina. The structures and the intermittent high flows through the turbines would present a significant hazard,
- The embankment and power station structure will be accessible to the public, either directly (at low water), by boat or by swimming. There will be significant safety issues to address both for protection of the public and for works operatives,
- The EU Birds and Habitats Directives are major pieces of legislation driving the EIA process. Extensive seasonal surveys are necessary to derive the necessary baseline data,
- The tidal lagoon configuration avoids the impact on migratory fish, an issue with estuarine barrages. Nevertheless there will be some impact on fish, marine mammals and the benthic ecology of the Bay. Detailed and seasonal baseline surveys will be required to assess the current status of the ecology,
- The tourism and leisure benefits of tidal lagoons claimed by some supporters of this scheme may be somewhat limited by the safety case and the, as yet unclear, visual impact,

- The lagoon, as proposed, encloses the outfall from a long sea sewage outfall. The cost of protection of this asset will have to be borne by this scheme. As a minimum, the pipeline would require protection where it is to be built over by the embankment. As a worst case, the changes to the discharge conditions may be such that the pipeline would have to be relocated or extensively extended. The implications for this structure will have to be analysed early in the EIA process.
- Decommissioning – discussed in Section 6 above.

9.6 Project timeframe

The implementation programme developed by TEL shows three years from the start of a 12-month planning and consenting process to completion.

The Reviewers consider this timeframe to be optimistic for the following reasons:-

- A realistic consenting phase would be around 5 years.
- Unless considerable resources were to be mobilised to accelerate construction, and reflected in the cost estimates, a realistic construction phase would be around 3 years.

Thus the time to first income is likely to be around eight years. For the evaluation of the cost of energy, a shorter programme of 3 years' planning and design followed by 2 years' construction has been used. The longer programme would increase the cost of energy.

9.7 Generic issues for tidal lagoons

The Reviewers see little prospect for reducing the cost of energy from this concept through replication, innovation or experience as it would use established and mature technologies. The cost of the lagoon is dominated by the materials cost where there is little prospect for cost reduction and much scope for cost increase.

The Reviewers consider that the issues surrounding the Swansea Bay scheme are sufficient to cast doubt on the economic and environmental value of the tidal lagoon concept for the foreseeable future. Locations with a higher tidal range offer a greater annual power output but cost more to build, and larger lagoons may offer some economy of scale. Studies of tidal barrages however have shown that the economies of scale are relatively minor, whereas the potential for unacceptable impacts will tend to increase with size. The potential sites where the economics and environmental constraints may be sufficiently favourable are considered by the Reviewers to be extremely limited.

Should TEL's engineering solutions prove deliverable, then the economics of the potential tidal barrage schemes around the UK would be significantly improved.

10 Conclusions

- The cost of the embankment has been estimated to be £137M compared with the TEL estimate of £48.5M. The difference in the estimated cost of construction is attributed to the following factors: maximum wave height for the impoundment; crest level; crest width; slope gradient and stability; and the weight of armour stone.
- The cost of the power house has been estimated to be c£50M compared with the TEL estimate of £12.7M. The difference in cost estimates is attributed mainly to the estimated all-in cost per cubic metre of concrete, cost items omitted in the TEL estimate and a contingency allowance.
- The mechanical and electrical plant based upon comparisons with tidal barrage studies is estimated cost £650/kW compared with TEL's estimate £223/kW. The lower value proposed by TEL is based on Chinese costs that have not been validated by the Review. These lower costs have been assumed however for the purpose of deriving a comparative cost for the Review.
- The total scheme cost estimated by the review, taking account of all the engineering parameters, is £234M. This contrasts with TEL's estimate of £81.5M and reflects different assumptions for the same general design.
- The predicted energy output is estimated to be 124,000 MWh/year. TEL has estimated that the same power plant configuration could generate 187,000 MWh/year. The reviewers' estimate has been based on tidal conditions at the site and turbine performance data used during the Severn Barrage studies. It has also assumed a different efficiency for two-way (ebb and flow) generation. The reviewers were not able to validate the calculations used for the TEL estimate.
- The unit cost of generation, taking account of the revised capital costs and estimated annual energy output is 17.2p/kWh at an 8% discount rate. This unit cost of generation is higher than barrage schemes of comparable size that have been investigated.
- The cost of the pre-consent phase and the timescale to a consent decision are anticipated to be higher and longer than anticipated by TEL.
- If the unit costs proposed for concrete and generating equipment by TEL could be verified, other tidal energy schemes investigated in the UK would become economically much more attractive than they are at present.
- In carrying out this Review assumptions have been made based upon a narrow project scope with limited site data. Some information provided by TEL has been included in the Review estimate without validation and potentially significant risk areas have not been addressed due to lack of information, e.g. the sewage outfall. It is likely that a fully scoped feasibility assessment would show that the cost estimate developed by this Review is at the lower end of the spread of probable costs.

