Joule Project JIRP106/03 Oct 2006 – Dec 2008

Tapping the Tidal Power Potential of the Eastern Irish Sea

FINAL REPORT

(Executive Summary)

www.liv.ac.uk/engdept/tidalpower

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EXECUTIVE SUMMARY

The medium to long-term procurement of energy and the related issue of climate change are set to remain at the top of government and public agendas, both nationally and internationally, for some time to come. No clear vision has yet emerged for a sustainable global energy future and the combination of rapid growth in both economies and populations in the developing world are set to place extreme pressure on fossil fuel reserves. It seems inevitable, therefore, that as the 21st century evolves, ever greater utilisation of renewable energy resources must be made if the means for modern living are to be preserved. From the perspective of the global community, it is argued that it will ultimately become an obligation for all societies to properly and fully exploit the renewable energy resources at their disposal for the common good.

The geographical location of the United Kingdom and the seas that surround it provide internationally enviable renewable resources. Technologies for wind power extraction are now mature and an increasing role for the opportunistic capture of this intermittent energy source for the electricity grid is firmly established. Marine wave energy offers even greater scope for the future with a somewhat lower degree of unpredictability but with necessary technological advances still outstanding at present. Even more exclusive, however, is the potential for tidal energy extraction from around the UK coastline. The most attractive locations for harnessing tidal power are estuaries with a high tidal range for barrages and other areas with large tidal currents (e.g. straits and headlands) for free-standing tidal stream turbines. Pertinent here is the fact that tidal barrage solutions, drawing on established low-head hydropower technology, are fully proven. The La Rance scheme in France has now passed its 40th year of operation.

Of about 500-1000TWh/year of tidal energy potentially available worldwide (Baker 1991), Hammons (1993) estimated the UK to hold 50TWh/year, representing 48% of the European resource, and few sites worldwide are as close to electricity users and the transmission grid as those in the UK. Following from a series of government-funded studies commissioned by UKAEA in the 1980s, 8 major estuaries were identified where tidal barrages would be capable of procuring over 40TWh/year: in rank order of scale - the Severn, *Solway Firth*, *Morecambe Bay*, Wash, Humber, Thames, *Mersey* and *Dee* (see UKAEA 1980 & 1984 and Baker, 1991), about half of this thereby being located in the North West of England. 118 further estuaries and embayments suitable for small-scale installations were also studied in follow-up work for the Department of Energy’s Renewable Energy R&D programme (DoEn, 1989). Of these, using a simple empirical means of assessment, 36 were found to be worthy of further consideration on the basis that unit costs of electricity fell within about 60% of the most competitive of the major schemes (Severn and Mersey) – in total 3600GWh, equivalent to a further ~ 1% of UK demand.

The case for a tidal barrage in the Severn estuary, with the highest tidal range in Europe, is being actively promoted with government support following the recent Sustainable Development Commission's review of tidal power in the UK (SDC, 2007). This scheme alone would be capable of meeting 4.4% of current UK electricity need. The estuaries of the North West of England offer fully complementary potential to the Severn by virtue of the tidal phase lag, as will be illustrated below. Based on the earlier studies (Baker, 1991) a total installed capacity in the North West of about 12GW might provide a potential energy yield of at least 17.5TWh/year, approximately 5% of present UK national electricity need and by inference around half the region's electricity demand.

Also within the Eastern Irish Sea, exploitable tidal stream resources have been identified to the north of Anglesey and to the north of the Isle of Man, with more localised resources in the approaches to Morecambe Bay and the Solway Firth (DTI, 2004). In the estuarial situation, however, it is unlikely that tidal stream options can come close to the energy yield of barrage alternatives. Recent assessments for the Mersey (**www.merseytidalpower.co.uk**) offer estimates of 40-100 GWh for tidal stream arrays, contrasting with 1200 GWh estimated for a barrage, at an equivalent location. In a similar vein, whilst tidal lagoons are often mooted as a viable alternative to estuary barrages, offering a similar operational function, it is highly unlikely that they could be realised at a comparable scale and remain competitive on cost against the major barrage schemes cited above.

It should be noted that a barrage solution attempts merely to delay the flux of water as the tidal level changes: holding back the release of water as the tide level subsides under 'ebb generation' so that the 'head' (water level) difference is sufficient for turbine operation; deferring the entry of rising tidal flow to the inner estuary basin for 'flood generation'. In 'dual mode', there is a combination of both. Each mode has some restricting effect, so reducing the range of tidal variation within the basin; ebb generation solutions generally uplift mean water levels, 'flood' generally reduces mean levels and dual mode results in little change. A degree of environmental modification is, therefore, inevitable, but this does not necessarily imply degradation from a physical or ecological perspective, though issues related to protection of habitats would need to be confronted.

It is also important to recognise that barrage schemes are unique amongst power installations, being inherently multi-functional infrastructure, offering flood protection, road and rail crossings and significant amenity/leisure opportunities, amongst other features. Thus, a fully holistic treatment of overall cost-benefit is imperative for robust decision-making. It is suggested that, to date, this position has been inadequately addressed, especially in respect of barrages' potential strategic roles in flood defence and transportation planning. It follows, therefore, that apart from the direct appraisal of energy capture, other complementary investigations should be sufficiently advanced to enable proper input in decision-making in respect of these 'secondary' functions (as well as the various adverse issues, such as sediment regime change, impact on navigation and environmental modification).

It was contended in making the case for the present study that robust estimates of the realisable UK tidal energy reserves be established so that they can properly be assimilated into future energy planning (accepting the 10-15 year time horizons necessary). Thereby, rational implementation of tidal schemes might be initiated as and when concerns over energy price, security, or carbon emissions dictate. Furthermore, it is considered paramount that this energy potential be fully appreciated when planning application is received for alternative schemes, which might compromise maximum exploitation of the renewable resource. Such instances might arise, for example, should a tidal stream array or tidal fence installation be promoted where the barrage option remains viable and for which a substantially increased energy capture might be expected.

Following this line of argument, the project aimed to re-appraise the earlier study estimates of the potential North West barrage energy yield and to further this detailed technical scrutiny with assessment of the various operational mode options (ebb, flood or dual) and the broader effect arising from their conjunctive action. To this end, two levels of technical evaluation were to be explored:

0-D (zero-dimensional) modelling – to synthesise the local behaviour of the barrage with turbine and sluicing systems assuming flat water levels either side, sometimes referred to as a ‘flat-estuary/basin’ or ‘two-tank’ model. This gave rigorous treatment of the hydraulics and energy generation, from the double-regulated bulb turbine systems considered here, but makes no allowance for the hydrodynamics of flows arriving to, or flowing from, the barrage. Alternative turbine characteristics could be assimilated, potentially to represent tidal ‘fence’ or ‘reef’ systems. The bespoke software routines were developed using Matlab, with the user interface shown in Figure 1:

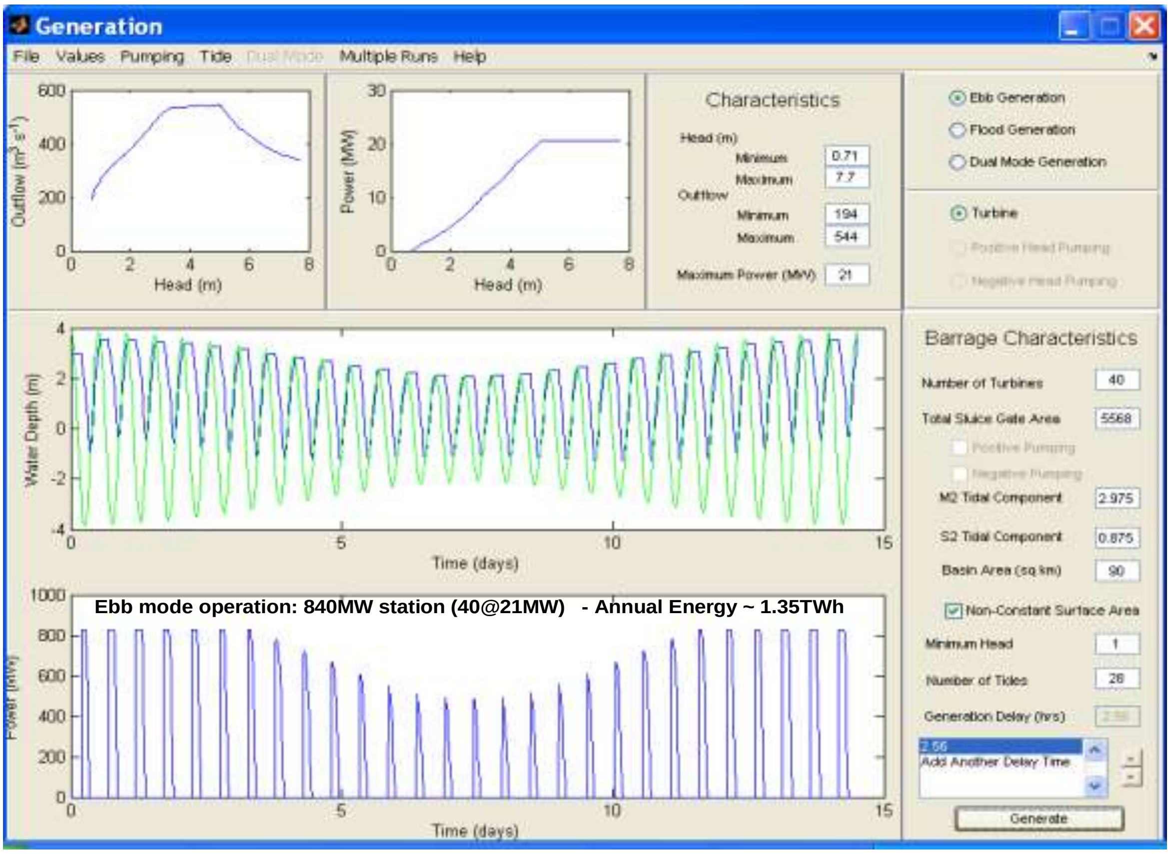

Figure 1. The 0-D modelling interface

2-D (two-dimensional) modelling – aims to fully account for the hydrodynamics of the flows arriving at and passing from the barrage structures, and thereby account for energy dissipation by bed friction throughout the modelling domain. Since multiple estuary sites were to be included, a model domain extending over the whole Irish Sea and beyond was required. In order to incorporate any likely impacts from the operation of a potential Severn barrage in the Bristol Channel, the model domain was extended to cover this region also. The challenges arising turned out to stretch the state-of-the-art with the ADCIRC modelling platform adopted, almost 750,000 cells forming the unstructured finite element grid to be subjected to 2-D depth-averaged modelling of the tidal hydrodynamics, as shown in Figure 2. The model allows the examination of the undisturbed and perturbated system with the option of including various tidal power schemes.

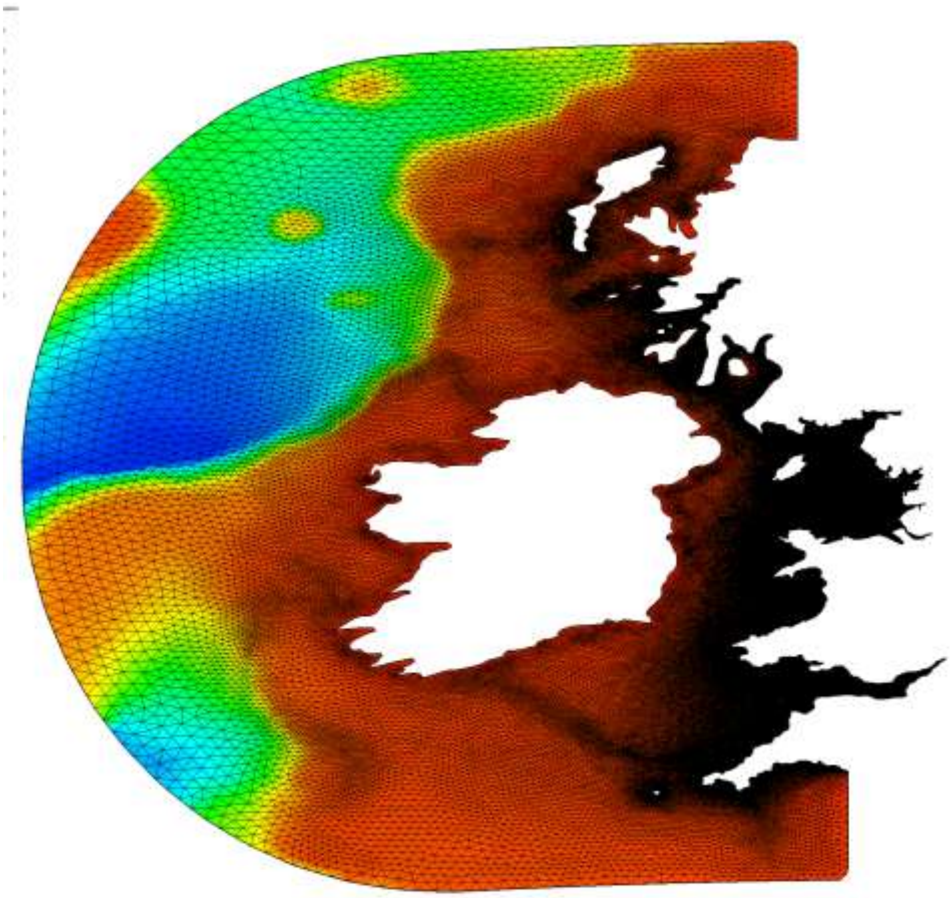

Figure 2. The final ADCIRC tidal modelling domain showing bathymetry and unstructured grid.

Project progress and delivery

Early developments in 0-D modelling of turbine/sluice systems in an estuary barrage were successfully completed and appraisals made against the outputs from earlier studies. To take proper account of the hydrodynamics in the external water bodies and therefore the tidal dynamics of the Irish Sea, 2-D modelling was proposed.

At an early stage, the decision was taken to switch from POLCOMS, POL's own computational model, to ADCIRC as the modelling platform. This action was taken so that the unstructured nature of the computational grid in the latter could accommodate the range of grid scales required, from vast expanses of the coastal sea (~ 10 km resolution) to the minor channels (and turbine/sluice flow streams) within the estuary regions (~ 50m).

