# Conceptual Feasibility Study for the Replacement of Derelict Sluice Gates at Carnsew Pool, Hayle with a Tidal Current Turbine Array

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Prepared for:

**Rubicon Marine Ltd, and**
**Western Hydro Ltd**

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## Executive Summary

This report summarises a conceptual feasibility study investigating replacement of the current sluice gates at Carnsew Pool Hayle with a 6m long array of vertical axis tidal current turbines.

In the report,

- the history of Carnsew Pool is reviewed,
- a procedure for accurately estimating the water levels inside and immediately outside Carnsew Pool is established,
- a suitable turbine design is been identified,
- consideration of the environmental constraints acting is given,
- the annual electrical power output is estimated over a 15 year period from 2006, and;
- project valuation calculations have been conducted.

The results of the feasibility study are broadly favourable but could be made much more favourable if it could be determined whether or not the project would be eligible for special Government support for marine renewable energy.

The total capital investment for the tidal current turbine project has been estimated at £132,350, a figure that will need to be refined through more detailed study, should a decision to proceed with this project be found. With a favourable determination from the DTI (for which there is every chance), the Net Present Value of the project over a 15 year project life and using a discount rate of 12% is £229,818. With no financial support whatsoever, electricity produced from the turbines has a break even (discounted) cost of around 7.5p/kWh.

Actions arising from this conceptual feasibility study reported at the conclusion of the report are also listed here for convenience:

1) A meeting should be arranged with ING Real Estate to communicate the findings of this report and to determine whether or not they are amenable to the idea of installing tidal current turbines within the Carnsew sluice tunnels as part of their developments.
2) Alternative tidal current turbines should be investigated for adoption within the Carnsew Pool context. A turbine runner efficiency higher than 56.5% will improve the yield and hence the financial returns arising from the proposed Carnsew turbines.
3) The DTI should be approached to confirm that the proposed Carnsew turbines would meet or will meet their criteria for capital grant support and marine renewable energy ROC enhancement. The Carbon Trust and possibly Government research councils should be similarly contacted.
4) Instrumentation to measure the levels of tides within and outside Carnsew Pool should be installed to conduct site monitoring for at least one year. This should be done as soon as possible.
5) The Carnsew tunnels need to be inspected in the context of the proposed tidal current turbines.
6) The locations of shafts and tunnels between Carnsew and North Quay need to be confirmed.
7) This report represents the results of a conceptual feasibility study. A more detailed feasibility study / detailed design and costing study will be required.

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## Introduction

ING Real Estate Development UK Support Ltd have extensive, phased plans for the redevelopment of Hayle Harbour. The plans include the renovation of quay structures, the construction of a marina and commercial and residential developments.

This document reports the results of a conceptual feasibility study that investigates the harnessing of the tidal energy resource at Carnsew Pool to produce electrical power based on a tidal barrage concept. This study has been undertaken for Rubicon Marine Ltd and Western Hydro Ltd, with a view to submission of a proposal to ING, the Hayle Harbour developers.

## A short history of works in Hayle harbour

The following represents a summary of the key facts in relation to the tidal pools within Hayle Harbour abstracted from Vale's 1966 book on the Harvey's of Hayle[1].

In the 1750's, prior to any development of Hayle as a commercial harbour, the estuary was a natural tidal lagoon that was essentially land locked apart from a narrow gap across the sand bar into St Ives Bay. This gap was maintained primarily by the River Hayle (meaning 'the Salty One') which flowed into the lagoon from the south but also by two smaller streams: the Copperhouse stream from the east and the Penpol stream from the south-east. The natural morphology of the lagoon comprised eastern and western lobes. In 1770, a 33 metre wide canal channel was dug along the southern flank of the eastern lobe of the lagoon by the Cornish Copper Company (CCC). Floodgates and sluices were installed close to Ventoleague in order that at high tide, sea water could be impounded and then released when the tide was at its lowest ebb, thereby flushing out the canal and keeping it navigable. Later, in 1788 further lock gates and sluices were constructed at the lagoon lobe's mouth at the western end of the canal. These works effectively dammed the whole eastern lobe of the lagoon forming what is now known as Copperhouse Pool. They were installed to extend the flushing principle into the channel from St Ives bay to the CCC quaysides in Copperhouse Pool to render the estuary navigable to vessels laden with mining supplies.

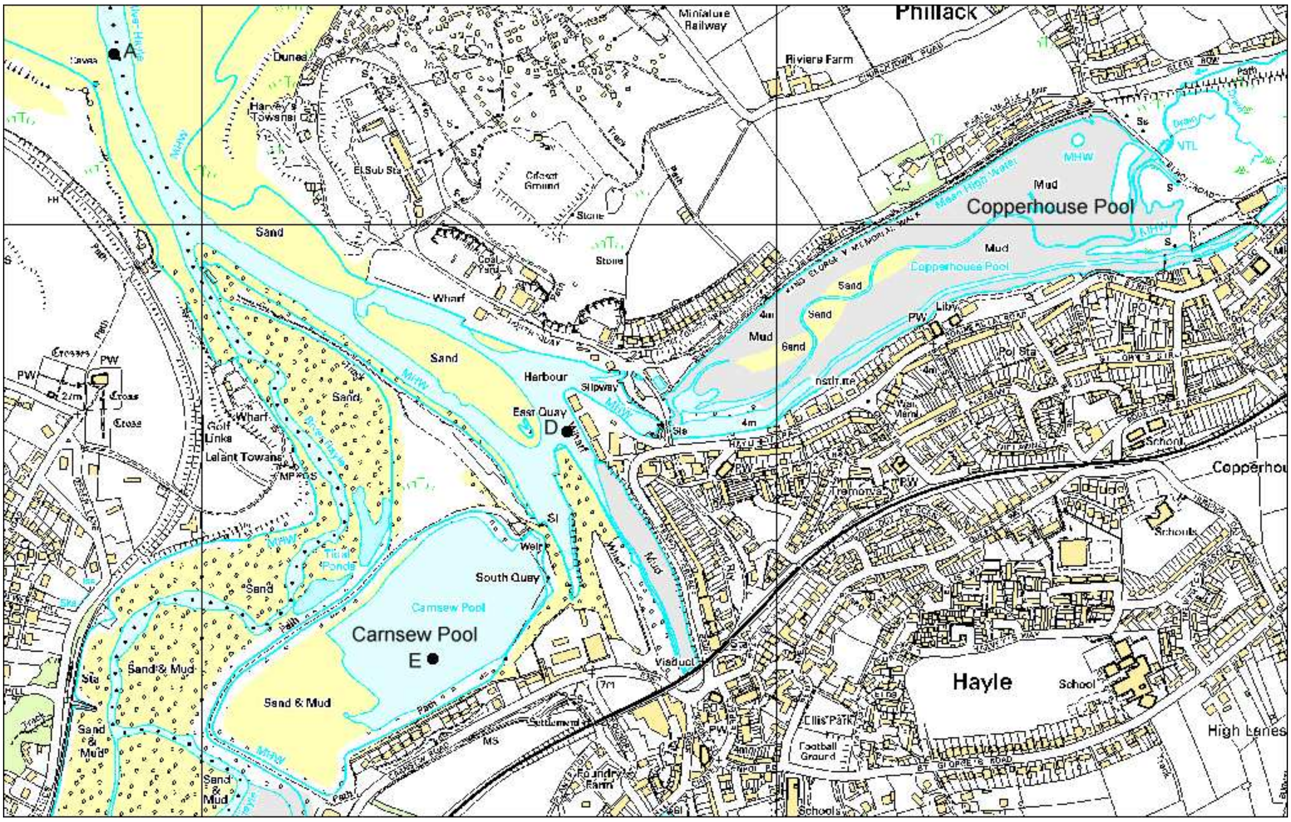

Figure 1 : General layout of Hayle Harbour showing Copperhouse Pool (LHS) and Carnsew Pool (RHS). Points A, D and E are locations for which tidal curves are available.

When the water level in the pool was at its highest, at the time of high tide, sluice gates at the entry to the pool were closed. The seawater behind the constructed gates was retained until the open water tidal level had fallen and the sluice gates were opened. Water in the pool then discharged rapidly and the high velocities in the harbour channel swept sediments that had accumulated in the harbour channel out to sea.

The first harbour works on the Carnsew side of the lagoon appear to be those associated with the excavation of a channel from the confluence of the Penpol stream and Copperhouse stream at the narrows between the two lagoon lobes to Carnsew Quay. These works took place around 1759. Twenty years later in 1779 this quay together with stone buildings and a timber yard were the premises originally secured by John Harvey for his foundry. In 1818 Harvey's son, Henry Harvey deepened the Carnsew channel and quay and started work on the 400 metre long wharf that became known as Harvey's Wharf but is now known as South Quay. Routine access to Harvey's Wharf and Carnsew Quay relied on the continued flushing out of the navigable channel by release of impounded sea water from Copperhouse Pool which still remained under the control of CCC. CCC constructed a new quay to the north east of the South Quay, now known as East Quay primarily to block access to Harvey's Wharf as CCC and Harvey & Co. were bitter competitors. The sand bank on which East Quay is constructed arose after the creation of Copperhouse Pool by means of modified sediment transport, resulting from the routine flushing of the tidal lagoon with water from Copperhouse Pool. The build up of this sand bank also had the effect of diverting the Penpol stream, which proved contentious as the original alignment of this watercourse also served as the boundary between Parishes and thus the lease areas held by the conflicting parties. In 1829, Harvey's claim over the East Quay was heard in court at Bodmin backed up by a three layered physical model of the Harbour made by Richard Trevithick, showing the various harbour modifications. The proceedings were not conclusive and required a second hearing three years later whereupon Harvey's were awarded ownership of East Quay, subject to offering CCC a lease to rent the quay back from them at £200 per annum. The offer was made and declined by CCC.

The reprisal from CCC was that from 1829 they discontinued daily scouring of the main channel into the quays by the regular operation of their sluices in Copperhouse Pool. CCC only did this when it suited their own purposes when one of their ships was due into the harbour. This clearly presented operational difficulties for Harvey's movements of supplies and products. Henry Harvey's response was to design and construct a 15 hectare area tidal pen within Lelant Water to provide himself with a capability to flush the navigable channel. This became known as Carnsew Pool and was first operated on 27th December 1834. From that time, the sluice gates in Carnsew Pool were operated continuously until the 1960s during which time a yearly average of not less than 400 vessels were using the port. It was at this time the flood gates, firstly at Copperhouse, and then at Carnsew had to be removed for repairs. The navigable channel remained serviceable when either of the tidal pools were not operating.

