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The energy gains realisable through pumping for tidal range energy schemes

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ABSTRACT

Some previous work has made optimistic claims about the potential energy gains that could be made by using pumping with tidal range structures (barrages, lagoons and offshore tidal impoundments). This paper explores the factors influencing whether such gains can be realised for positive head pumping (pumping once water levels have equalised), using 0-D modelling concepts.

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1. Introduction

With concerns mounting over the UK's energy future due to the related issues of energy security and cost of energy, focus has naturally turned to renewable alternatives. Tidal range energy (using a structure to delay tidal motions as sea level changes, thereby creating a water level difference to drive turbines) is of interest as it is a proven technology delivering energy at predictable times, the barrage at La Rance in France having operated successfully since 1966 [1]. This interest has been reflected in a number of recent major studies in the UK, such as the Peele Holdings (2011) study of the Mersey [2], and the Department of Energy and Climate Change (2010) study of the Severn Estuary [3].

Barrages and Lagoons are capital intensive (though arguably they produce energy that is price competitive with other renewable sources over the 120+ year lifespan of such structures), and so some (limited) attention has been given to boosting energy gains via pumping, thereby improving the economic case for such structures.

For example MacKay [4] simplistically explored the potential energy between high and low tide levels, concluding that energy gains of 300+% could theoretically be achieved if it were possible to pump to optimum boost height (which was 6.5 times the tidal amplitude). Similar results were reported by Anderson [5] (pers-comm) for dual mode (two-way) operation of a tidal range structure. Such claims are significantly above the pumping energy gains of ~10% reported by Hillairet and Weisrock [6] for the operational La Rance barrage, and roughly the same figure was reported by Shaw and Watson [7] from computer modelling of a proposed barrage on the Severn Estuary.

With such a range of reported energy gains, there is a need to systematically examine the assumptions behind these estimates, in order to elucidate the key factors controlling realisable energy gains using positive head pumping, and this is what is presented in this paper.

The principles of tidal range energy schemes are illustrated in Fig. 1. For 'ebb-mode' electricity generation, the release of high tide out of the basin is held back; for 'flood-mode' entry of water into the basin is deferred as tide levels rise; and 'two-way (dual) mode' is a combination of both (Fig. 1). Each mode permits generation for typically between 8 and 11 h a day. Fig. 1 also illustrates positive head pumping, which uplifts (or lowers) the basin (estuary) water levels. With suitable turbine and pump efficiencies, the energy expended in pumping is outweighed by the additional energy gained in turbine operation, giving a net energy gain.

2. Pumping energy gains

2.1. Idealised 'Tidal Pool'

MacKay [4] calculated pumping energy gains for a 'Tidal Pool', assuming that it could be filled or emptied instantaneously (which implies infinite flow rates). In his analysis, the energy captured is then the potential energy change (by dropping the water levels)