This switch avoided the need for nesting of models which would have proved cumbersome and operationally imprecise for the intended investigation of conjunctive operation over multiple estuaries, each of which, at the finest level of resolution, would be likely to have been placed in different model meshes. As it transpired, the problem to be tackled proved to be a challenge to the modelling platform and unanticipated problems in grid development (not unusual in unstructured finite element modelling studies) severely hampered development and caused readjustment to the work programme. The absence of calibrated 2-D modelling outputs by mid-programme prevented the introduction into the 0-D modelling of up-rated local tidal range/phase information at barrage sites for enhanced investigation of conjunctive operation, as had been intended before the final runs of the 2-D model.

Other obstacles to progression resulted from the complexity of incorporation of 'LIDAR' (Light Detection and Ranging) inter-tidal bathymetry data for the Dee (see Figure 3), Mersey and Ribble, the incomplete 'LIDAR' coverage for the bathymetry of Morecambe Bay, and its absence for the Solway Firth.

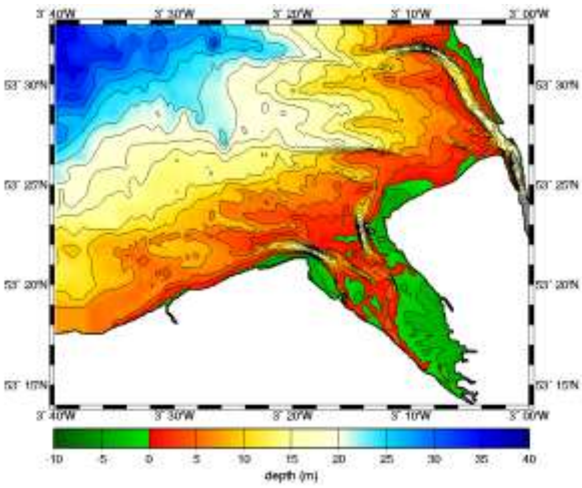

Figure 3. EA LIDAR bathymetry data for the Dee Estuary

The result was that fewer test cases than anticipated have been explored – though a sufficient range of studies has been completed for robust indicative outcomes to be achieved in both the 0-D and 2-D modelling work. Contingency action taken to maintain the programme goals, while forced with the exhaustive efforts necessitated by the ADCIRC modelling, included the commencement of new PhD studies using external (EPSRC-DTA) funding. The mature appointee, Nick Yates, was fast tracked to make a substantial contribution to the study by way of the guided 0-D energy modelling studies. A further PhD project on sediment transport in the Mersey with a barrage has also contributed.

Notwithstanding the delays incurred in achieving the robust outcomes presented herein, the opportunity was taken to disseminate early findings to professional and scientific audiences, including:

- Evening Seminar at Institution of Mechanical Engineers NW region, Liverpool - 29th April 2008
- Presentation at ICE Coastal Sustainability Conference, Llandudno, - 29th May 2008.
- Poster exhibition – North West Coastal Forum, Morecambe – 5th June 2008.
- Evening seminar, Energy Institute, London - 23rd June 2008.
- Presentation at Physics of Estuaries & Coasts (PECS) Conference, Liverpool – 26th August 2008.

- Presentations at Ocean University and 1st Oceanographic Institute, Qingdao, China – 3-7th Sept 2008.
- Presentation at British Hydropower Association, Annual Conference, Bristol – 17/18th Sept 2008.
- Presentation at PIANC International Workshop, Liverpool – 26th September 2008.
- Presentation and Exhibition at NWTEG Launch Event, Lancaster – 17th December 2008.

Other related interactions have included liaison at various stages with other tidal power interest groups in the North West, including Solway Energy Gateway, Bridge Across The Bay (Morecambe), Mersey Tidal Power (Peel Holdings/NWDA) and Wyre Tidal Energy, culminating with the inception of the Northwest Tidal Energy Group (NWTEG). Publications to date include the evidence to the House of Commons Review into Renewable Energy Technologies (HoC, 2008) and draft papers prepared for special issues on marine renewable energy to appear in The Institution of Civil Engineers (Proc ICE) Maritime Engineering Journal and in the Elsevier Journal on Applied Ocean Research.

At the conclusion of the Joule Centre funding phase of the studies, successful modelling developments have been completed and important findings achieved in relation to the scale of the North West's tidal energy resource, meeting the main ambition of the original project objectives.

It should be understood that the technical evaluation falls short of detailed engineering design but is sufficiently well founded to provide robust estimates of the scale of resource available and the indicative economics. By the nature of developmental technical research, as was the case here, rates of progress could not be reliably estimated in advance, and with challenges encountered in the ambitious 2-D numerical modelling developments and limitations in time and resources available, deliverables have been achieved from a somewhat reduced range of operational scenarios than were originally anticipated. Consequently, many issues remain to be followed up as outlined later.

The research, therefore, remains a work in progress and refinements to the modelling and further optimisation of potential scheme performance remain outstanding. Incorporation of sediment transport studies in the 2-D modelling is also anticipated through the further collaboration between the University of Liverpool and Proudman Oceanographic Laboratory, where the research team remains in place.

The content of this report is a statement of the position at the conclusion of funding (December 2008) and draws heavily from computations completed in the last days running up to this deadline. The interpretation of the findings offered herein, therefore, has yet to benefit from the considered reflection that would normally be desirable. It is the intention, as a result, that updates will be offered, as successors to this report (initially *version 01*), accessible from the website:

(***www.liv.ac.uk/engdept/tidalpower***).

This internet resource will also hold the full range of follow-up publications (journal papers and news articles, etc), which form the normal means of dissemination of academic inspired research, and related work.

<u>Concurrent activities and related issues</u>

- Running in parallel but ahead of the present study, a Peel Holdings/NWDA funded project reported on tidal power options for the Mersey estuary (see www.Merseytidalpower.co.uk).

- A Sustainable Development Commission study entitled 'Turning the Tide: Tidal Power in the UK' (SDC, 2007) also reported during the timeframe of the project. With focus on the Severn Estuary, well understood to be the largest and most economically viable of the UK's tidal power resources, the report restated on a range of issues surrounding the development of substantial tidal power resources. Whilst flawed in some respects, not least its omission of reference to the early, Department of Energy commissioned studies for the Dee, Morecambe Bay and Solway Firth of the 1980s (and in so doing seriously underplaying the potential scale of the UK estuary barrage resource), the SDC findings offered encouragement for further investigation on the case for tidal range exploitation.
- It is anticipated that, following from the generally positive outcome from the SDC report, the recently initiated 2-year cross-Government feasibility study for a tidal power scheme in the Severn Estuary (led by BERR - http://www.berr.gov.uk/energy/severntidalpower), and including a Strategic Environmental Assessment (SEA) under the lead of Parsons Brinckerhoff Ltd, will confront the issue holistically, taking full account of the climate change and energy sustainability drivers of change.
- A more recent review by Fells Associates (2008) further promotes the reappraisal of tidal barrage solutions, arguing that previously held concerns over environmental impact require urgent reassessment in the light of present climate change and energy sustainability challenges, thus being supportive of the Government's ongoing 2-year SEA for tidal energy from the Severn.
- In due course, it is expected that the Severn SEA (above) outcomes will prove the test case upon which the progression of other major estuary barrage schemes, such as those evaluated for energy capture here, will subsequently draw.
- The House of Commons review into renewable technologies, to which the present project contributed (HoC, 2008), has recently exposed the true scale of the challenge ahead, that EU targets for renewable energy consumption in 2020, set at 15% for the UK, will actually require between 35-40% of electricity in the UK to be sourced by renewables, since little replacement of fossil fuels can be envisaged in the areas of transport and heating. This far exceeds the planned capacity expansion of wind energy. With more onerous targets ahead (60% or even 80% reduction in CO_2 by 2050), it is improbable that success will be achieved without the potential 15-20% contribution that could come from the combination of tidal range and tidal stream energy exploitation from the UK's coastal waters.
- It is also improbable, however, that any large scale tidal resource exploitation can proceed under the constraints of EU environmental protection policy, presently dictating absolute protection of habitats. Environmental modification from major energy extraction is inevitable, but it can be contended that this does not imply ecological degradation. The scale of the 'compensation areas' which would be required under the Habitats Directive to protect affected species would seem to become implausible where entire estuaries have suffered change.
- It is to be hoped that the Government's ongoing feasibility studies will offer incisive guidance since much effort is being expended presently on the basis of what the environmental legislation will permit rather than how climate change mitigation and energy sustainability can best be achieved.