Appendix 1 General description of the Swansea Bay proposal

TEL's current design proposal for Swansea Bay is for a $60MW_e$ hydro-power installation driven by tidal flows into and out of a $5km^2$ artificial lagoon. The lagoon is to be created using sand and rock dumped on the sea-bed using 'standard breakwater' design techniques forming an embankment wall over 9km long.

The crest of the impoundment is to be kept to a level only slightly above MHWS to reduce material costs and to reduce the visual impact. Thus in periods of storm surge, high wave action and with rising sea levels over the life of the structure, the embankment is to be allowed to be overtopped.

The objective for the embankment is to locate it in water depths of between 1m and 5m below MLWS tide level in areas with a high tidal range. The mean tide range in Swansea Bay varies between 4.1m and 8.5m.

The power station would comprise six concrete caisson structures each 40m long by 30m wide set in deeper waters (~7m below MLWS) in a salient extension of the lagoon embankment. The power station would house 24, $2.5MW_e$ low-head hydro-turbine and generator sets to produce the required $60MW_e$ rating. The intention is to generate primarily on the ebb (emptying) tide with secondary generation on the flood (filling) tide.

TEL claim that this configuration offers a number of cost and environmental benefits against a comparable tidal barrage installation, such as:-

- Cheaper construction costs for a lower specification embankment structure in relatively shallow waters,
- A greater choice of sites,
- A load factor of 35% or more, giving a typical annual output of 187,000MWhr per annum,
- Bi-directional generation considered to be worthwhile,
- A low profile embankment structure presenting minimal visual impact,
- No interference with migratory fish,
- Reduced fish mortality,
- No interference with navigation,
- No impact on inter-tidal habitat,
- No impact on estuary and river flooding regime,
- Potential benefit for coastal protection.

Power would be generated at 11kV and stepped up locally to 132kV for dispatch to shore via sub-sea cable. On shore, an overhead line would connect to the local power company's distribution network at 132kV.

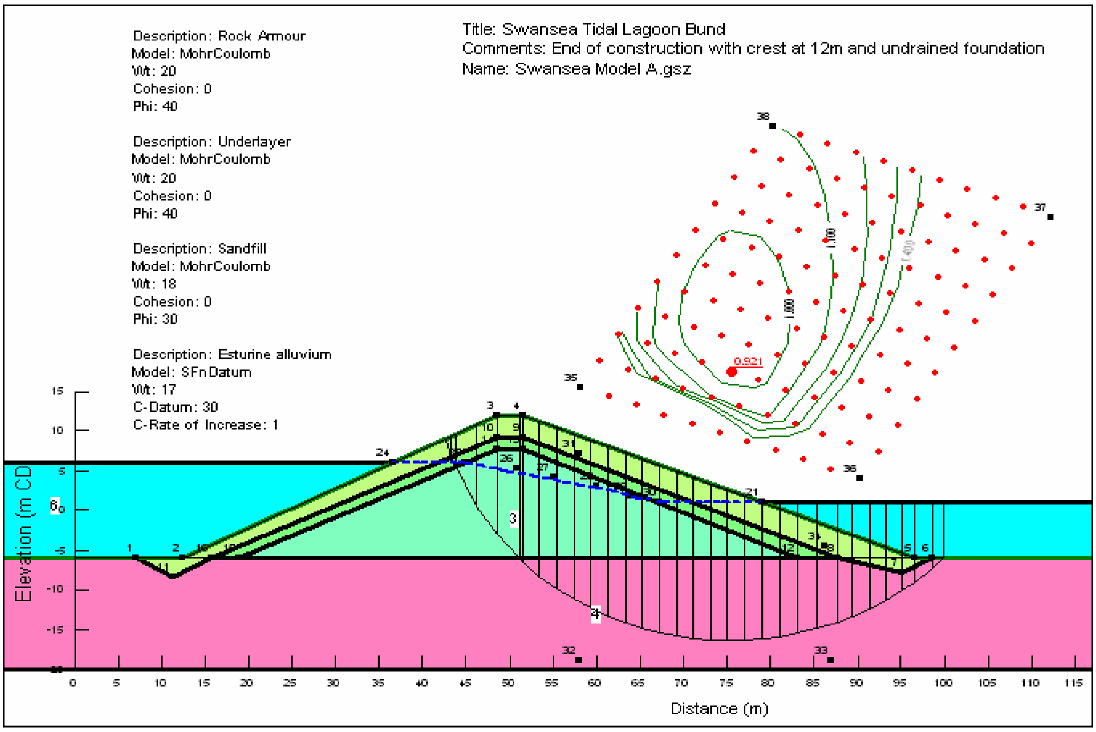
TEL estimate a capital cost of £79 million for the Swansea Bay scheme with a further £2.5m investigative work to get the project consented. They have programmed 12months to consent and a further two years to complete (three years total).