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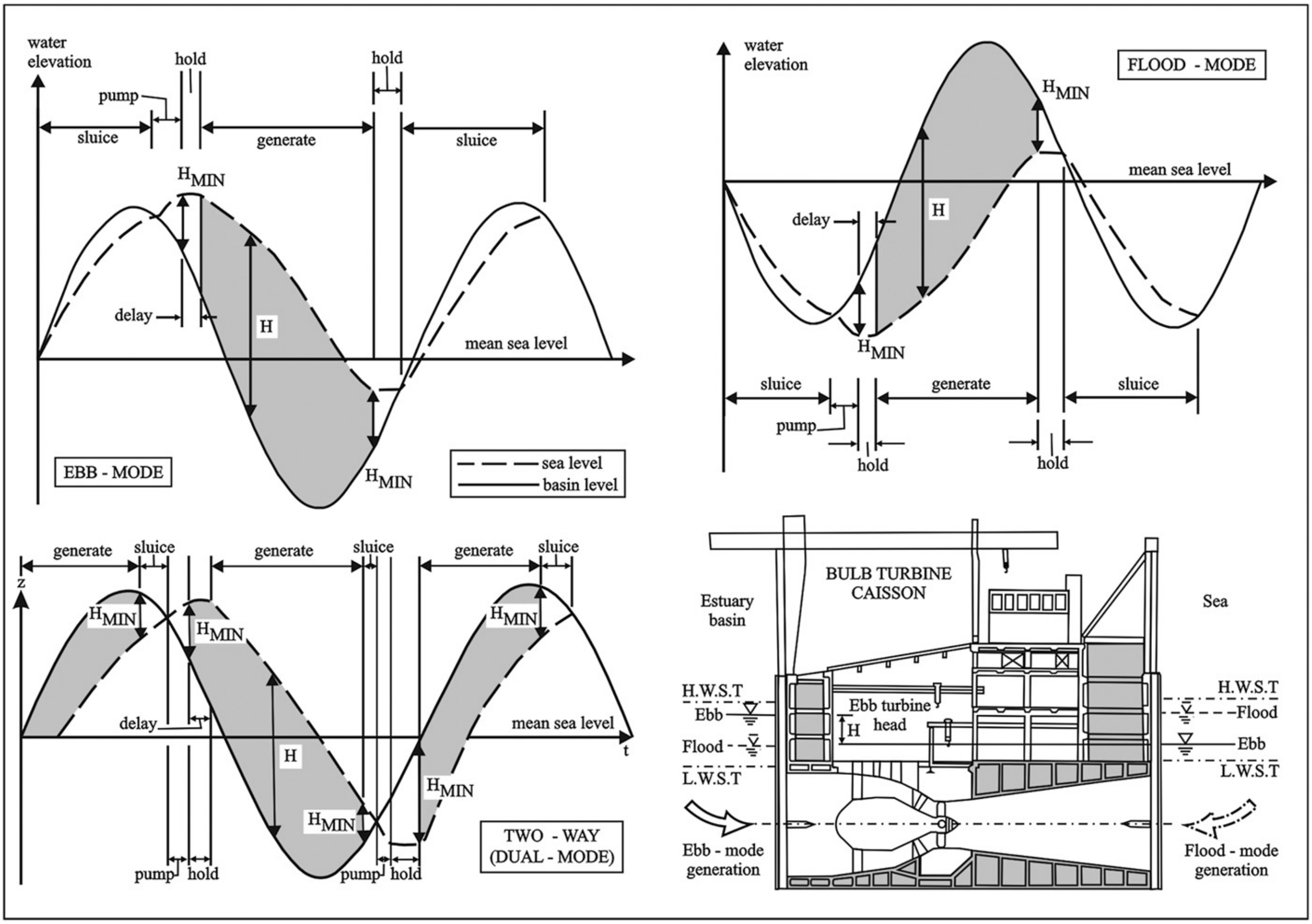

Fig. 1. Modes of operation of tidal range structures together with an illustration of a turbine caisson, from Burrows et al. [13].

multiplied by the turbine efficiency, η_t. Equally, pumping raises the potential energy of the water, at an energy cost of the potential energy gained multiplied by 1/(the pump efficiency, η_p). From this analysis, the optimum pumping height ("boost height", b_{optimum}) is then given by

$$b_{\text{optimum}} = 2h\frac{\varepsilon}{1-\varepsilon} \tag{1}$$

where h is the tidal amplitude and ε is the round trip efficiency ($=\eta_t\ \eta_p$).

The net energy gained by pumping is given by

$$\Delta E(\text{Pumping}) = \left[\frac{(2h+b)^2}{2}\rho g\eta_t\right] - \left[\frac{b^2}{2}\rho g\frac{1}{\eta_p}\right] - \left[2h^2\rho g\eta_t\right] \tag{2}$$

where b is the boost height and ρ is the water density.

MacKay's analysis assumed values of 0.95 for η_t, and 0.8 for η_p, based on realistic values from conventional pump storage hydropower schemes where turbines operate constantly at their optimum efficiency, and pumping heads are large.

The first part of the analysis performed in this paper was to explore the impact of (single value pair) turbine and pump efficiencies on the pumping energy gain and boost height, retaining the assumption of instantaneous adjustment of water levels. The results of this exploration are shown in Table 1, with the percentage net energy gain as a function of the round trip efficiency shown in Fig. 2.