Copperhouse Pool: created in 1788 by Cornish Copper Company.
Carnsew Pool: created in 1834 by Harvey's of Hayle.

## Production of Electricity

The following represents a summary of information presented by the South Western Electricity Historical Society[2].

An agreement with Harvey & Co. was made for the construction of a coal fired power station at Hayle in 1910 subject to a lease when the station was completed. The lease was signed in 1915 and covered *inter alia.* rights of way, payment of landing fees for coal handled through the Hayle quays (by Harvey & Co. workmen) and the obtaining of steaming and cooling waters.

Between 1910 and 1916 a total of 6 generating sets had been installed with a combined installed capacity of 8.8MW. 7.5MW and 10MW generating sets were added to the pre-existing units in 1928 and 1932 respectively. All of these generators produced electricity at 25Hz until 1933 when the larger two latterly installed units were upgraded to 50Hz and the station was connected to the National Grid. In 1936 the 25Hz generators were scrapped. In 1938 ICI built a plant close to the gates of the power station. This plant was to extract bromine from sea water and required the water to be hot. Thus condenser cooling water from the power station was diverted to the ICI plant. The ICI plant was taken over by Associated Octol in 1948.

Figure 2: Hayle power station circa 1934.

Figure 3: Hayle power station circa 1950[2].

In 1939 an additional 15MW generating set was installed. The planned additional generating capacity at that time was a total of 70MW. It was found that due to recirculation, cooling water drawn from the River Hayle was too hot at times of the highest tides. It was decided to use water in

Carnsew Pool as a second source of cool water. To this end a dam was constructed within Carnsew Pool to ensure that some water was retained within the Pool at all times. In April 1939, a 33.5 metre deep shaft was sunk from the base of Carnsew Pool. In 1941 a tunnel was driven underneath the river to a similar shaft located next to the power station on North Quay[3]. The connection between Carnsew Pool and the power station was designed to sustain a flow rate of 3.8 $m^3/s$ for a period of 2 ½ hours. The photograph shown in Figure 4 shows a structure located on the north flank of Carnsew Pool, slightly west of the sluice gate location. This general location is confirmed by a drawing presented by SeaSediments Ltd[3] in 1983. The shaft at North Quay has approximate OS coordinates of 155,400mE, 37,950mN.

Figure 4: Hayle Harbour from the air, 1960[1].

The South Western Electricity Historical Society[2] states that the diameter of the tunnel was “7 inches”. It is considered that this was a typographic blunder and that 7 feet is the probable diameter of the tunnel, but this has not been confirmed as yet. The ‘dam’ referred to is thought to be the weir structure constructed ahead of the sluice gate tunnels in Carnsew Pool, as shown in Figure 5.

Figure 5: Sluice gate tunnels and weir photographed from within Carnsew Pool. The white line represents the height between the weir and the MHW level.

In 1947 a further 15MW steam turbine generating set was installed at Hayle resulting in a total installed capacity of 47.5MW at this time. This was added to, in 1949, when a 20MW generating set was installed and a second 20MW unit was installed in 1959 meaning that the peak installed capacity at Hayle was 87.5MW. Hayle operated in this configuration until 1971 when the 7.5MW and 10MW units installed in 1928 and 1932 were taken out of service. In September 1973 the Associated Octol plant closed, with the result that they no longer consumed the warm cooling water from the power station condensers. The station then slipped down the merit table as newer power stations were being constructed around the country that carried the electrical system base load. The station was closed in the mid 1970s, moveable items and office furniture were offered for sale in April 1977 and in June 1981 the power station's two stacks were felled and the remaining buildings were demolished.

The closure of the coal-fired power station at Hayle also seems to have marked the discontinuation of sluicing operations to maintain the navigable channel to the harbour. SeaSediments Ltd stated in their 1983 report[3] that the practice is believed to have finally ceased in 1976. This is unsurprising, as a main use of the harbour in the 1970s must have been to deliver coal to the power station.

## Current Condition of Carnsew Pool

Carnsew Pool falls within the Hayle Estuary and Carrick Gladden Site of Special Scientific Interest (SSSI). The primary reason for the SSSI status is the importance of the estuary for birds[4]; the western end of Carnsew pool is also designated as an RSPB reserve.

Although the sluice gates at entry to Carnsew Pool are now in a derelict condition they have remained open and have allowed sea water to flow in to and out of each pool with the tides. This has also allowed the free movement of marine species into and out of Carnsew Pool. It is well known for the variety of fish species that can be caught there. ING Real Estate[4] report 21 species of fish inhabiting the pond, including two rare species: Gilthead Bream and Golden-grey Mullet. Flounder is also commonly caught in the pool. Until recently, a set of flood gates located a few metres west of the bridge connecting South (Carnsew) Quay were buried in made ground. The debris has now been excavated such that the flood gate arrangements could provide an alternative ingress and egress for estuarine species.

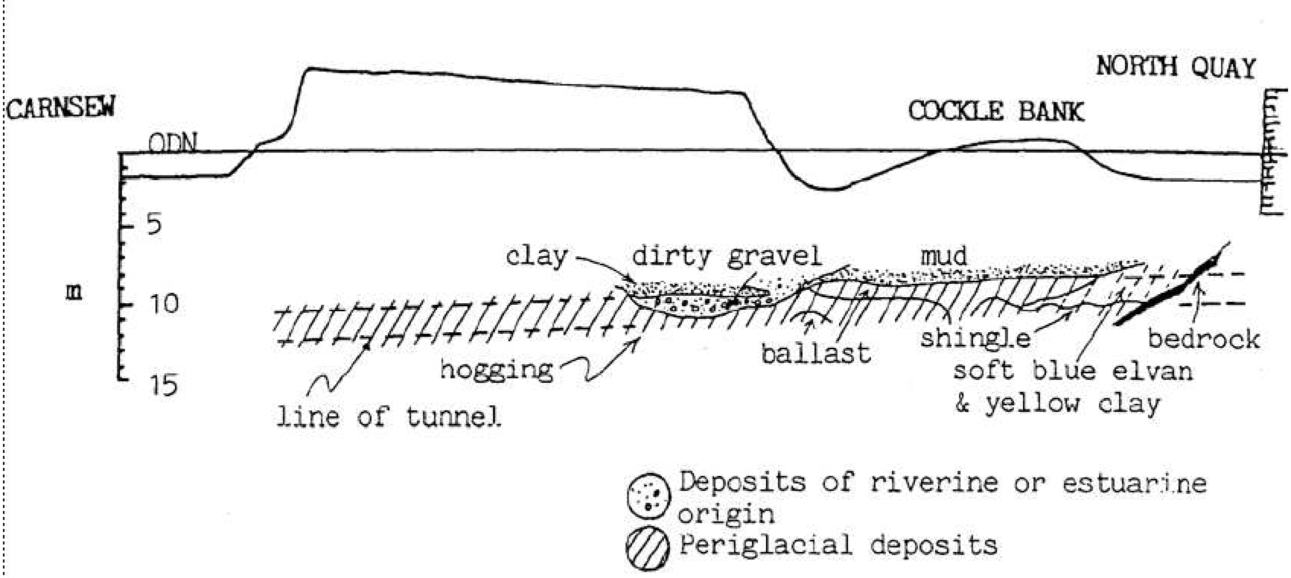

Figure 6: Cross section between Carnsew Pool and North Quay showing tunnel driven in 1941 and geological sediments encountered. Reproduced from SeaSediments Ltd, 1983[3].

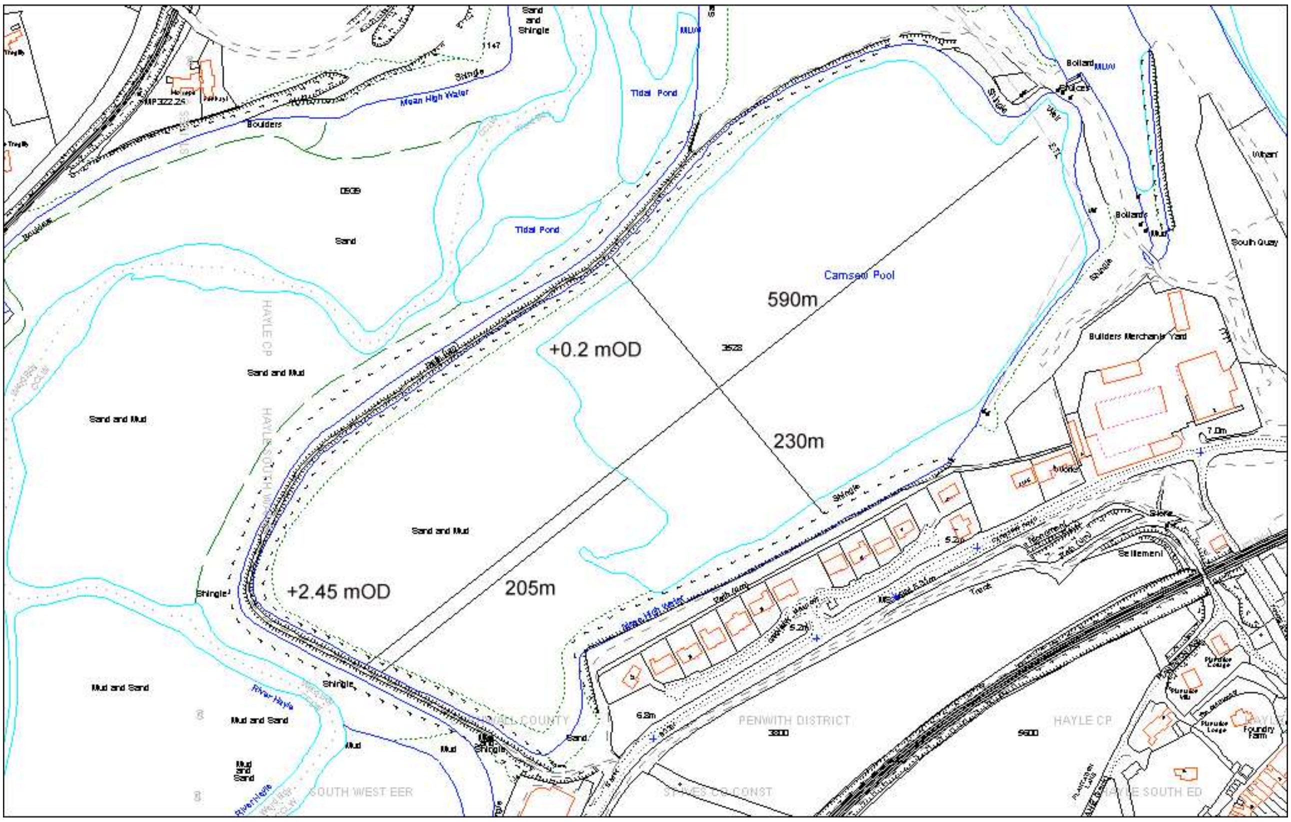

Figure 7: Plan showing layout of Carnsew Pool, showing principal dimensions and levels.