More speculative or contentious issues:-

- The Times newspaper (11th April 2008) reported the Association of Train Operating Companies 'vision for the network in 2057', with rail crossings over barrages of the four main estuaries considered herein as part of an enhanced west coast transport route extending from North Wales to the West of Scotland.
- Worldwide food shortages and conflict from land take-up for biofuels, issues leading to topical debate in 2008, are likely to increase the value of low-lying coastal land, protected by barrages against sea level rise, for productive use. This constraint on

biofuel production is likely to increase demand for alternative renewable energy sources, such as tidal barrages for the UK, if climate change CO_2 targets are to be achieved.

- The Environment Agency's Position Statement to the effect that we cannot allow concern over impacts of climate change to override need to protect estuarine habitats.

Joule Project Achievements and Comment Arising:

In the following discussion, a 'DoEn' (or 1xDoEn) barrage installation is here taken as one with installed turbine capacity (and complementary sluicing) consistent with the outcomes of the UK Department of Energy's 1980s studies, with the characteristics of extracting about half the available ebb-phase energy, in a scheme where the basin in ebb-mode of operation drains only to near mean tide (sea) level. This was found from these early studies to yield electricity at minimum cost. This is adopted as a baseline here because later, schemes of multiples of this turbine capacity (ie 2xDoEn, 3xDoEn, etc) will be considered as alternatives, operating in either ebb-mode or in dual (two-way) generation mode.

- The 0-D modelling routines developed (Turgency/Generation), consistently under-predict the DoEn energy generation figures by approximately 15%, this being attributable to: different assumptions in the treatment of sluicing characteristics; unquantifiable departures in turbine performance characteristics; and the different levels of tide-to-tide control on the optimal generation window selected.

- Nevertheless, the work described here confirms the scale of resource predicted by DoEn in the 1980s for ebb-only power generation, resulting in estuary basin levels normally maintained above mean water level. These 1xDoEn scale turbine installations, are also confirmed as generally leading to the lowest cost of energy produced over a 120-year operating lifetime.

- For studies on the Dee, Mersey and Ribble estuaries, high resolution LIDAR bathymetry data have been employed improving the accuracy of calculation of tidal prisms mobilised for energy generation and wetting and drying, for the assessment of tidal range in the basin and the amount of intertidal area preserved.

- Use of positive head pumping, to uplift the basin immediately after levels equalise at the conclusion of flood phase sluicing, is found to increase energy capture generally by somewhat less than 10% in ebb-mode operations, and the gain is found to be sensitive to barrage configuration and estuary bathymetry. Higher returns in energy with pumping are found to be achievable from dual (two-way) generation and for schemes of higher installed capacity (ie 2xDoEn, 3xDoEn, etc).

- In the 0-D studies, a range of different turbine sizes, generator ratings and sluice capacities have been investigated and the 'best' options selected in summarising outcomes are shown in Figure 4 and Table 1. Whilst these figures are considered to be a reasonable estimation of potential energy returns, it should be appreciated that further turbine conditioning (choice of diameter, generator rating and rated 'head', etc) and increased sluice capacity might be expected to further enhance energy capture. At the same time, the detailed hydraulic design of turbine ducts and sluice passageways might give rise to minor (entry/exit) head losses so reducing the turbine driving head and hence energy production. As a result of these contrasting factors, an uncertainty range in the region of ± 10% would seem appropriate in interpretation of the figures given.

- Summary of 0-D outcomes:

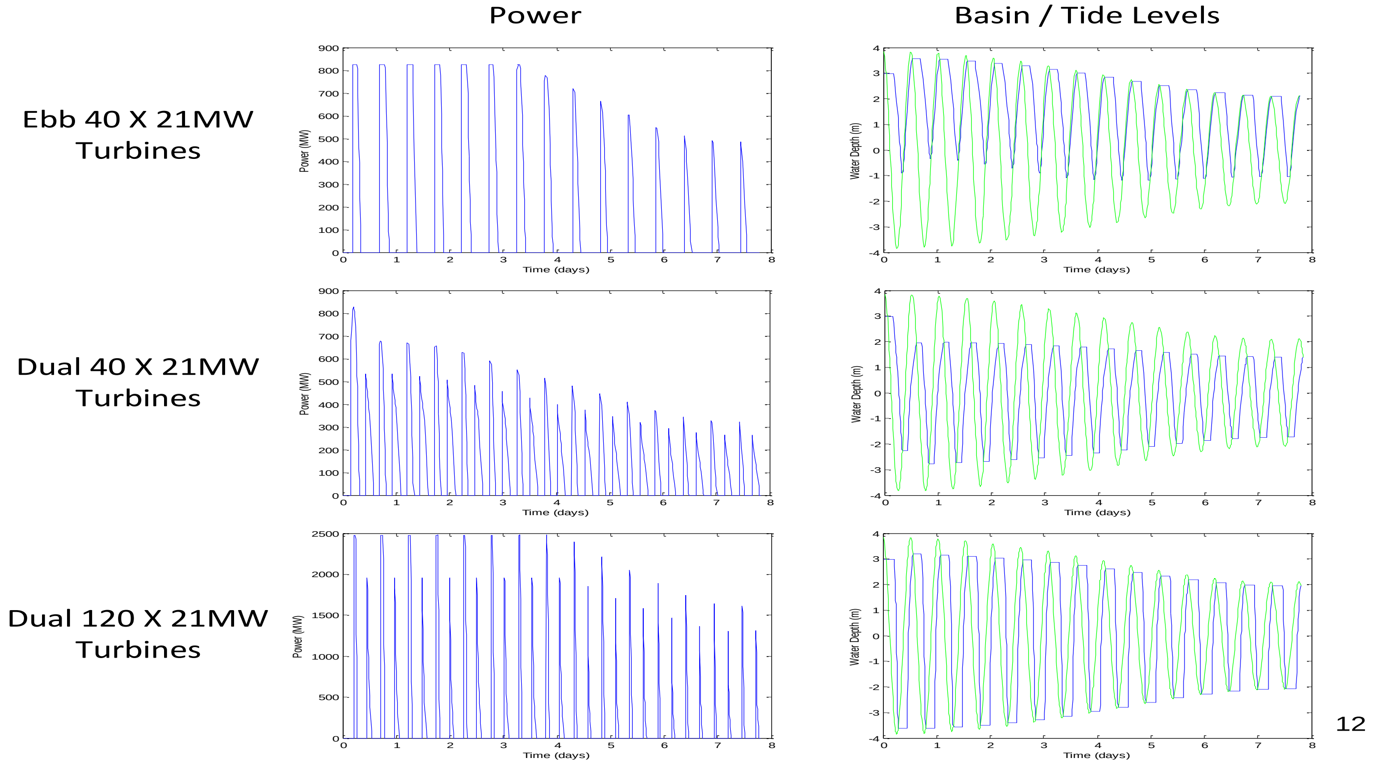

Figure 4. Illustration of power pulses and basin levels for schemes on the Dee

Ebb / Dual mode based on DoEn installation	**1xDoEn Ebb Mode Energy TWh (Cost p/KWh)**		**1xDoEn Dual Mode Energy TWh (Cost p/KWh)**		**3xDoEn Dual Scheme Energy TWh (Cost p/KWh)**	
Solway Firth	8.44 (5.83)		7.78 (6.71)		17.84 (5.86)	
Morecambe Bay	5.83 (6.04)		5.75 (6.46)		11.45 (7.39)	
Ribble	0.08 (7.75)		0.06 (11.03)			
Mersey	1.07 (4.28)		0.98 (5.12)		1.72 (6.16)	
Dee	1.35 (6.81)		1.30 (8.15)		2.21 (10.20)	
Dee Outer / Lagoon	4.60 (8.15 / 11.32)					
	Energy TWh	% of UK Electricity	Energy TWh	% of UK Electricity	Energy TWh	% of UK Electricity
NW Total (Dee/Outer)	16.76 / 20.01	4.3 / 5.2	15.87 / 19.17	4.1 / 5.0	33.30 / 35.69	8.6 / 9.2
Severn (SDC 2007)	17.00	4.4				
UK Total (Dee/Outer)	33.76 / 37.01	8.7/ 9.6				

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Table 1. Summary findings from the 0-D study.

- Drawing from Table 1 it can be seen that for schemes in the North West ebb-only generation with 1xDoEn turbine provision could meet about 5% of UK demand at the lowest unit cost of electricity produced, including the Dee Outer shown inset (or an equivalent offshore lagoon). With the further scheme optimisations mentioned above and refined representation of pumping efficiencies, a figure closer to 6% might be achieved.

- Dual-mode operation with 1xDoEn turbine installations is found to yield energy in the range 78-98% of that achieved from the equivalent ebb-mode, and at a cost penalty in the region of 20% on the basis of the turbine having a relative efficiency in the 'reverse' mode of about 80%.

- By adopting the relatively more expensive 3xDoEn system installations (3 times the number of turbines) and dual (two-way) generation, with suitably conditioned turbines, the renewable energy capture would theoretically increase to more than 9% of UK consumption. This would be achieved without substantial increase in unit cost of electricity produced according to the assessment made here, but see the outcome of 2-D modelling below which finds that these energy returns are not achieved.

- Nevertheless, adopting higher installed capacity (2-3xDoEn) in dual (two-way) generation mode enables mobilisation of a larger portion of the tidal prism, so preserving more of the intertidal zone, as can be seen in Figure 4, resulting in a much reduced impact on the environment. In the example of a 3xDoEn scheme on the Mersey about 90% of the intertidal area would be retained, against ~ 65% for 1xDoEn ebb operation, as shown in Figure 5 (the curves representing different 'delays' before generation, with that offering maximum energy return shown in the legend). Positive head pumping before turbining can increase this retention still further. Again these results arise from the 0-D analysis but may not be fully recaptured when accounting for the 2-D hydrodynamics, as discussed later.

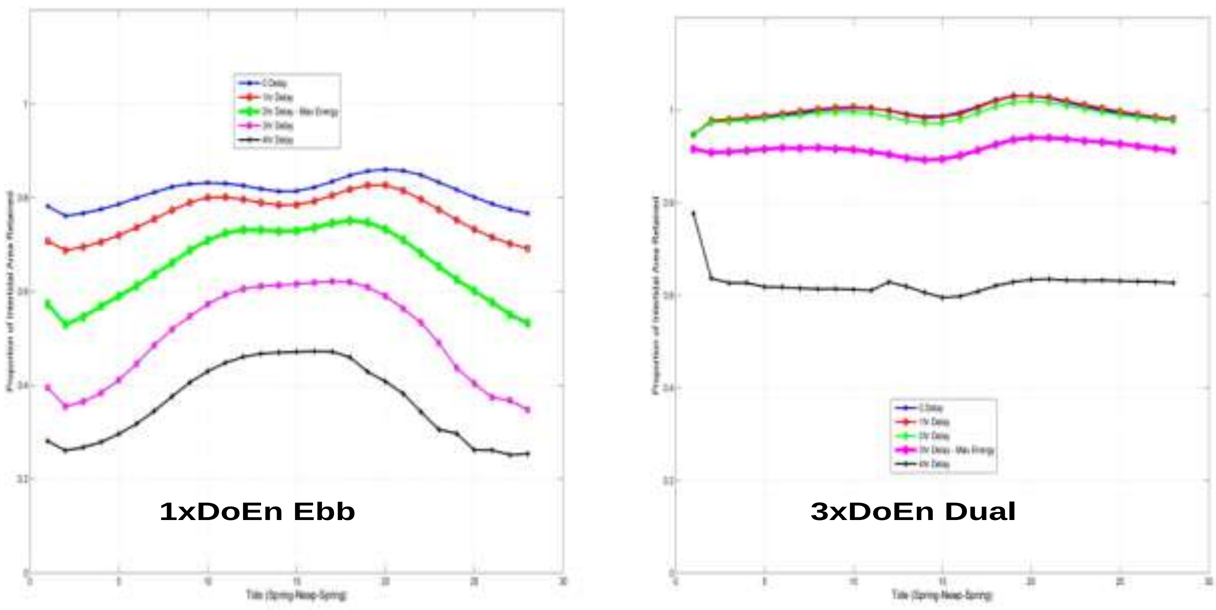


Figure 5. Intertidal area retained in the Mersey

- In the North West estuaries, a combination of ebb-mode and flood-mode operation could potentially be considered to provide an extended daily energy generation window. This could only be achieved, however, at the sacrifice of cost effectiveness, since flood-mode operation is found to be typically only 60-70% as efficient as ebb-generation. This reduction in efficiency is a result of the reduced volume of the tidal prism mobilised, combined with lower turbine driving heads attained. In future scenarios where the Severn estuary might be developed for tidal power, then the tidal phase lags arising (see 2-D outcomes) will provide an equivalently extended generation window.

- In ebb-mode only operation for most cost-effective energy return (1xDoEn installations), inclusion of flushing cycles to drain the basin during neap tides would aid expulsion of intruded sediments, but would be unlikely to eliminate all maintenance dredging needs that may be required. Changes to estuary morphology and local sediment management are issues requiring further research.