MacKay [4] used units of power per unit area (W/m^2) to allow comparison across different energy sources. Equation (2) gives results in terms of energy, and so, in order to allow comparison with MacKay's results, these energy figures were translated into an energy figure per unit area, and then divided by the time for a tidal cycle to give a 'power' per unit area. These units are arguably misleading, since MacKay's treatment assumes instantaneous water flows, which, given that power is strictly the rate at which work is done, implies infinitely large power pulses at the time of water release.

As can be seen from Table 1 and Fig. 2, the energy gain possible from pumping is critically dependent on the turbine and pump efficiencies, even with the assumption of instantaneous flows and unlimited pumping height (and depth).

The values used by MacKay seem overoptimistic, since tidal range power schemes operate over a range of head values (as shown by Baker [8]). The actual performance of the turbine at any time is governed by its performance Hill Chart, turbines being typically operated along the maximum output line of this chart. The maximum hydraulic efficiency in practice is typically ~92%, and the turbine efficiency will decrease from this value when being operated at heads different from the turbine's rated head. This is especially an issue for ebb mode operation because of the wider range of heads experienced during operation.

In this paper, an average turbine efficiency of 75% was assumed as a reasonable first estimate, which was then reduced by 0.95

Table 1
Energy change arising from the use of pumping, with varying turbine and pump efficiencies, for a tidal amplitude h, allowing instantaneous flow release and unconstrained pumping.

Turbine efficiency	Pumping efficiency	Optimum boost height/h	Power consumed in pumping per unit area/h^2 (W/m^2)	Power generated per unit area with pumping/h^2 (W/m^2)	Power generated per unit area without pumping/h^2 (W/m^2)	% net energy gain using pumping
0.9	0.85	6.51	10.94	14.31	0.79	325.53
0.9	0.65	2.82	2.68	4.59	0.79	140.96
0.9	0.45	1.36	0.90	2.23	0.79	68.07
0.9	0.25	0.58	0.30	1.32	0.79	29.03
0.8	0.85	4.25	4.66	6.86	0.70	212.50
0.8	0.65	2.17	1.59	3.05	0.70	108.33
0.8	0.45	1.13	0.62	1.71	0.70	56.25
0.8	0.25	0.50	0.22	1.10	0.70	25.00
0.75	0.85	3.52	3.19	5.01	0.66	175.86
0.75	0.65	1.90	1.22	2.51	0.66	95.12
0.75	0.45	1.02	0.51	1.50	0.66	50.94
0.75	0.25	0.46	0.19	1.00	0.66	23.08
0.7	0.4	0.78	0.33	1.19	0.61	38.89
0.7	0.5	1.08	0.51	1.45	0.61	53.85

(following the approach of UKAEA [9]) to account for generator efficiency, giving an overall efficiency of ~0.7 for conversion of fluid energy to electrical energy. A more reasonable average pump efficiency was estimated from examination of real pump efficiencies for low head pumping of ~1m (the DTI Duddon study [10] and Balls [11]), giving an (assumed) value of 0.4.

With these assumed efficiencies, the overall energy gain from pumping fell from 325% to 39%, though this increased to 54% for a pump efficiency of 0.5. It is also worth emphasising that MacKay's 325% estimated gain also implies a huge (6.5 × h) raising of the embankment crest, with a matching extreme lowering of the impoundment bed levels.

2.2. Idealised 'Tidal Pool' under spring/neap tides with constrained water levels

This exploration was repeated with the addition of the S_2 (Solar) tidal component to the larger M_2 (lunar) tide, allowing a spring to neap cycle to be examined. Such a tide can be modelled as:

$$Y = A_{M_2}\cos(\omega_{M_2}t) + A_{S_2}\cos(\omega_{S_2}t) \qquad (3)$$

where Y is the tidal elevation, A_{M_2} is the M_2 tidal amplitude, ω_{M_2} is the M_2 frequency (28.984°/hour), A_{S_2} is the S_2 tidal amplitude, ω_{S_2} is the S_2 frequency (30.000°/hour), and t is the time in hours, ignoring the real phase difference in the M_2 and S_2 components.