The company suggest that the decommissioning plan would be to dismantle and remove the mechanical and electrical equipment but leave the civil engineering works in place with perhaps the power house dismantled to reduce flow intensity through the breach.

Appendix 2 Embankment stability and rock armour analyses

The safety of slopes for impoundment structures can be analysed by industry-standard programmes[28] that determine the circular slip failure surface with the lowest factor of safety (FoS). If the structure becomes unstable the embankment could slump along this surface causing it to collapse. Experience has shown that, when a steep slope fails, the failure surface is usually circular, i.e. a 'slip circle'. The computer program is used to analyse a large number of slip circles to find the one with the lowest factor of safety (FoS), i.e. the total of the forces resisting failure around the circle divided by the total of the destabilising forces. The FoS is calculated at design stage for two points in the future, the first immediately after construction is completed, before the foundation strata have had time to settle and gain strength by squeezing out the excess water. The second once the long-term conditions have become established when the strata have drained, consolidated and thus gained strength.

Figure A2.1 1V:2.5H slope stability analysis



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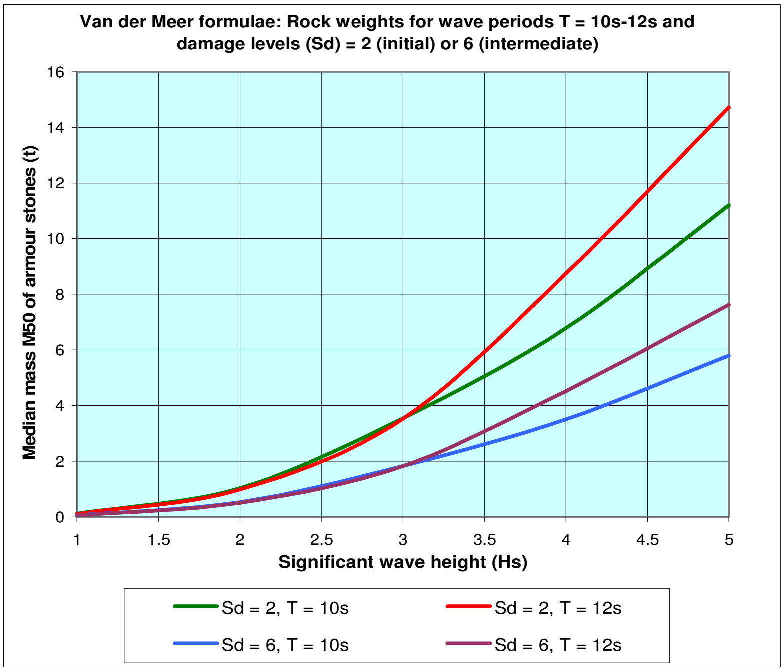
28 E.g. SLOPE/W. Web site: http//www.geo-slope.com/products/slopew2004

Figure A2.2: Sizes of main rock armour



Notes

Sd = damage criterion.
Sd = 2 = initial damage, requiring reasonably prompt repair.
Sd = 6 = intermediate damage requiring immediate repair.
T = wave period (seconds).
Significant wave height is the mean of the heights of the 1/3rd largest waves.