Carnsew Pool is approximately rectangular in shape, being 590m long and 230m wide. A bathymetric survey (Figure 6) of Carnsew Pool produced in 1983[3] shows pool bottom levels of –1.7 m O.D. at the eastern end of the pool. Figure 8 is reproduced from the ING Real Estate Development Plans[4] and shows that the level of the water in the basin is +0.17m OD at low tide. This level is controlled by the presence of the weir on the pool side of the sluice tunnels at the extreme north eastern end of the pool. The MLW line within Carnsew Pool (Figure 7) identifies the locations of this water level at the time of a Mean Low Water.

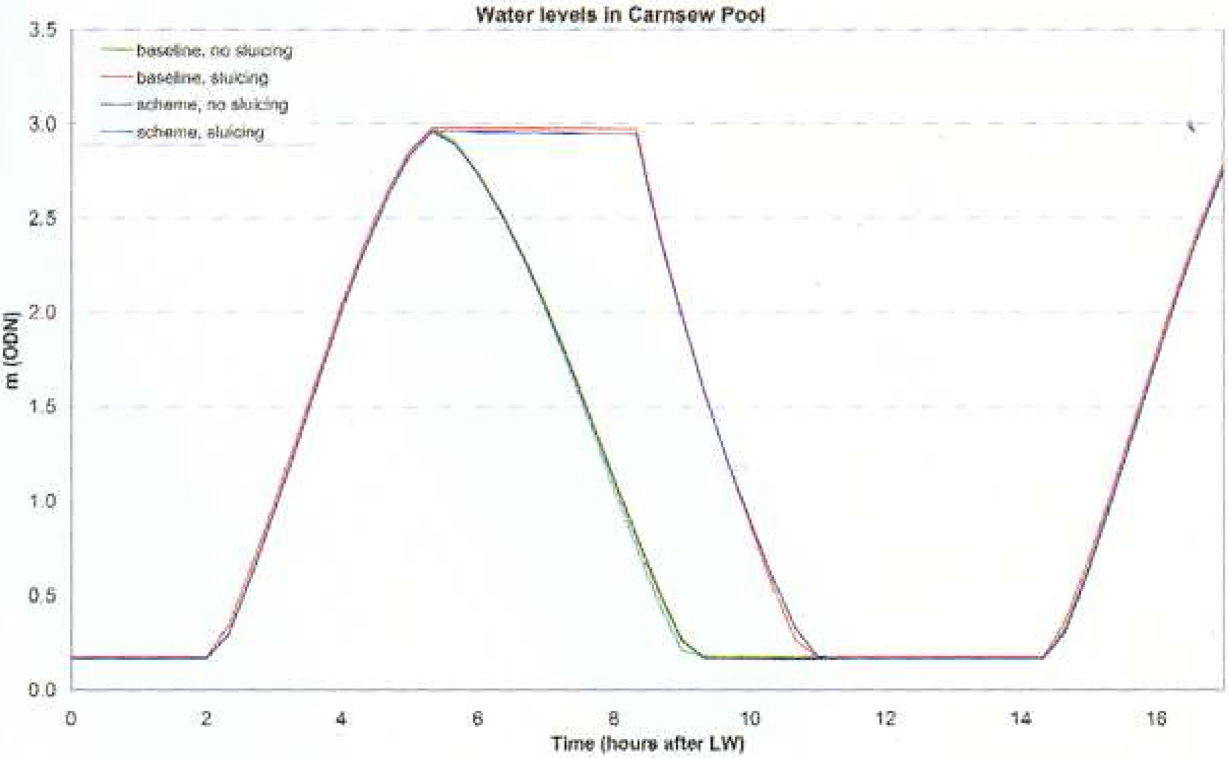

Figure 8: Spring tidal levels in Carnsew Pool presented by ING Real Estate[4].

The level of Mean High Water in Carnsew Pool is not controlled by the weir but reflects a level that will be similar to that in Lelant Water. The peak of a spring tidal curve for Carnsew Pool is approximately +2.95m OD (Figure 8). It is useful to note that the corresponding peak for Copperhouse Pool is ~+3.15m. The surface area of the mean high water line within Carnsew Pool is 141,866 m$^2$; the surface area of the mean low water line is 77,682 m$^2$.

## Tidal Levels for St Ives Bay

Table 1: Tide levels for St Ives Bay

| Tide state | Metres (ODN) |
|---|---|
| Mean high water springs (MHWS) | +3.21 |
| Mean high water (MHW) | +2.45 |
| Mean high water neaps (MHWN) | +1.51 |
| Mean tide level (MTL) | 0.27 |
| Mean low water neaps (MLWN) | -1.01 |
| Mean low water (MLW) | -1.91 |
| Mean low water springs (MLWS) | -2.63 |

Mean High Water Springs (MHWS) and Mean Low Water Springs (MLWS) levels have been taken from data in the Shoreline Management Plan[5] for the area prepared in 1999. The same source was used for the neaps levels. The levels apply at St Ives, the nearest location where these tidal levels are available. The mean tide level was computed from the average of the midpoint of the springs and neaps tidal ranges. The levels of Mean High Water (MHW) and Mean Low Water (MLW) have been calculated from tidal levels computed using Admiralty harmonic tidal constants applicable to St Ives. High and low water tide levels were determined for every tide between 1997 to 2006. The mean tidal variation determined was 4.352 m, which was then centred on the mean tide level to estimate MHW and MLW levels.

It is important to stress that these levels apply in broadly open water. For example, it is clear that due to the presence of the weir the MLW, MLWS and MLWN will all be +0.17m within Carnsew Pool. However low water tidal levels will also be affected by the morphology of the tidal lagoon and quays outside Carnsew Pool.

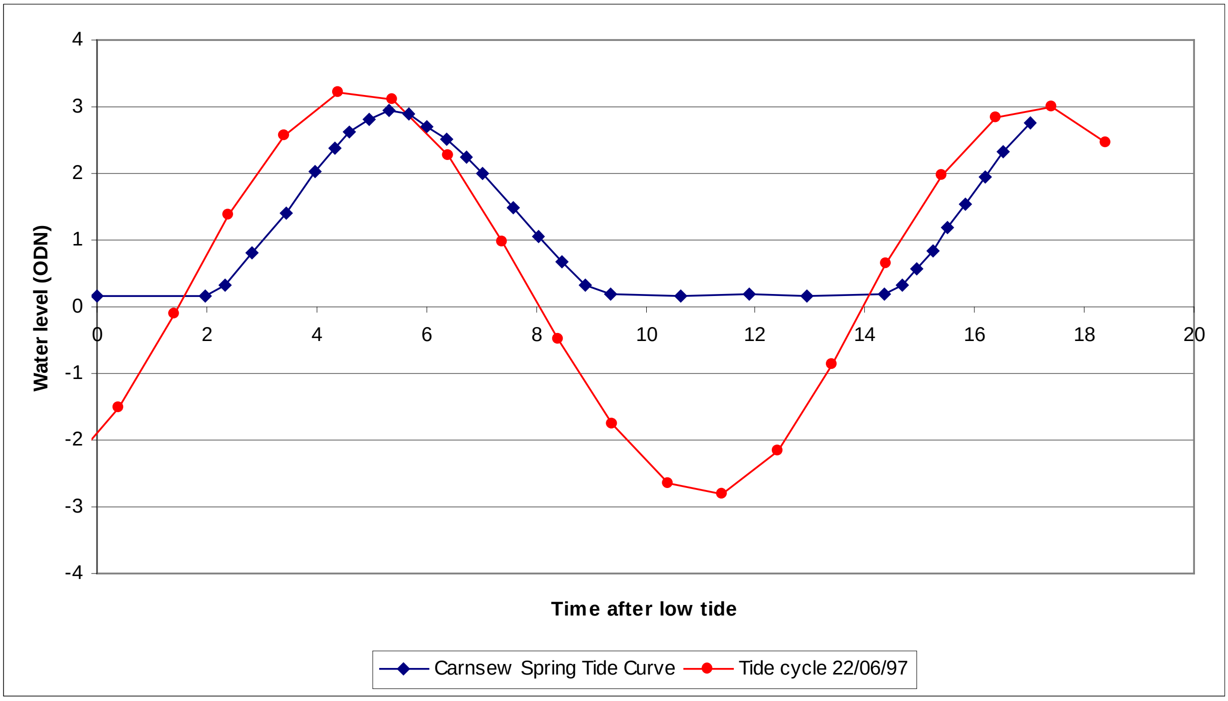

Figure 9: Comparison of an open water spring tidal cycle with a high water level of +3.15m OD with the tidal curve for Carnsew Pool digitised from Figure 8.

This is illustrated in Figure 9, which shows an open water tidal cycle with a high water level equal to that observed in Copperhouse Pool (+3.15m OD) for the same tidal cycle for Carnsew Pool presented in Figure 8. It is clear that:

i) The presence of the sluice tunnels means that Carnsew Pool does not experience the same high tide levels as in open water conditions.
ii) The presence of the weir means that Carnsew Pool only experiences low water levels equal to the upper level of the weir in Carnsew Pool
iii) The tidal range experienced within Carnsew Pool is approximately half that of open water conditions.
iv) It is likely that there is appreciable head difference between the open water side of the Carnsew Pool sluice tunnels and the impounded side during both ebb and flood phases of tides.