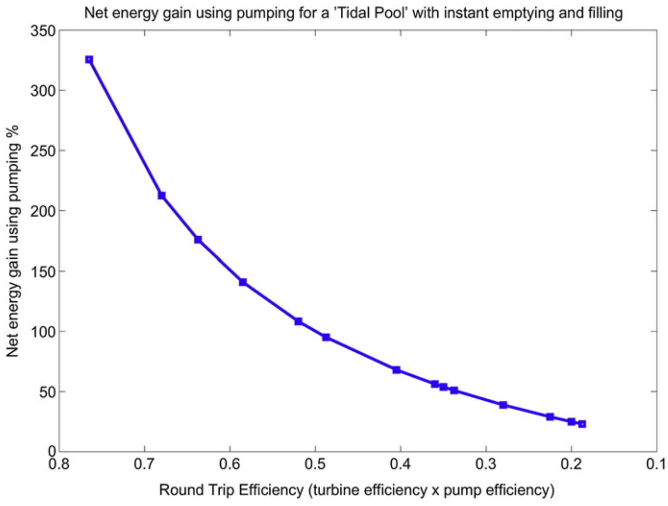

Fig. 2. Net percentage energy gain with pumping as a function of round trip efficiency, allowing instantaneous flow release and unconstrained pumping.

In order to model the situation behind an estuarial barrage, simulated water levels (changed through pumping) were not permitted to be larger than high or low water spring tide. Pumping was thus limited to the smaller of the boost height for that tide or high (or low) water spring tide. The high water restriction simulates flood restrictions which would be a consideration for estuarial barrages, whilst the low water constraint means that no dredging is (theoretically) required to drop low water levels.

In this analysis, the 'Tidal Pool' is dropped (or raised) instantaneously from high water to low water (or low to high) for each pair of high and low water levels through the spring-neap cycle. The difference between these water levels, divided by two, was taken to be the tidal amplitude for that cycle, from which the optimum boost height could be calculated using Equation (1). Simulated instantaneous pumping was then performed to the smaller of high (low) water spring tide or the boost height.

The times of high and low water are known from Equation (3), and so it was straightforward using this equation, and Equation (2), to compute the pumping energy gains from ebb and flood independently, and then to combine them into a total figure for a range of turbine and pump efficiencies. This was performed for an M_2:S_2 ratio of 2:1 (expected from equilibrium tidal theory) and 3:1 (more often encountered for estuaries in the North West of England in the observed tidal record), a summary of the results of which are shown in Fig. 3. The addition of the S_2 tidal component increases the total potential energy of the tide by 10% for a 2:1 M_2:S_2 tidal amplitude ratio, and 4% for 3:1 ratio.

Percentage pumping energy gain was found to be dependent only on the M_2:S_2 ratio, a range of value pairs (2:1, 4:2, 3:1 and 4.5:1.5) having being tested in addition to the ones shown in the figure.

The addition of constraints to high and water levels through a spring to neap tide, still with the assumption of instantaneous flows, caused pumping energy gains to fall to 17% for the assumed 'reasonable' efficiencies of 0.7/0.4. Even with 100% turbine and pump efficiencies, the maximum pumping energy gain was restricted to 27% (for a 3:1 M_2:S_2 ratio) due to the height and depth restrictions.

2.3. 0-D modelling

The next stage of analysis performed in this paper was to add in the constraints of cost effective numbers of turbines and sluices,

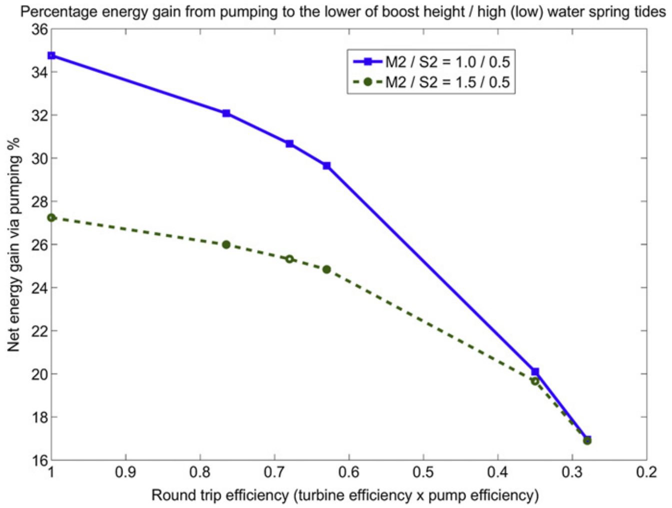

Fig. 3. Net percentage energy gain arising from the use of pumping to the lower of boost height/high (low) water spring tide with varying turbine and pump efficiencies for a range of M_2 and S_2 tidal amplitudes, with a 2:1 and 3:1 M_2:S_2 ratio.

with finite flow velocities through the tidal range structure, but still with constant turbine and pump efficiencies. As argued in Section 2.1, 'realistic' turbine and pump efficiencies were taken to be 0.7/0.4.