In this figure, damage criterion (s_d) is an empirical indicator of the amount of damage and hence the speed with which repairs should be undertaken. M_{50} is the median weight (mass) of the armour stone, related to the D_{50} size by the density of the stone.

Figure A2.2 shows that for a design wave height of 4.0m and a wave period of 10s, as proposed by TEL, the median rock armour stone weight should be about 7te, and for a 12s wave period, about 9te. For a design wave height of 5.0m, the median rock armour weight would increase to 11te for a 10s wave period and 15te for a 12s wave period.

Appendix 3 Glossary

(Technical Terms and Units)

CD	Chart datum – the datum for Admiralty chart depths of water, equal approximately to the level of a lowest astronomical tide.
k	kilo (1000).
kWh	kilowatt-hour(s).
m	metre(s).
M	mega or million(s).
m/s	metre(s) per second.
m^3/s	cubic metre(s) per second.
MWHS	mean high water level of spring tides
MLWS	mean low water level of spring tides.
MW_e	Megawatts electrical output.
MWh	Megawatt-hour(s).
te	tonne(s); 1te = 1000kg.
kt	kilotonnes, 1,000 tonnes
1V:2H	A slope of 1 vertical to 2 horizontal.
Armouring	A construction technique used to protect an embankment either with rock or specially designed concrete units .
Availability	The availability of a power station is the ratio of the energy which it would produce if restricted only by plant faults and maintenance to that which it could produce if there were no limitations.
Axial-flow turbine	A turbine where the axis is positioned in line with the direction of flow.
Bulb turbine	A type of water turbine generator particularly suited to tidal energy. The generator is housed in a sealed steel bulb within the water passage, upstream of the turbine rotor.
Caisson	A large prefabricated steel or concrete structure which is floated into position and then sunk into place.
Cavitation	Cavitation is the formation of vapour-filled cavities in the water, for example in the turbine passageway, as a result of a local drop in pressure. Their subsequent collapse in regions of higher pressure, for example adjacent to solid surfaces such as the turbine blades, can in time cause pitting and disintegration.
Discount rate	This is a rate expressed as a percentage, used in discounting all benefits and costs to present day values.

Discounting	This is a method of assessing the present worth of a stream of costs or benefits arising at various times in the future. The calculation is made in real terms and is not an allowance for inflation. It attempts to allow for the preference for money now rather than later.
Double regulated turbine	This is a type of turbine which enables two separate methods of regulating the water flow and hence power output, e.g. one with adjustable guide vanes (distributor) and runner blades.
Draft tube	A draft tube is the water passageway downstream of the turbine runner. It is designed to maximise the amount of energy which can be extracted from the water by ensuring a rapid flow past the turbine runner but a minimum discharge velocity.
Ebb generation	A mode of tidal power in which generation takes place as water passes through the turbines on the ebb tide, i.e. from the basin to the sea.
Embankment	A mound, bank, dam or dyke made from rock, sand and similar materials.
Flood generation	A mode of tidal power operation in which water passes through the turbines in the same direction as the flood tide, i.e. from the sea to the basin.
Flood pumping	A mode of tidal power operation in which the turbines are used to pump water from the sea into the basin at around the time of high water, to increase the volume of impounded water.
Generator rating	The generator rating or rated electrical output is the normal maximum output.
Habitat	The normal abode or locality of an animal or plant.
Head of water	This is the difference in levels between the basin and the sea which drives a tidal power turbine.
Inter-tidal area	The zone between low water and high water.
Kaplan turbine	A turbine similar to a propeller with upstream guide vanes.
Load factor	A ratio of the actual amount of energy produced by a power station to the maximum energy it would produce if running at full load all the time.
Low-head	A head of only a few metres, as in a tidal scheme. This may be compared with high heads of tens or hundreds of metres in hydroelectric and pumped storage schemes.
Mean neap tide	The average tidal range of tides with the lowest range in the spring-neap cycle. These tides occur when the sun's gravitational field is acting at right angles to that of the moon.