## Present tidal flows in Hayle Harbour and Carnsew Pool

In November 2002 Hayle Harbour and Penwith District Council published hydrodynamic modelling work undertaken by Babtie Group[6] on their behalf. The numerical modelling work was calibrated using results from physical modelling undertaken by HR Wallingford[7] in 1989. The numerical modelling work for Carnsew Pool has been ignored by this author, as it exhibited significant differences with the physical models in higher areas of the harbour alongside the quay areas and the impounded tidal lagoons. However the Babtie report is useful in that it does comprehensively report the results of the earlier HR Wallingford studies. Importantly, the HR Wallingford work utilised direct observations of tide levels in the channel area at the entrance to the harbour taken on 10th January 1989. The observations were taken at Point A shown in Figure 1, which is also described as Chapel Anjou Point. HR Wallingford made predictions of tidal levels in areas higher up within the harbour area (Point D, shown in Figure 1) and within Carnsew Pool (Point E, shown in Figure 1). Points D and E coincided with locations of tide gauges deployed in the physical survey in 1989 by HR Wallingford. Presumably, these were also used by HR Wallingford as calibration points in their own work and as such are assumed as observations in this work. Figure 10 plots these observations, digitised from screen grabs from the Babtie report.

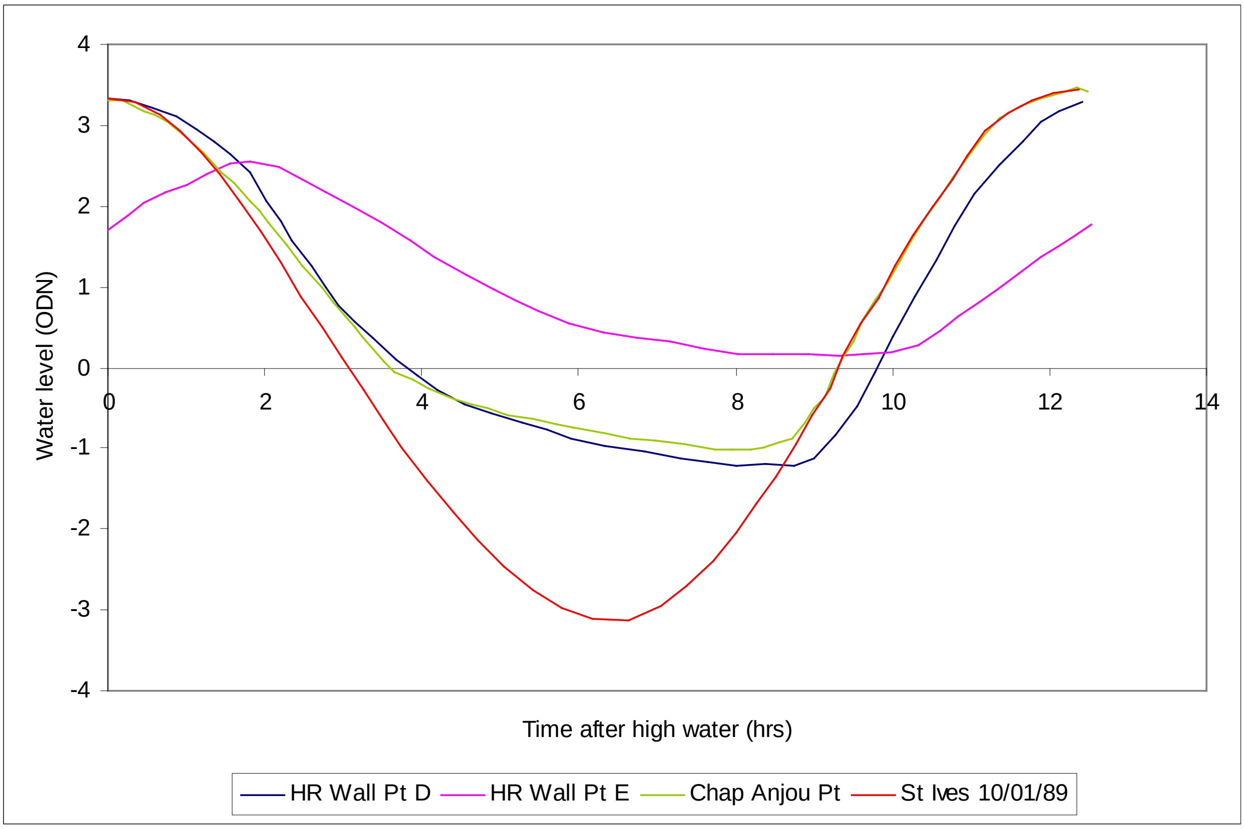

Figure 10: Observations of tidal levels within (Pt D, Pt E, Chap Anjou) and outside Hayle harbour on 10th January 1989.

Observations that can be made from Figure 10 are as follows:

i) The tidal range experienced in open water on 10th January 1989 was approximately 6.56 metres; this is approximatelyt 0.72 m higher than the mean spring tidal range for St Ives of 5.84m. The tide measured on 10th January 1989 was a fairly extreme spring tide.
ii) On the ebb of the tide, the tidal level measured at Chapel Anjou Point is higher than the open water tidal level, suggesting that ebbing flows from the harbour are restricted by the narrowness of the channel to the open sea.
iii) On the ebb of the tide (but not close to low tide), the tidal level at Chapel Anjou Point is lower than that at the head of South Quay, suggesting a peak frictional hydraulic gradient of around 0.2m/1000m.
iv) Low tide at Chapel Anjou Point lags the open water low tide by approximately 1 ¾ hours.
v) Low tide at South Quay lags the open water low tide by approximately 2 ½ hours.
vi) Close to low tide, the water level at South Quay is lower than the water level at Chapel Anjou Point. It is suggested that this can be accounted for by the River Hayle water outflow experienced at Chapel Anjou Point. This is not experienced at the head of South Quay which experiences the far more modest outflows of the Copperhouse and Penpol streams.
vii) On the middle part of the flood of the tide to high tide, the open water tidal curve and the tidal curve at Chapel Anjou Point are coincident. This is to be expected as the cross sectional area of flow in the channel between the two locations rapidly increases with a rising tide.
viii) On the middle part of the flood of the tide to high tide, the tidal curve at Chapel Anjou Point leads the tidal curve at the head of South Quay by a little over ½ hour; the frictional hydraulic gradient between the two points remains approximately constant at around 0.8m / 1000m during this part of the tidal cycle.
ix) High water in Carnsew Pool lags the open water high water by approximately two hours.
x) There is a peak head difference of approximately 1.6 metres across the sluice tunnels between Carnsew Pool and Carnsew Quay (the latter presumed to have the same tidal level as the head of South Quay).
xi) Around high water in Carnsew Pool there is a period of approximately 1.9 hours when the head across the Carnsew sluice tunnels is less than 1 metre and a period of approximately 45 minutes when the head across the Carnsew sluice tunnels is less than 0.5 metres.
xii) Around the beginning of the tidal flood in Carnsew Pool, there is a period of approximately 1 hour 20 minutes when the head across the Carnsew sluice tunnels is less than 1 metre and a period of approximately 35 minutes when the head across the Carnsew sluice tunnels is less than 0.5 metres.

Conclusions based on these observations are as follows:
i) The tidal curve at Chapel Anjou Point is presently dominated by the narrowness of the channel connecting this position with St Ives Bay.
ii) The tidal curve at South Quay and Carnsew Quay is presently dominated by the narrowness of the channel between these locations and Chapel Anjou Point.
iii) The tidal curve within Carnsew Pool is presently dominated by the presence of sluice gates and tunnels that restrict the flow into and out of the pool despite the fact that the sluice gates are open and have remained that way since sluicing operations ceased in 1976.
iv) The present regulatory protections active on Carnsew Pool (the SSSI and the Bird Sanctuary designation) protect a tidal condition that already experiences the full impact of the weir and sluice arrangements.
v) Any modifications to the sea water ingress and egress arrangements, such as replacement of the sluice gates with tidal current turbines, should seek to preserve the current tidal conditions experienced by Carnsew Pool.
vi) Sufficient head is maintained across the Carnsew sluice tunnels to warrant further estimation of the energy recoverable through the tidal cycle.
vii) In order to achieve a reliable estimation of recoverable energy, it is essential to model the effect of the geometry of the navigable channel to Carnsew Quays to provide suitable boundary conditions for a subsequent model of the Carnsew sluice tunnels.

## Tidal flow model from St Ives Bay to Carnsew Quay

The tidal flow between open water within St Ives Bay to HR Wallingford Point D was modelled with the following equation:

$$Q = C_d A\sqrt{2gH} \tag{1}$$

where $Q$ is the discharge in m$^3$s$^{-1}$, $C_d$ is a discharge coefficient having a value of 0.65, $A$ is the cross sectional area of the flow, $g$ is the acceleration due to gravity and $H$ is the total head between St Ives Bay and Point D. An imaginary weir was assumed to be located at Point D, the level of which was found, heuristically, to be –1.07m OD. The effect of this imaginary weir was to maintain the level of water at Point D once the tidal curve had fallen to this point within the tidal cycle. Once the discharge rate is found, the total volume of water flow is determined through consideration of a short time increment $\Delta t$ taken to be 60 seconds in this and all computations conducted. This time increment is very small relative to a tidal period of 12.4 hours and thus conditions can be assumed stationary for the duration of each increment. The total volume of flow, $V$ (m$^3$) over $\Delta t$ is:

$$V = Q\Delta t \tag{2}$$

The volume of flow is divided by the surface area of the harbour lagoon, $A_B$ (m$^2$) to yield the change in level of water, $\Delta L$, in the impounded basin over the duration $\Delta t$:

$$\Delta L = \frac{V}{A_B} \tag{3}$$

This increment is algebraically added to the existing level of the harbour lagoon to obtain a revised harbour lagoon water level, taken to apply at Point D and Carnsew Quay.

$$L_{t+1} = L_t + \Delta L \tag{4}$$

The open water tide level and the new water level at Point D are used to determine the total head available to drive the flow into the harbour or out of the harbour and equation (1) is applied again over the next time step.