This simulation was performed using so-called 0-D modelling, in which it is assumed that water arrives, and departs from, the tidal range structure instantaneously, and so the only flow consideration affecting water levels behind the structure are the flows through the structure. More sophisticated models (2-D or 3-D) are needed to explore the hydrodynamics external to the structure.

Following the approach outlined by Baker [8], 0-D models have the governing equation:

$$S(z)\frac{dz}{dt} = Q(H) \tag{4}$$

where z is the water level in the basin, t is time, $S(z)$ is the surface area of the enclosed basin, H is the difference in water levels across the barrage and Q is the flux through the barrage. For turbine operation, the flux values are obtained from the turbine operating path, with linear interpolation used to determine exact values.

When sluices are used or the turbines are operating in sluicing mode the flux is given by the sluice equation:

$$Q = C_d A\sqrt{2gH} \tag{5}$$

where C_d is the sluice coefficient, and A is the sluice area (so C_dA is the effective sluice area).

More detail on 0-D modelling, including extensive studies of barrage operating modes and configurations, may also be found in Burrows et al. [12–14].

Since this exercise was illustrative, a vertical sided basin of area 100 km^2 was used with turbines and pumps of fixed efficiency (0.7/0.4) regardless of head, and a constant 100 m^3/s flow rate at all heads was assumed for both pumping and turbining. Whilst these choices were to some extent arbitrary, they are broadly consistent with Prandle's approach [15] who also assumed a constant flow rate through the turbines. In order to allow a comparison with Section 2.2, 0-D modelling was performed with the same tidal amplitudes of $M_2 = 1$m, $S_2 = 0.5$ and $M_2 = 1.5$m, $S_2 = 0.5$. Again following Prandle, the start/stop head for turbining was selected as 0.4*the M_2 tidal amplitude.

The UK Department of Energy Studies (DoEn) of the 1980s [9,16], found that the most cost effective configurations had capacity which dropped the basin level to about mean water level in ebb mode. (Herein referred to as a '1xDoEn' scheme). From trial and error, a capacity of 60 idealised turbines of 70% efficiency was found to be an approximate 1xDoEn configuration for the vertical sided test basin with tidal amplitudes of $M_2 = 1$m, and $S_2 = 0.5$m, this being increased to 90 turbines for $M_2 = 1.5$m, $S_2 = 0.5$m. A rough estimate of an affordable sluice capacity was obtained by following the approach of Prandle [15] (taking a dimensionless gate area of 7.0) for the 100 km^2 basin used in this exercise, giving corresponding sluice areas of 3535 m^2 and 4330 m^2.

Using these configurations of pump-turbines and the vertical-sided basin, 0-D modelling was used to explore the energy gained by pumping for ebb and dual (two-way) barrage operation, with pumping both constrained and unconstrained by restricting high (low) water to high (low) water spring tide, and the results are shown in Table 2.

As can be seen from the table, with the addition of finite flow velocities, and finite turbine and sluice capacities, pumped energy gain is at best 6%, compared to 17% allowing instantaneous constrained flow (for turbine/pump efficiencies of 0.7/0.4). This is to be expected, as pumping at finite rates means that water levels cannot be uplifted (or lowered) to the same extent before changes to the external tidal level make pumping uneconomic. Also apparent from the table is the fact that ebb mode operation experiences larger gains from pumping than dual mode, and this is broadly in line with the findings of Burrows et al. [14], reflective of the fact that 1xDoEn dual mode operation (which oscillates around mean water) has a shorter generation window and lower average head than ebb mode operation.