Mean spring tide	The average tidal range of tides with the greatest range in the spring-neap cycle. These tides occur at, or near, new and full moon when the solar and lunar gravitational fields reinforce each other.
Migratory fish	These are fish whose life cycle involves migration between river and sea. In the Severn Estuary the known migratory species are salmon, sea-trout, allis-shad, twaite-shad and eel. Sea and river lamprey also migrate.
Neap tides	The tides of lowest range in the spring-neap cycle. They occur when the sun's gravitational field is acting at right angles to that of the moon.
Net present value	This is the net amount of the discounted future costs and revenues expressed in real terms associated with a capital investment.
Numerical model	A computer-based simulation of a real situation. In the case of numerical hydrodynamic models, the equations of motion and continuity are usually solved in one or two dimensions.
Ordnance Datum	Arbitrary zero height, assumed to be the mean sea level at Newlyn, Cornwall, and from which the heights above sea level of all official benchmarks in Britain are measured.
Runner	The rotating part of a turbine which converts the energy of flowing water into mechanical energy for driving a generator.
Sand-fill	Sand used as fill material, e.g. for the core of an embankment.
Sediment transport	The process of movement of sediment by air or water.
Spring tides	Tides of greatest range in the spring-neap cycle. They occur at or near new and full moon when the solar and lunar gravitational fields reinforce each other.
Spring-neap cycle	The 14-day periodic cycle of tides. This is due to occurrence of maxima and minima in the combined effects of the sun's and moon's gravitational fields.
Tidal range	The difference in water levels between high water and low water.
Turbidity	A measure of the clarity of water from which the amount of suspended solids in the water may be inferred.
Two-way generation	A mode of tidal power generation on both the ebb and flood tides.
Wave height	For this assessment, taken as the significant wave height, which is the mean height of the 1/3rd largest waves.
Wave period	The time between successive wave crests.

Appendix 4 Curriculum Vitae of the Authors

Name	**Clive Baker**
Profession	Civil Engineer
Present occupation	Consultant
Years experience	45

Education and Professional Status

BSc(Eng) Kings College, London; Fellow, Institution of Civil Engineers

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Summary of recent experience:

2005 - 2006: Member of technical advisory groups advising Meridian Energy Ltd, New Zealand, on pre-feasibility studies of two hydro projects.

Nov 2003 – May 2004, Black & Veatch Consulting: Chief Engineer of a 5-firm team working on the design of a 500MW low-head hydro project in South Island, New Zealand. The project included power stations with bulb turbines.

2000 – Oct 2003 & May 2004 – present: Independent Assessor, for FES, of proposals for water-based renewable energy technologies (hydro, tidal, wave).

1990-2, 1994-2000, Binnie & Partners (Overseas) Ltd: Chief Engineer leading the 5-firm design team on the feasibility studies, design, international tendering and construction of the 1450MW Ghazi-Barotha hydropower project on the River Indus in Pakistan (fully commissioned in 2003).

1977 – 1988, Binnie & Partners: Project Engineer on former Department of Energy (DEn) funded studies of the 8000MW Severn Barrage. Main responsibility was to identify: the most cost-effective location of the barrage; the numbers, types and sizes of turbines and sluices, and the best method of operation. Co-ordinated the input from about 40 organisations involved in engineering and environmental studies. Subsequently led studies of other estuaries (Conwy, Wyre, and Loughor) and carried out a parametric assessment of the total UK resource and the likely unit cost of energy. During this period, also carried out assessments of many proposals for tidal and hydro schemes submitted to DEn/ETSU. At the end of this period, responsible for detailed studies into optimisation of the operation of the Severn Barrage for the Severn Tidal Power Group, including reverse pumping from sea to basin.

In **1986**, lead a UK team working on feasibility studies of a tidal stream project and a tidal power barrage in South Korea.

1975-6 Resident Engineer supervising the construction and monitoring of a demonstration off-shore water storage lagoon in the Wash.

1991: Author of book "Tidal Power" published by Peter Peregrinus on behalf of the Institution of Electrical Engineers.

Name	**Jane Walbancke**
Profession	Geotechnical Engineer
Present occupation	Technical Director, Black & Veatch
Years experience	40

Education and Professional Status

PhD, MSc, DIC Imperial College, London; Member, Institution of Civil Engineers; Fellow, Geological Society

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Summary of experience:

May 2006 to date: Technical Director, Geotechnical Dept, Black & Veatch Ltd.