The parameters determined to achieve a good match between the HR Wallingford observations and the model results for the tidal curve at Point D (Figure 11) are as follows:

$A$ = 127.2 m$^2$.
$A_B$ = 800,000 m$^2$.
$C_d$ = 0.65
$\Delta t$ = 60 secs
Weir level = -1.07 m OD

## Tidal flow model from Carnsew Quay to Carnsew Pool

The procedure adopted between St Ives Bay and Carnsew Quay was repeated for the new set of circumstances between Carnsew Quay and Carnsew Pool, through the sluice tunnels. In this case, a cap was placed on the discharge rate, reflecting a choked flow through the tunnels, in addition to the constraint imposed by the level of the weir within Carnsew Pool. Equation (1) was used to determine a 'trial' discharge rate over the timestep. If this exceeded the threshold value, the discharge was assigned the capped value, otherwise the trial value was adopted. Results showing differences between HR Wallingford observations and the model results for the tidal curve at Point E are presented in Figure 12. The parameters controlling the computations are as follows:

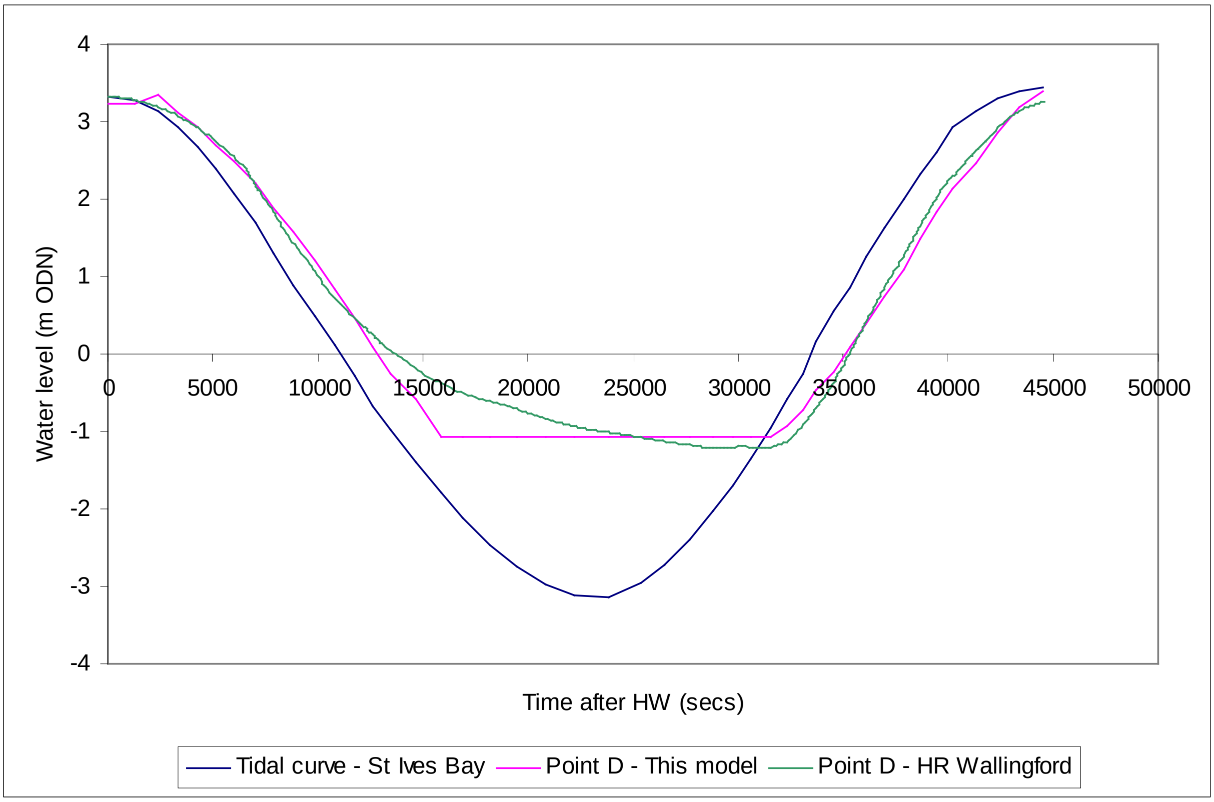

Figure 11: Results of calibrated model for flow between St Ives Bay and Carnsew Quay.

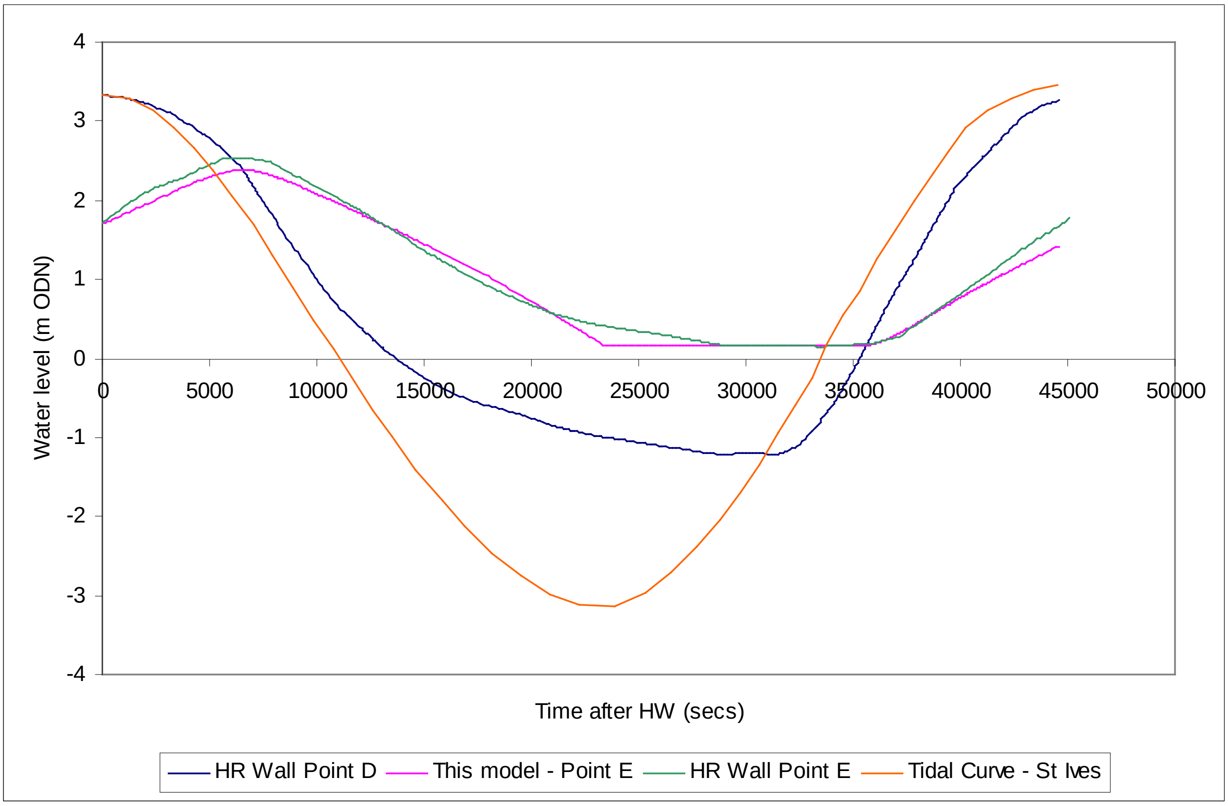

Figure 12: Results of calibrated model for flow between Carnsew Quay and Carnsew Pool.

$A$ = 6.3 $m^2$.
$C_d$ = 0.6
$\Delta t$ = 60 secs
Weir level = +0.17 m OD
Max discharge = 15.5 $m^3s^{-1}$.

Due to the gradient of the pool bed to the west of Carnsew Pool, a constant impounded basin area was not used. Rather, a new length of the water surface was calculated based on the Carnsew Pool geometry assumed in Figure 13. The results of the computations shown in Figure 12 show that the model was accurately calibrated under this tidal condition. Trials were also conducted ignoring the sloping pool base and revealed insignificant differences between the corresponding tidal curves. Consequently, subsequent computations adopted the simpler geometry with $A_B$ = 114,800 $m^2$.