2.4. 0-D modelling with real turbine and pump characteristics

The final analysis performed was to use 0-D modelling to explore the energy gained by pumping for the Duddon estuary, because real turbine and pump performance curves were available from the 1994 DTI study of this estuary [10]. This final 0-D modelling adds on the constraints of bathymetry and real hydraulic machinery performance characteristics to a realistic and cost effective barrage configuration. The turbine and pump efficiencies used in this study are presented in Fig. 4. In addition to exploring pumping energy gains for the estuary, calculations were performed for a hypothetical 'Duddon Lagoon', assumed to have vertical sides (constant bathymetry), and an area equal to the average area exposed during a typical ebb barrage operating cycle from high to mean water. This was to explore the effects of pumping with unconstrained water levels. More detail on this study can be found in Yates [17], and summary results are shown in Fig. 5 and Table 3.

Table 2
The net energy gain from pumping for 'cost effective' ideal turbine and sluice capacities for a 100 km^2 vertical sided basin. Machine efficiency was assumed to be the same for forward and reverse (dual) mode operation.

Configuration	Operating mode	M_2/S_2 amplitude (m)	Net energy gain with pumping % (constrained)	Net energy gain with pumping % (unconstrained)
1xDoEn	Ebb	1.0/0.5	4	6
1xDoEn	Dual	1.0/0.5	2	2
1xDoEn	Ebb	1.5/0.5	6	6
1xDoEn	Dual	1.5/0.5	3	3

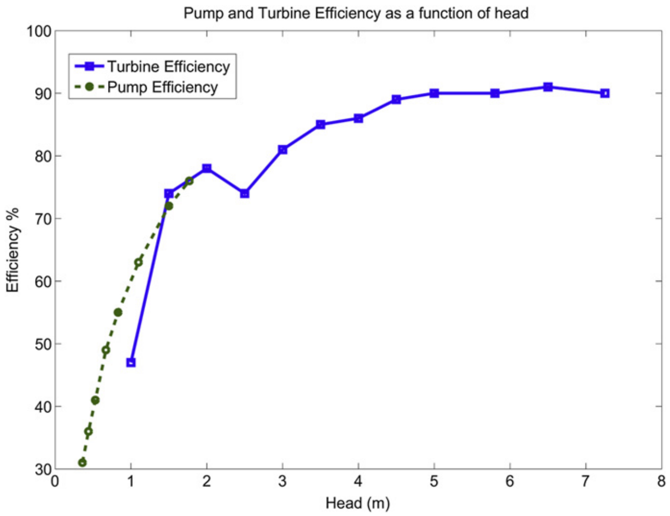

Fig. 4. Turbine and pump efficiencies as specified in the 1994 DTI Duddon report [10].

The best pumping energy gain was 11% for dual mode and 13% for ebb mode with a 1xDoEn configuration, with water levels constrained to high/low water spring tide. Ebb mode pumping energy gains have benefited from higher pump efficiencies at 1.8m pumping head (the limit of the available data) compared to 1m, the energy gain increasing from 8 to 13%. For dual mode operation, the energy gain during dual pumping decreases with increasing head, again due to the characteristics of this operating mode (shorter generation window and lower average head compared to ebb mode).

The removal of the water level constraint did not improve on these results, though the Duddon 'Lagoon' results are not strictly comparing like-with-like with the Duddon estuary. Higher installed turbine capacities gave an ebb mode pumping gain of 24% (comparable to the results presented by Burrows et al. [14]), though it is yet to be established if such gains can be realised in practice, nor if they are sufficient to offset higher capital costs.

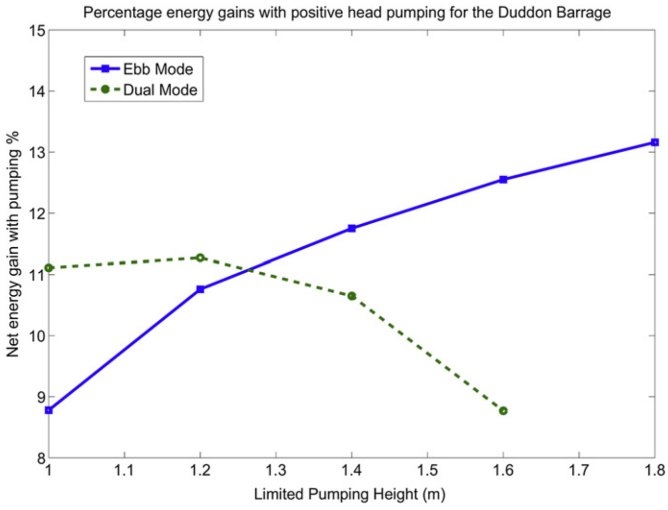

Fig. 5. Best net percentage energy gain with positive head pumping for the Duddon Barrage by barrage operating mode, with optimum delays. Water levels constrained to be within high/low water spring tide, +/−3m, pumping to the specific maximum pumping height.