Oct 2004 – May 2006: on long term leave from Black & Veatch Working with Beca Infrastructure Ltd, New Zealand and as a consultant. Highway design and groundwater control systems.

Oct 2003 – May 2004, **Black & Veatch**: Lead Geotechnical Engineer in a 5-firm team working on the design of canal embankments for a 500MW low-head hydro project in New Zealand.

1999-2003, Binnie Black & Veatch: Dams Engineer for Can-Asujan Dam, Philippines; Segara Anakan Scheme, Indonesia and geotechnical design of embankment dams, flood embankments and landslide remediation, UK and overseas.

1995-2001, Binnie & Partners (Overseas) Ltd: Geotechnical Advisor to the 5-firm design team for the design and construction stages of the 1450MW Ghazi-Barotha hydropower project on the River Indus in Pakistan. Pakistan and UK based.

1985-1995, Binnie & Partners UK: Design of embankment dams, service reservoirs, flood embankments, land reclamation, irrigation schemes, sea outfalls and foundations UK, Singapore Malaysia, Hong Kong, Indonesia, India

1984-1985, Binnie & Partners, Hong Kong: Design of 440 ha land reclamation for Tin Shui Wai new city on soft marine alluvium in Deep Bay.

1982-1984, **Binnie & Partners UK:** Dam design for the Mantaro transfer scheme, Peru: remedial works on several UK dams.

1976-1982, Binnie & Partners, UK and Hong Kong: Landslide studies, embankment dam design and monitoring, land reclamation. Seconded to Hong Kong

Government to upgrade their soils laboratory. Wrote the 1st Edition of the Hong Kong Manual for Slopes.

1970-1976, Imperial College, London: Research Assistant to Prof A W Skempton, Soil Mechanics Dept.

1968- 1970, Soil Mechanics Ltd.

1965 – 1967, Sir Bruce White, Wolfe Barry & Partners

Name	**Peter Leach**
Profession	Civil Engineer
Present occupation	Consultant
Years experience	35

Education and Professional Status

BSc, C.Eng., MICE, MCIWEM

Summary of recent experience:

2000 – present: as **ESS Consulting** or in collaboration with Associates. Development of an integrated catchment planning framework and establishment of catchment area plans for a major water utility's long term asset planning function. Design, implementation and management of a pilot Welsh Energy Industry Supplier Network (EISnet) Programme. Development and due diligence appraisal of energy projects for European funding. Preparation of ERDF grant aid submission for two marine renewable energy projects. Preparation of guide notes and design of a small-scale and community energy project support framework. Development of a multi-criteria assessment model for project due diligence and eligibility appraisal. Project Management of an audit and review of the Welsh Energy Sector and development of the Welsh Development Agency's Outline Energy Strategy for Wales. Tender appraisal and preparation of selection model for Operational element of Design Build and Operate Contractors for Water Utility assets. Preparation of a Quality Assurance System for the self monitoring of EA discharge consents. Project management, peer review and design validation of several water utility and industrial projects. Optioneering for off-shore wind farm cable land-fall and network connection.

1997 - 2000 - **Hyder Consulting**: Energy Sector Business development covering power generation, energy transmission, upstream and downstream oil and gas industries, and mining. Key account manager for a number of corporate businesses. Project Manager for regional economic and technical studies for a proposed 500MW CCGT gas fired power station and Energy Park optimising the local beneficial use of co-generated heat and power. Preparation of a successful case for S36 consent during the Government's moratorium on gas fired power station construction. .

1990 - 1997 – Acer Consulting: Proposals and Project Manager for multi-disciplinary, multi-project schemes for municipal and industrial waste water treatment and small-scale hydropower. Assessment of potential for hydro-power generation from Water Utility assets. Project management of successful PFI pre-tender design and tender negotiation phase for a major waste water treatment plant in Northern Ireland. Project management of pharmaceutical waste water treatment facility from feasibility through pilot scale testing, design and construction to plant commissioning. Multi-contract procurement under Design Build Finance and Operate contract:

Engineering advice to fibreboard and glass fibre insulation companies in the North West and North Wales.

Pre 1990 – Project management, design and supervision of water, wastewater and flood alleviation projects, including emergency repairs to coastal defences and a major city centre tunnelling scheme. Early site experience with highway construction contracting including setting up a materials testing laboratory.