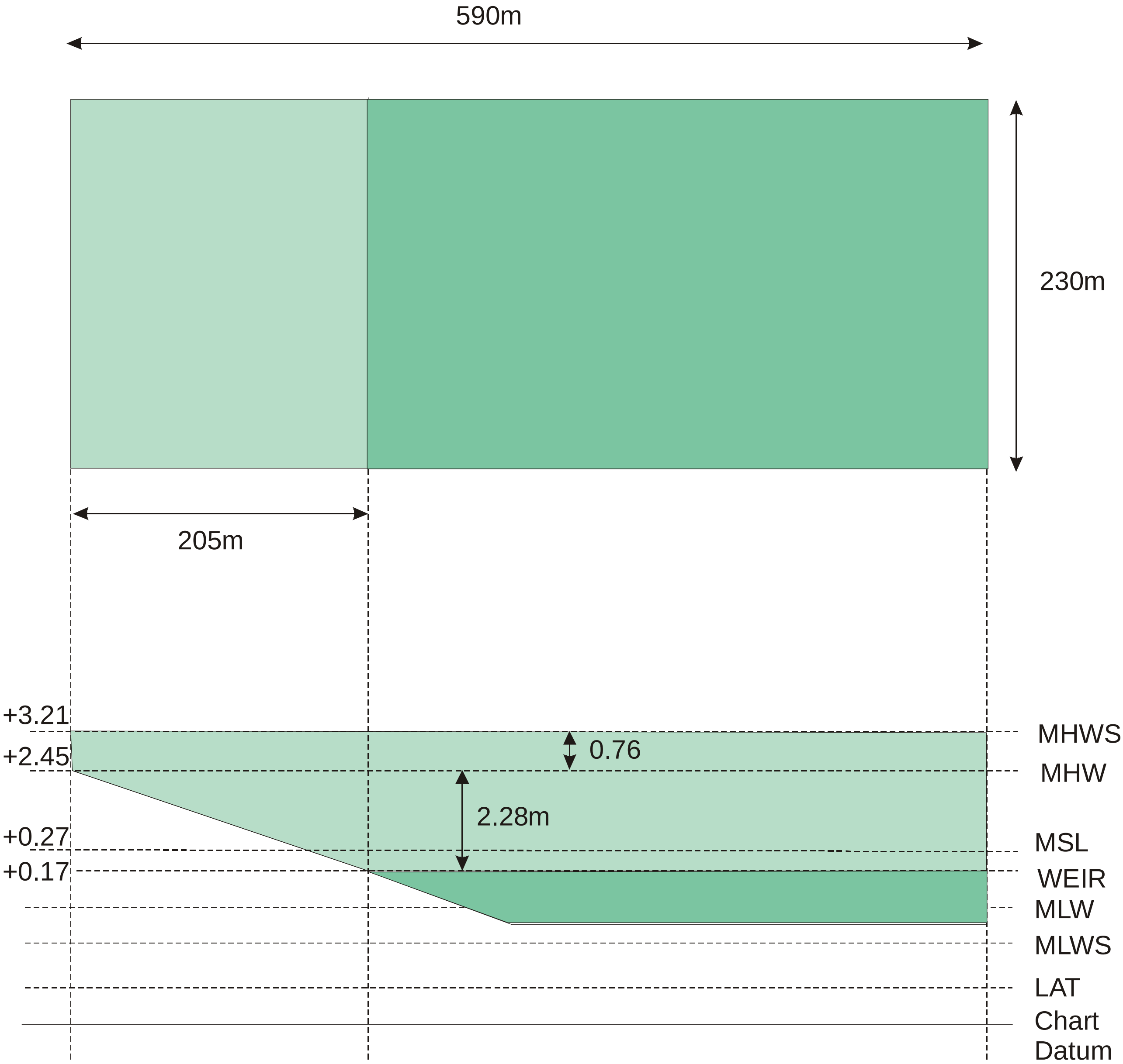

Figure 13: Assumed Carnsew Pool geometry for flow modelling computations between Carnsew Quay and Carnsew Pool.

# Tidal flow model from St Ives Bay to Carnsew Pool

A two stage flow model was prepared that linked the open water tidal condition in St Ives Bay to the tidal level at Carnsew Quay and used the output of this first stage to provide initial and boundary conditions for the second stage, that predicted the tidal level within Carnsew Pool.

All computations used the calibrated parameters determined as described in the previous two sections.

The purpose of formulating this compound model was to allow it to generalise to open water tidal ranges unlike the specific conditions observed on 10th January 1989. A series of single tidal cycle simulations involving open water tidal ranges varying from 1.0 m to 6.9 m were conducted. The simulations varied through systematic increase of the tidal range in increments of 0.02 m. In each step, the tidal curves at Point D and Point E were computed and the total available tidal energy resource was estimated.

In addition, the output that would be obtained from 4 x 1.44 metre diameter vertical axis ducted Darrieus tidal current turbines, operating in parallel under the same head and flow conditions as with the present sluice tunnel arrangements, was computed. The performance of these turbines was determined using experimental performance data for geometrically similar turbines reported by Takenouchi *et al*[8].

The results of applying this compound model to a tidal range of 6.56m (the same range as for the 10th January 1989) are presented in Figure 14 (without turbines) and Figure 15 (with turbines). The observed curves for HR Wallingford's Point D and Point E are shown for comparative purposes. It is important to realise that the open water tidal curves shown in Figures 14 and 15 are sinusoids with period 12.4 hours, whereas in the calibration studies physical tidal level observations were used. For this reason, the figures that will subsequently be presented for the energy yield of an array of tidal current turbines should be considered estimates rather than definitive.

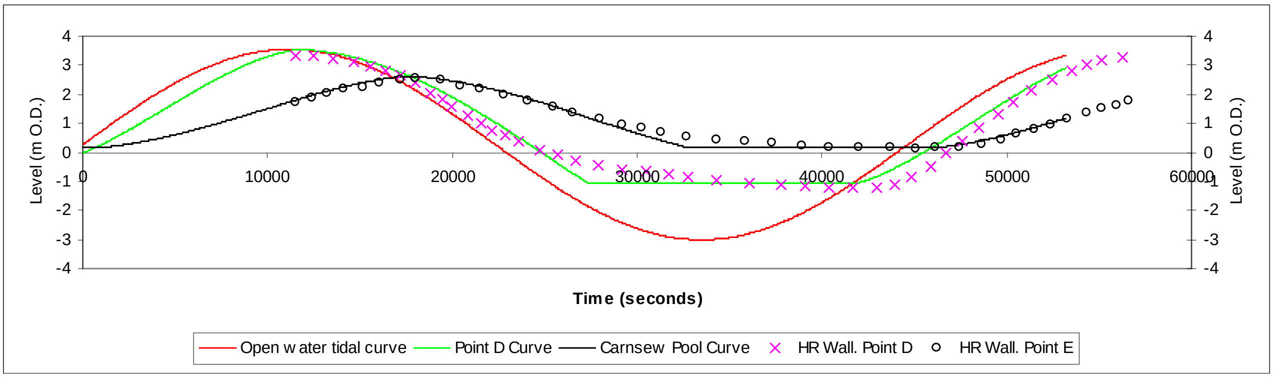

Figure 14: Results of compound model for an open water tidal range of 6.56m without a Darrieus tidal current turbine array.

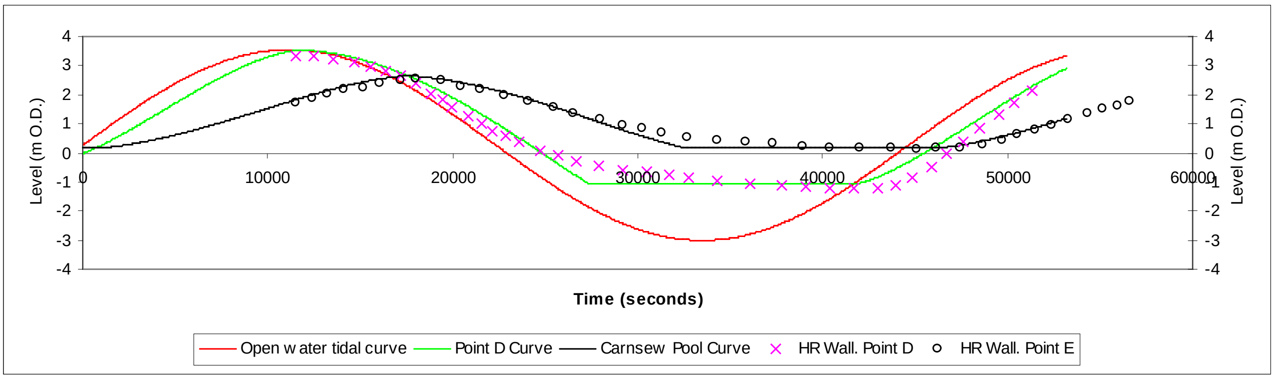

Figure 15: Results of compound model for an open water tidal range of 6.56m with a Darrieus tidal current turbine array.

Despite this, Figures 14 and 15 demonstrate that it is possible to engineer a turbine array such that the tidal curves in Carnsew Pool before and after turbine installation are identical against all practical measures. The principal design parameter is the span of the rectangular duct in which the turbine runners are located. In the simulation presented in Figure 15, the turbine duct span has been set at 1.55 metres to give the closest agreement between 'with' and 'without' Carnsew tidal curves. Details of the turbine geometry and performance are given in Figures 16 and 17.

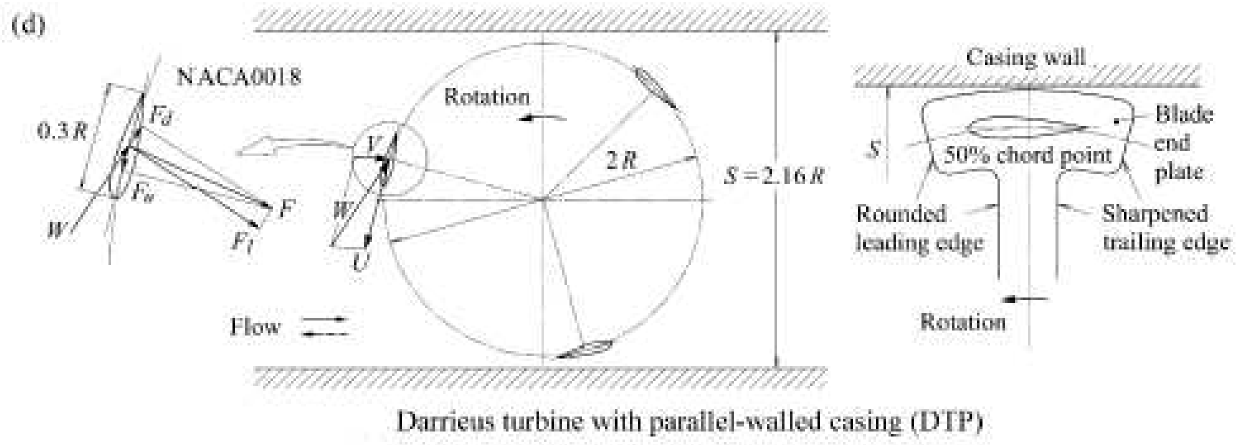

Figure 16: Diagram illustrating runner and duct geometry for the tidal current turbines considered in the simulations (taken from Takenouchi *et al*[8].)