- 2-D modelling has provided a new model which predicts potential power production through the accurate modelling of the hydrodynamics of the tidal circulation whilst incorporating both the operational behaviour of tidal range devices and the inclusion of tidal stream farms.

- For barrages, this has been achieved by introducing the turbine characteristics and basic sluice flow characteristics as internal boundary conditions in ADCIRC, together with the definition of operational controls, via Matlab coding routines. Extraction of barrage water levels and turbine flows for energy output is also achieved through routines developed in Matlab.

- Only a limited number of 2-D runs were completed in the time available and, for ease of application, unified operational controls were applied (ie constant time delay before generation commences across all barrages in the system). As a result, no attempt has been made to replicate the best performance achieved by each individual scheme in the 0-D modelling. From these investigations:

  - power predictions for the 5 major tidal range schemes have been made under conjunctive operation in a number of operating modes, for which:

    - changes in tidal amplitude and timings are directly modelled and are included in the power predictions, see table 2;

    - changes in regional hydrodynamics are obtained which reveals the necessity of modelling all the tidal range schemes in conjunction; and

    - climate change scenarios of increased sea level are modelled.

	M2 (m)		S2 (m)	
	Amplitude	Difference	Amplitude	Difference
Severn	3.10	-0.80	1.18	-0.19
Dee	2.32	-0.56	0.68	-0.21
Morecambe Bay	2.84	-0.15	0.92	-0.03
Solway	2.50	-0.14	0.80	-0.02
Mersey	2.82	-0.36	0.86	-0.13

Table 2. Change in tidal amplitude at barrage locations with 1xDoEn ebb-mode operation.

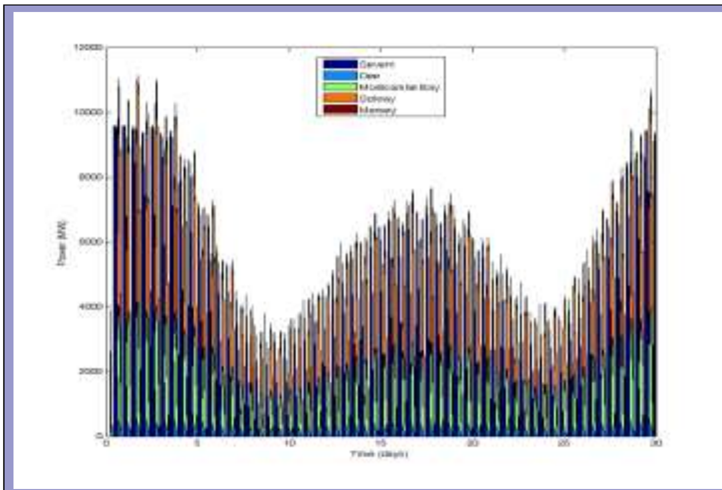
  - Location specific and hydrodynamic effects have been revealed which alter the power predictions significantly from the 0-D modelling which demonstrates the necessity of the 2-D modelling approach.

  - The possible changes in circulation locally due to the inclusion of tidal stream farms have been explored.

- Figure 6 summarises energy outputs from the 2-D analysis for 1xDoEn ebb-mode generation.

(1xDoEn)

Ebb Mode Power Output

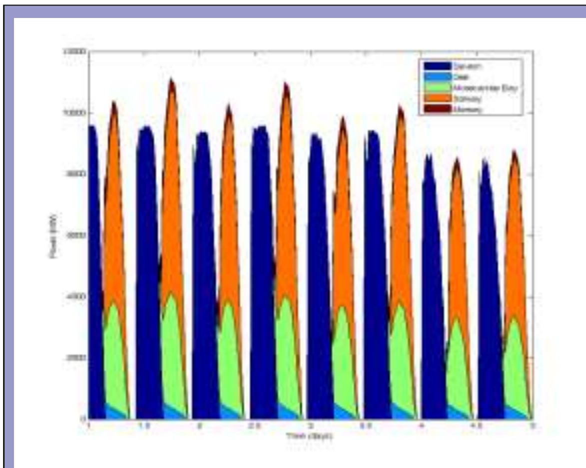


	Annual Output (TWh)
Severn	15.81
Dee	0.89
Morecambe Bay	5.98
Solway	9.66
Mersey	0.57
Total	32.91

Common Delay of 2 hours imposed

(1xDoEn) ebb

Spring / Neap Power



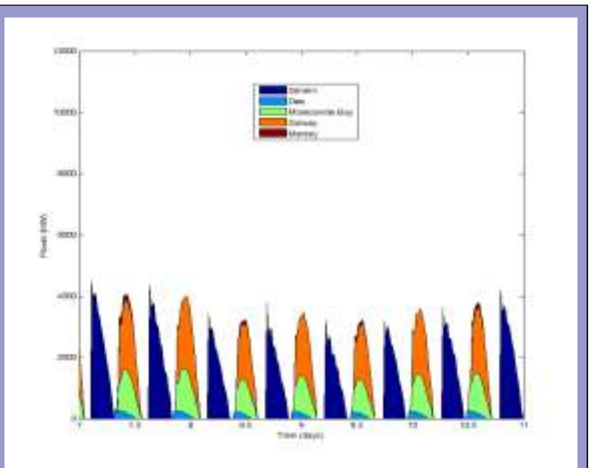


Figure 6. *1xDoEn* schemes in Ebb-mode only operation.

- The 2-D modelling demonstrates that the Eastern Irish Sea resources are highly synchronised in tidal phase. They are, nevertheless, out of phase with the resource of roughly equivalent scale on the Severn estuary (potentially supplemented also by those on the Wash and Humber estuary) making possible extended (~ 20 hrs inputs into the grid) from single ebb-mode operation.

- Comparing the energy generation from the 2-D model with those from the 0-D modelling above, for the 1xDoEn schemes, it is seen that predictions are in close agreement for the Solway and Morecambe Bay (and the Severn), but are significantly lower for the Dee and Mersey. The latter, together with the Severn, suffer a proportionally larger reduction in tidal amplitudes under the conjunctive actions simulated (see Table 2) and this may go some way to explaining the apparent inconsistency.