Table 3
Annual energy output from Duddon hypothetical Lagoon as a function of operating mode for a variety of schemes scheme with positive head pumping, optimum delays, and pumped water levels unconstrained.

Configuration	Operating mode	Net energy gain with pumping %	Optimum pumping height (m)
1xDoEn	Ebb	+11.12	1.8
1xDoEn	Dual	−0.19	0.3
2xDoEn	Ebb	+24.21	1.8
2xDoEn	Dual	+8.51	1.8

Table 4
Summary of net percentage energy gains from pumping against theoretical assumptions.

Scenario	Net energy gain through pumping %
Instantaneous water flow, 90% efficient turbine, 85% efficient pump, M_2 tide only	325
Instantaneous water flow, 70% efficient turbine, 40% efficient pump, water level unconstrained, M_2 tide only	39
Average total potential energy added to a tide by the addition of the S_2 tidal constituent (compared to M_2 alone)	10 (2:1 M_2:S_2 ratio) 4 (3:1 ratio)
Instantaneous water flow, 100% efficient turbine, 100% efficient pump, water level constrained to high/low water spring tide (to model estuary) for an M_2 and S_2 tide	35 (2:1 M_2:S_2 ratio) 27 (3:1 ratio)
Instantaneous water flow, 70% efficient turbine, 40% efficient pump, water level constrained to high/low water spring tide (to model estuary) for an M_2 and S_2 tide	17 (2:1 and 3:1 M_2:S_2 ratio)
DoEn cost effective turbine capacity, 70% efficient turbine, 40% efficient pump, sluice capacity estimated after Prandle with a dimensionless gate area $g = 7.0$ for an M_2 and S_2 tide. Pumping restricted to high water spring tides for the smaller percentage gains; high water levels and maximum pumping heads unconstrained for the higher percentage gains	2–6
DTI cost effective turbine and sluice capacity for Duddon estuary, real turbine and pump efficiencies pump. Pumping restricted to high/low water spring tide level.	8–13 (Ebb Mode) 8–11 (Dual Mode)
1xDoEn and 2xDoEn turbine numbers, cost effective sluice capacity for Duddon 'equivalent' lagoon, real turbine and pump efficiencies pump. Pumped high/low water levels unconstrained.	12–24 (1xDoEn–2xDoEn Ebb) −0.3–9 (1xDoEn – 2xDoEn Dual Mode)

3. Conclusions

The results of these explorations are summarised in Table 4. MacKay's headline figure of 325% has been shown to be unrealistic, as it depends on overoptimistic turbine and pump efficiencies, instantaneous flows, and a huge raising of the embankment crest and similar lowering of the impoundment bed levels. Simply by using more realistic turbine and pump efficiencies (0.7/0.4), the pumped energy gain drops to 39%, and further to 17% if water levels are constrained, as would be the case in an estuary.

With the addition of finite flow velocities, and finite turbine and sluice capacities, pumped energy gain was at best 6% with these same turbine and pump efficiencies. Use of real turbine and pump efficiencies from the Duddon case study gave slightly higher energy gains (up to 13% for ebb mode), but still broadly in line with what has been reported elsewhere in the literature.

Whilst the headline pumping energy gains have been shown to be unrealisable, elements of the arguments of MacKay [4] and Anderson [5] are still worthy of consideration. Anderson in particular has pointed out that tidal range technology has potential for innovation, the few barrages implemented in the world using modified (unidirectional) conventional hydropower technology. This machinery has been optimised for large, constant heads with fixed operating directions, and so is unlikely to be optimal for tidal operation which experiences lower and variable heads, nor for operating in dual mode where operating direction changes.

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