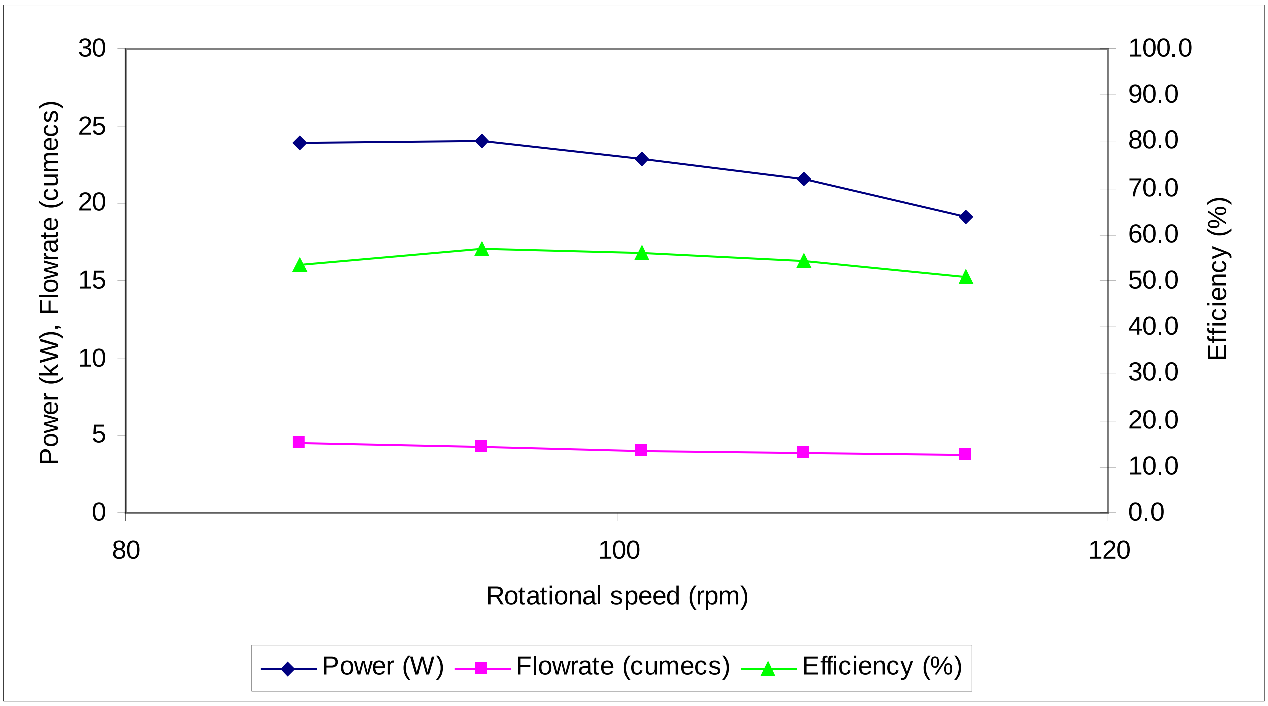

Figure 17: Performance curves for a vertical axis Darrieus tidal current turbine with S = 1.55m. Derived from experimental data reported by Takenouchi *et al*[8].

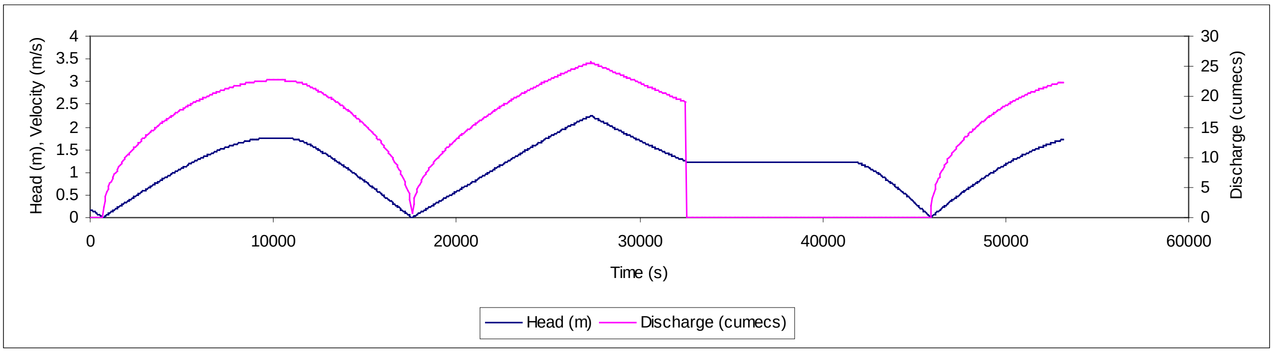

Figure 18: Variation of head and (combined) discharge across the turbine array model over a single tidal cycle with open water tidal range of 6.56m.

Figure 18 shows that any installed turbines that replace the sluice tunnels at Carnsew Pool could neither run under a condition of constant head or constant discharge. Accordingly, it is assumed that, always, the turbine is operated at the rotational speed corresponding to maximum efficiency of this turbine (which will vary) and that the generator is used with a variable voltage – variable frequency type inverter, that can effect control through variation of the excitation voltage and frequency. Consequently a rather low electrical generator efficiency of 80% has been used in determination of electrical energy produced. The maximum efficiency of the turbine runner is 56.5%. No frictional losses through the turbine ducting have been accounted for, as the duct lengths are likely to be short and the duct materials smooth.

## Annual Yields of Proposed Turbine Arrangements

Admiralty harmonic constants have been used to calculate high tide levels and low tide levels in the open water location of St Ives Bay for a period of 15 years. This information has then been used to calculate tidal ranges for the 10,607 tidal cycles within this period. Each tidal range has been applied in turn to the compound flow model discussed in previous sections and the electrical power output under the scenarios detailed has been estimated for each tidal cycle. Tidal cycle outputs have then been summed for each year to produce the following schedule of annual electrical power output. A total generating capacity of 265kW will be installed.

Table 2 : Annual output and array capacity factors

| Year | Output (kWh) | Capacity Factor |
|---|---|---|
| 1 | 371707 | 16.03 |
| 2 | 375687 | 16.20 |
| 3 | 381119 | 16.44 |
| 4 | 384448 | 16.58 |
| 5 | 388023 | 16.73 |
| 6 | 395615 | 17.06 |
| 7 | 404269 | 17.43 |
| 8 | 410367 | 17.70 |
| 9 | 413013 | 17.81 |
| 10 | 412756 | 17.80 |
| 11 | 413078 | 17.81 |
| 12 | 413381 | 17.83 |
| 13 | 408881 | 17.63 |
| 14 | 398222 | 17.17 |
| 15 | 391267 | 16.87 |

## Valuation Model of Carnsew Tidal Turbines

The four vertical axis Darrieus tidal current turbines will have a total width of 6.2 metres and a length of around 2 metres. Thus they should be easily accommodated within the confines of the existing sluice tunnel arrangements. The turbines could be operated with bearings at the top end only, with all electrical generators, drive train components, inverters and switch gear contained in a single freight container sized package, mounted over the existing sluice gate service chamber. There are good prospects for the bulk of this package to be fabricated and assembled off-site and craned into position.

The economic feasibility of the Carnsew tidal turbine array has been assessed using discounted cash flow procedures under the following set of base case financial assumptions:

| | | | |
|---|---|---|---|
| 1) | Value of electricity produced | 7.95 | p/kWh |
| 2) | Site rent | 2% | of annual revenue |
| 3) | Tax rate | 30% | with one year tax lag |
| 4) | Capital allowances | Straight line over project life (15 years) | |
| 5) | Working capital | 8.3% | of annual operating costs |
| 6) | Fixed operating costs | 5% | of capital costs |
| 7) | Variable operating costs | nil | |
| 8) | Capital expenditure | £500 | per kW installed capacity |
| 9) | Grant rate | 0% | of capital costs |
| 10) | Discount rate | 12% | |

The results of the analysis indicate that the break even cost of electricity produced from the site is 7.95p/kWh. This is a price for which there is a good expectation of receiving, under the current market arrangements for electricity produced using renewable energy resources. It implies a Renewables Obligation Certificate (ROC) price of 5.5p/kWh, given a pool price for electricity of 2p/kWh and a climate Levy Exemption Certificate (LEC) price of 0.45p/kWh.

Site rent is assumed to be paid to ING Real Estate.

A figure of 5% of capital expenditure has been used to estimate fixed operating costs for the installation, these primarily comprising spares, maintenance and insurance. This is a rate considered typical for the wind power industry and should not be expected to be hugely different.

Capital expenditure is estimated at a rate of £500 per kW of installed capacity. This is appreciably lower than would be considered for a virgin tidal lagoon project, the rationale for this being that all the rather expensive civil infrastructure costs for constructing the dam walls were incurred by Henry Harvey in 1834. Turbine runner manufacture should be cheap, as the Darrieus turbine runners are simple to fabricate in comparison to other types of turbine. Connection to the electrical distribution grid may be possible cheaply at the proposed WaveHub sub-station. A cable run of around 500 metres would be required to connect output from the Carnsew turbines to the WaveHub sub-station. This assumes that overhead wires or cables laid on the harbour bed are acceptable. It may also be possible to use the existing tunnel connection with North Quay, if the shafts and tunnel are still serviceable. In any event, 11kV lines exist overhead at the Carnsew sluice tunnels and an 11kV direct connection may be possible. In short, there are good prospects that the capital costs could be less than £500 per kW of installed capacity.

A grant rate of 0% has been applied in the base case model to test the true financial viability of the Carnsew turbines under the technical constraints that will apply to the site. However, there are good prospects that grant funds will be able to be drawn down against this project, grant being awarded via the Department of Trade and Industry. Grant rates for commercial projects are typically around 45% of the total capital cost.

Finance Cornwall Ltd., have negotiated loan rates of 12% for small, speculative commercial projects such as this. Accordingly, a discount rate of 12% has been applied in the project valuation process.

The results of the base case financial valuation process under the above conditions are presented in Table 3.