Flow simulations around the Dee & Mersey Barrages

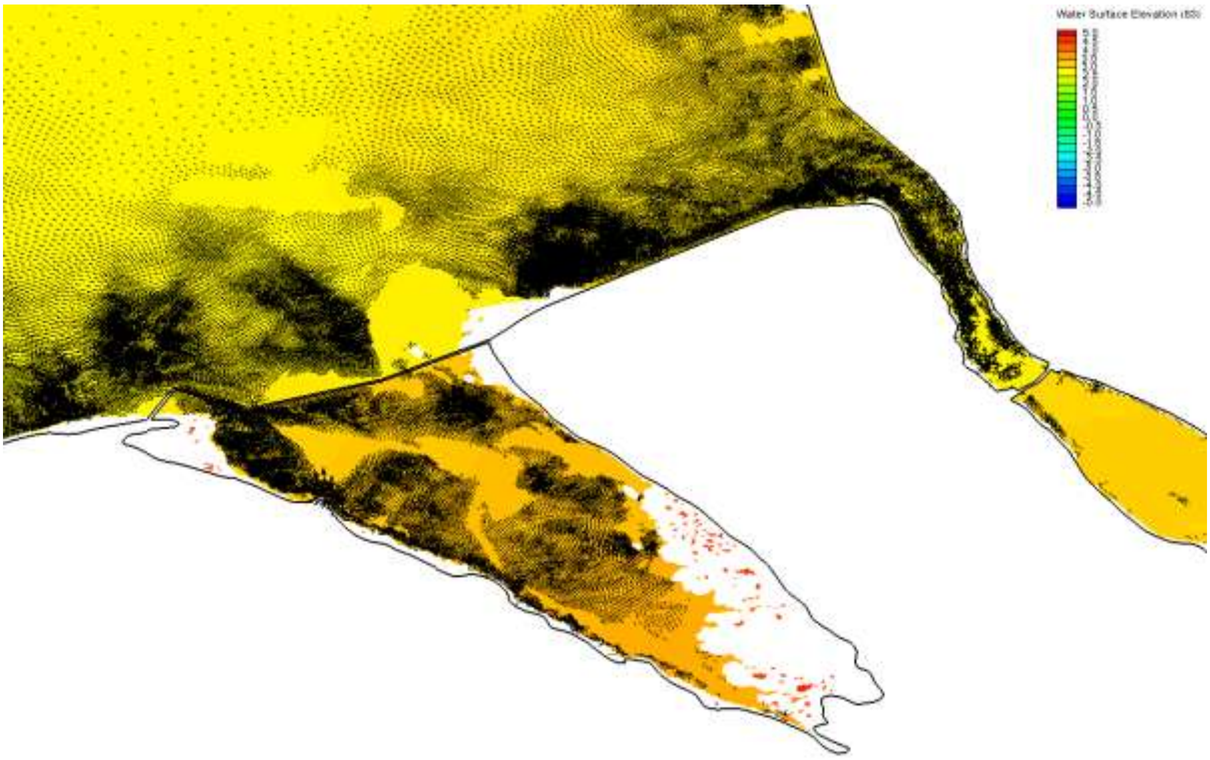


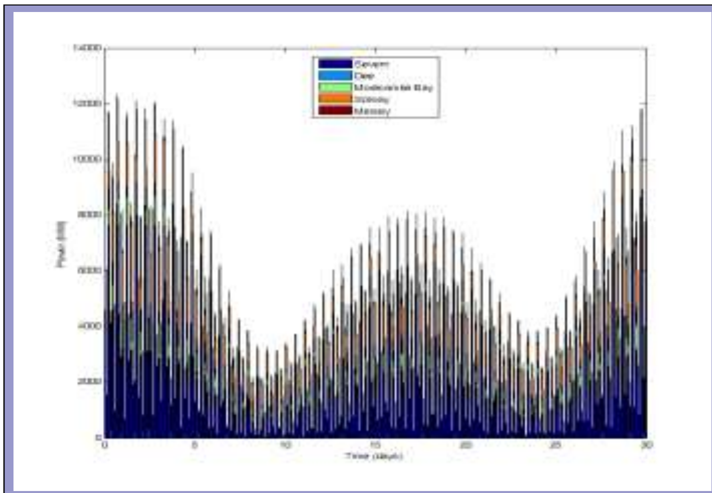
Figure 7. Detail of 2-D flow modelling around barrages and representation of wetting and drying.

- For the estuaries with constrained outlets, the Mersey by way of the down river 'narrows' and the Dee by its constrained deep channel and skewed turbine/sluice arrangement (see Figure 7), the hydraulic flow capacity might also be compromised under enhanced local releases and further exploratory study is called for.

- Figure 8 summarises energy outputs from the 2-D analysis for 1xDoEn dual-mode operation.

(1xDoEn)

Dual Mode Power Output



	Annual Output (TWh)
Severn	14.01
Dee	0.80
Morecambe Bay	3.99
Solway	6.82
Mersey	0.74
Total	26.35

Common Delay of 1 hour imposed

(1xDoEn) dual

Spring / Neap Power

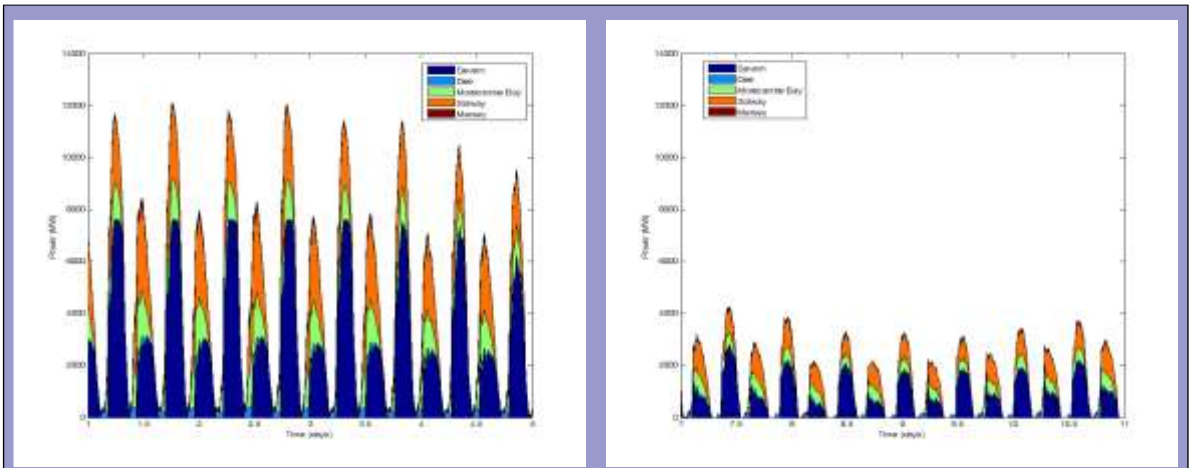


Figure 8. 1xDoEn schemes in dual (two-way) operation

	1xDoEn Ebb-Mode Energy (TWh)		1xDoEn Dual-Mode Energy (TWh)		3xDoEn Dual-Mode Energy (TWh)	
Solway	**9.66**		**6.82**		**10.80**	
Morecambe Bay	**5.98**		**3.99**		**7.13**	
Mersey	**0.57**		**0.74**		**0.97**	
Dee	**0.89**		**0.80**		**1.35**	
	Total Energy (TWh)	**UK (%)**	**Total Energy (TWh)**	**UK (%)**	**Total Energy (TWh)**	**UK (%)**
North West	**17.10**	**4.5**	**12.34**	**3.2**	**20.24**	**5.3**
Severn	**15.81**	**4.2**	**14.01**	**3.7**	**20.01**	**5.3**
Total	**32.91**	**8.7**	**26.35**	**6.9**	**40.25**	**10.6**

Table 3. Summary of 2-D modelling findings as they stood on contract completion.

- Figure 8 confirms again that dual-mode operation for schemes sized at the 1xDoEn level are less effective in energy generation (and hence cost) than one-way ebb-mode generation. For the larger open estuaries (Solway, Morecambe Bay and Severn) the 2-D results are in reasonably close accord with the 0-D findings. Furthermore, in this mode the power pulses become additive, now being time synchronised, giving rise to higher peaks likely to be more difficult to assimilate into the electricity grid.