Table 3: Carnsew Tidal Current Turbines Cashflow Model illustrating break even cost of electricity production.

| | | |
|---|---|---|
| Life of Project | 15 | years |
| Site rent | 2 | % |
| Tax rate on profits | 30 | % , one year tax lag |
| Capital allowance calculation | Straight line | |
| Working Capital | 8.3 | % of accounting period operating costs |
| Installed capacity | 265 | kW |
| Revenue | 0.0795 | £/kWh |
| Annual fixed operating costs | 6617 | £ |
| Variable operating costs | 0 | £/unit |
| Year 1 Capital expenditure | 500 | £/kW |
| Grant rate | 0% | |

| End of Year | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | Totals |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Output (kWh) | | | 371707 | 375687 | 381119 | 384448 | 388023 | 395615 | 404269 | 410367 | 413013 | 412756 | 413078 | 413381 | 408881 | 398222 | 0 | |
| Revenue | | | 29551 | 29867 | 30299 | 30564 | 30848 | 31451 | 32139 | 32624 | 32835 | 32814 | 32840 | 32864 | 32506 | 31659 | 0 | 442860 |
| Fixed Operating Costs | | | 6617 | 6617 | 6617 | 6617 | 6617 | 6617 | 6617 | 6617 | 6617 | 6617 | 6617 | 6617 | 6617 | 6617 | 0 | 92645 |
| Variable Operating Costs | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Site rent | | | 591 | 597 | 606 | 611 | 617 | 629 | 643 | 652 | 657 | 656 | 657 | 657 | 650 | 633 | 0 | 8857 |
| Operating Margin | | | 22342 | 22652 | 23076 | 23335 | 23613 | 24205 | 24879 | 25354 | 25560 | 25540 | 25565 | 25589 | 25238 | 24408 | 0 | 341358 |
| Capital Expenditure | | 132350 | | | | | | | | | | | | | | | | 132350 |
| New Capital Allowance in period | | | 9454 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Total Capital Allowances for period | | | 9454 | 9454 | 9454 | 9454 | 9454 | 9454 | 9454 | 9454 | 9454 | 9454 | 9454 | 9454 | 9454 | 9454 | 0 | 132350 |
| Taxable Income | | | 12889 | 13199 | 13622 | 13881 | 14160 | 14751 | 15426 | 15901 | 16107 | 16087 | 16112 | 16135 | 15785 | 14954 | 0 | |
| Loss c/f | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Tax on Income | | | 3867 | 3960 | 4087 | 4164 | 4248 | 4425 | 4628 | 4770 | 4832 | 4826 | 4834 | 4841 | 4735 | 4486 | 0 | 62703 |
| Working Capital | | 0 | 551 | 551 | 551 | 551 | 551 | 551 | 551 | 551 | 551 | 551 | 551 | 551 | 551 | 551 | 0 | |
| Increase in Working Capital | | | 551 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -551 | 0 |
| Grants | 0 | | | | | | | | | | | | | | | | | |
| Cashflow | 0 | -132350 | 21791 | 18786 | 19116 | 19248 | 19449 | 19957 | 20454 | 20727 | 20790 | 20708 | 20739 | 20755 | 20398 | 19673 | -3935 | 146306 |
| Cumulative Cashflow | 0 | -132350 | -110559 | -91773 | -72657 | -53409 | -33960 | -14003 | 6451 | 27177 | 47967 | 68676 | 89415 | 110170 | 130568 | 150241 | 146306 | |
| Discount rate | 12% | | | | | | | | | | | | | | | | | NPV(12%) |
| Discounted cashflows | 0 | -118169 | 17371 | 13371 | 12149 | 10922 | 9853.5 | 9027.5 | 8260.9 | 7474.2 | 6693.9 | 5953.1 | 5323.3 | 4756.6 | 4173.8 | 3594.1 | -641.9 | 113 |

Table 4: Carnsew Tidal Current Turbines Cashflow Model illustrating project value with 45% grant, electricity price 8.5p/kWh and 100% capital allowances in the year capital expenditure is made.

| | | |
|---|---|---|
| Life of Project | 15 | years |
| Site rent | 2 | % |
| Tax rate on profits | 30 | % , one year tax lag |
| Capital allowance calculation | 100 | % in year spent |
| Working Capital | 8.3 | % of accounting period operating costs |
| Installed capacity | 265 | kW |
| Revenue | 0.085 | £/kWh |
| Annual fixed operating costs | 6617 | £ |
| Variable operating costs | 0 | £/unit |
| Year 1 Capital expenditure | 500 | £/kW |
| Grant rate | 45% | |

| End of Year | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | Totals |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Output (kWh) | | | 371707 | 375687 | 381119 | 384448 | 388023 | 395615 | 404269 | 410367 | 413013 | 412756 | 413078 | 413381 | 408881 | 398222 | 0 | |
| Revenue | | | 31595 | 31933 | 32395 | 32678 | 32982 | 33627 | 34363 | 34881 | 35106 | 35084 | 35112 | 35137 | 34755 | 33849 | 0 | 473498 |
| Fixed Operating Costs | | | 6617 | 6617 | 6617 | 6617 | 6617 | 6617 | 6617 | 6617 | 6617 | 6617 | 6617 | 6617 | 6617 | 6617 | 0 | 92645 |
| Variable Operating Costs | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Site rent | | | 632 | 639 | 648 | 654 | 660 | 673 | 687 | 698 | 702 | 702 | 702 | 703 | 695 | 677 | 0 | 9470 |
| Operating Margin | | | 24346 | 24677 | 25130 | 25407 | 25705 | 26337 | 27058 | 27566 | 27787 | 27765 | 27792 | 27817 | 27442 | 26554 | 0 | 371383 |
| Capital Expenditure | | 132350 | | | | | | | | | | | | | | | | 132350 |
| New Capital Allowance in period | | | 132350 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Total Capital Allowances for period | | | 132350 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 132350 |
| Taxable Income | | | -108004 | -83327 | -58197 | -32790 | -7085 | 19252 | 27058 | 27566 | 27787 | 27765 | 27792 | 27817 | 27442 | 26554 | 0 | |
| Loss c/f | | | 108004 | 83327 | 58197 | 32790 | 7085 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Tax on Income | | | 0 | 0 | 0 | 0 | 0 | 5776 | 8117 | 8270 | 8336 | 8330 | 8338 | 8345 | 8233 | 7966 | 0 | 71710 |
| Working Capital | | 0 | 551 | 551 | 551 | 551 | 551 | 551 | 551 | 551 | 551 | 551 | 551 | 551 | 551 | 551 | 0 | |
| Increase in Working Capital | | | 551 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -551 | 0 |
| Grants | 59557 | | | | | | | | | | | | | | | | | |
| Cashflow | 59557 | -132350 | 23794 | 24677 | 25130 | 25407 | 25705 | 26337 | 21282 | 19449 | 19517 | 19429 | 19462 | 19480 | 19097 | 18322 | -7415 | 226881 |
| Cumulative Cashflow | 59557 | -72792 | -48998 | -24321 | 809 | 26216 | 51921 | 78258 | 99540 | 118989 | 138506 | 157935 | 177397 | 196877 | 215974 | 234296 | 226881 | |
| Discount rate | 12% | | | | | | | | | | | | | | | | | NPV(12%) |
| Discounted cashflows | 59557 | -118169 | 18969 | 17564.8 | 15970.4 | 14416.6 | 13022.9 | 11913.6 | 8595.63 | 7013.39 | 6283.85 | 5585.42 | 4995.5 | 4464.22 | 3907.65 | 3347.32 | -1209.5 | 76228 |

Under a slightly more optimistic scenario (Table 4) of 45% grant being awarded, 100% capital allowance in year of expenditure being permissible (as is the case for the majority of renewable energy projects at present) and a price for the electricity produced at 8.5p/kWh, the financial performance measures are as follows:

Payback period = ~3.9 years
NPV(12%) = £76,228
IRR = >60%
Cost of electricity = 4.35 p/kWh

There are opportunities to improve the project performance measures further, through consideration of financing some of the project cost via a loan, to improve early years' cash flows. These considerations are not taken into account here.

The Department of Trade and Industry has committed to the promotion of marine renewable energy through the payment of an additional 10p/kWh for wave and tidal energy projects. Undoubtedly, the DTI thrust in tidal energy is toward offshore marine current turbines. Despite this, the proposals herein for Carnsew Pool in Hayle Harbour do utilise tidal energy and thus there are good prospects that this enhanced payment for electricity arising from the turbines will apply. Under this scenario, the total value of each kWh of electricity produced would be around 17.5p/kWh. Assuming 0% grant, the NPV(12%) for this project is £170,261. Assuming 45% grant, the NPV(12%) for this project is £229,818 indicating a definite 'go' for development.

## Conclusions

1) The tidal curve experienced by Carnsew Pool is already determined by the constriction in available flow area imposed by the presence of the Carnsew sluice gates and tunnels.
2) It is technically feasible to install an array of tidal current turbines where the current Carnsew sluices are installed, subject to the constraint that currently applying tidal curves within Carnsew Pool are maintained post installation.
3) A second connection to Carnsew Pool from Carnsew Quay has been reinstated as part of current site improvement works. This could accommodate a new fish migration route. Fish screens could easily be installed at inlet and outlet of tunnels leading to the proposed turbines.
4) The natural resource could sustain a total installed capacity of tidal current turbine generators equal to 265 kW operating with a capacity factor between 16.0 and 18.8%, depending on the year concerned.
5) The base case financial valuation scenario suggests a break even cost of electricity production of 7.95 p/kWh.
6) The practical financial scenario has positive project valuation measures.
7) An interpretation center is being actively pursued by ING Real Estates as part of their Hayle Harbour redevelopment. Should this centre be planned to be located close to the existing Carnsew sluices, the proposed Carnsew turbines could feature within it to highlight benefits of the physical, as well as the ecological environment.
8) Government Policy in relation to tidal barrage schemes is lukewarm at present but nevertheless the Carnsew Turbines could well be eligible for the Marine Renewable Energy ROC enhancement. In this instance, this project should be expedited without delay.

## Actions Arising

8) A meeting should be arranged with ING Real Estate to communicate the findings of this report and to determine whether or not they are amenable to the idea of installing tidal current turbines within the Carnsew sluice tunnels as part of their developments.
9) Alternative tidal current turbines should be investigated for adoption within the Carnsew Pool context. A turbine runner efficiency higher than 56.5% will improve the yield and hence the financial returns arising from the proposed Carnsew turbines.
10) The DTI should be approached to confirm that the proposed Carnsew turbines would meet or will meet their criteria for capital grant support and marine renewable energy ROC

enhancement. The Carbon Trust and possibly Government research councils should be similarly contacted.

11) Instrumentation to measure the levels of tides within and outside Carnsew Pool should be installed to conduct site monitoring for at least one year. This should be done as soon as possible.
12) The Carnsew tunnels need to be inspected in the context of the proposed tidal current turbines.
13) The locations of shafts and tunnels between Carnsew and North Quay need to be confirmed.
14) This report represents the results of a conceptual feasibility study. A more detailed feasibility study / detailed design and costing study will be required.

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