- In contrast to the 1 x DoEn schemes, however, Table 3 indicates that for dual-mode operation with high installed capacity (3xDoEn) the expected payback in energy extraction (predicted from 0-D modelling) does not materialise. At the time of writing, the full explanation for this is unclear, beyond the effect of the reduction in tidal amplitudes experienced at the barrages. Though the hydrodynamic requirement to shift higher flows to and from the barrage is a likely additional factor, resulting in the possibility of transient motions and resonant effects arising, computational instabilities and ill-configuration also remain plausible causes.

- Notwithstanding these unresolved power generation issues, it seems inevitable that local scour will be a feature beneath the concentrated flow streams arriving at and emerging from both the sluices and the turbine outlets. Physically, these might be designed for in the dredging operations during construction or else will emerge as self scour features subsequently. Noting that local deepening was embedded in the computational grid for the 2-D modelling to avoid computational instabilities, whilst the ‘patching’ process imposed some alteration of the local bed details, it may be necessary to investigate a wider scale of bathymetric deepening to better represent the likely scour induced by the emerging flow jets to ensure that hydraulic resistance in this near-field region is suitably represented.

- With a reported 64GW mean tidal energy input to the Irish Sea and installed turbine energy extraction capacity in the region of 20GW for (1xDoEn) ebb-mode barrage operations in the North West estuaries and in the Severn (giving rise to a mean extraction rate in the region of 5-6GW), some change to tidal circulation might be envisaged. This was one of the main questions to be investigated in the study. The 2-D modelling outcomes for conjunctive operation of the 5 major estuary barrages (Severn and Dee, Mersey, Morecambe Bay and Solway Firth) do manifest discernible changes:-

    - At all the barrage locations the approaching mean tidal amplitudes are reduced (see Table 2) and an increase is experienced on the east coast of Ireland, which whilst small (< 200mm), would need to be fully investigated for impacts on flood risk.

    - At the time of writing, the small changes observed to: tidal residual currents, bottom stress and stratification parameter within the Irish Sea are being evaluated for their likely influence on such factors as sediment drift, benthic conditions and eutrophication risk, with potential influence on biodiversity and fisheries, etc.

    - As a result of the major local changes to the distribution of tidal flux across the line of a barrage, in comparison with the original distribution, it is to be expected that morphological readjustment by means of new channel formations, etc, will result in a transient state of enhanced sediment mobilisation and potential contaminant release for some time (perhaps several years) before water quality reaches its new dynamic equilibrium. Where this might be an issue, as in industrialised estuaries such as the Mersey, with heavily contaminated sediments, novel approaches might be called for to suppress plume dispersal and for utilisation or disposal of dredgings.

- Tidal-stream devices, in the form of single turbines or multiple units in arrays or cross-river fences, installed in estuaries are unlikely to be able to exploit a significant proportion of the tidal range resource extractable by barrages. A theoretical study conducted within this project suggests that only single figure percentage returns on the equivalent barrage figures are achievable. In the light of this, no concerted attempt has been made to produce a detailed study into tidal stream exploitation in the estuaries considered here.

- However, in the 2-D modelling, tidal-stream farms have been investigated at an exploratory level at sites under consideration for such developments within the modelling domain, including within the Mersey Estuary and the Skerries off the Isle of Anglesey. Installed capacity and turbine rated flow characteristics have been chosen to match those published in recent reports for the various farms. The principal observation from the indicative tests completed is that the scale of these resources is dwarfed by the estuarial barrage potential, so that Irish Sea tidal stream farm deployments are unlikely to have discernable additional effect on the tidal hydrodynamics compared to that displayed by the conjunctive barrage operations.

- As an additional cautionary note, it is evident in the 2-D modelling that the tendency for flows to divert around the tidal-stream farm, as a consequence of the blockage, is likely to have a significant effect on the fraction of incident energy extractable. This is a factor that may not have been properly accounted for in a number of the earlier tidal stream resource assessments.

Other general comment:

- Flood risk benefits from the installation of barrages are likely to be significant, though the review conducted here was not sufficiently focused to provide quantitative data in support of this. Most readily perceived is the protection afforded against tidal flooding, which is likely to increase over the coming century as a result of sea level rise.

- Similarly, though less widely appreciated, proactive operation of a barrage scheme should be capable of mitigation of fluvial (river) flood risk and thereby alleviate the adverse effects of increased river flows arising from climate change. This protection would extend from the estuary shore up-river to the tidal limit and beyond to the furthermost reach affected by ‘backwater’ surcharge during the superposition of peak river flow discharge upon high-tide receiving levels. The benefit would be achieved by draining the basin at low tide (and closure of the barrage’s sluice/turbine ducts) preceding the peak flood’s arrival, to provide a maximum storage volume to absorb the flood. When necessary, under extreme floods, the full turbine complement could then forego power generation and instead be operated to pump out water from the basin to lower the levels until the flood subsides.

- The decision to advance any of the ambitious schemes proposed herein for the North West will clearly depend upon the outcome of the ongoing government backed Strategic Environmental Assessment (SEA) and economic appraisal studies on the Severn tidal power proposals, that has followed from the supportive Sustainable Development Commission review (SDC, 2007).

- At the time of writing, it remains unconfirmed from the 2-D studies that substantially more energy (~80%), as predicted from 0-D modelling, can be achieved from more expensive 3xDoEn turbine installations.

- Most unit energy costs arising from the schemes discussed here fall below 10p/KWh on the basis of the low discount rate of 3.5% applied. These are likely to be competitive against alternative energy sources as illustrated in the SDC report, and will inevitably become competitive against fossil fuels as the drawdown in these reserves takes place over coming decades. The SDC report goes further and suggests that Treasury rules would permit lower figures of 2.5% to be set for support of infrastructure with 100+ year operational lives, such as those envisaged for tidal barrage installations.

- The outcomes presented in this report provide an outline of what might be achievable in renewable energy procurement from the Eastern Irish Sea. It does not include the further potential for tidal-range energy procurement, of similar major scale, from shore attached lagoons that have been mooted for the North Wales coast (Anderson, 2008).

- From a technical perspective the work completed here merely provides a guide for detailed engineering designs to follow, at such time that the national need for additional renewable energy dictates.

Conclusions

1. Barrages on the Solway, Morecambe Bay, Mersey and Dee, operating in ebb-only generation with 1xDoEn turbine provision could meet about 5% of UK demand. With the further scheme optimisations and refined representation of pumping efficiencies, a figure close to 6% might be achieved. Based on the scale of the North West's 'economy' at approximately 12% of the UK total, this energy capture should supply about half the North West's present electricity needs.

2. In economic terms, this project has shown that the North West schemes should be no more than 70% more expensive in unit cost of energy produced compared to that achievable from the Severn with, in each case, lowest cost arising from installations consistent with the Department of Energy's 1980s studies (1xDoEn turbine installations).

3. Increasing turbine provision substantially (to up to 3 times the default provision) would increase energy capture further and enable retention of more of the intertidal area in the estuarial basin, so alleviating some of the environmental concerns but at extra cost of electricity produced.

4. Location specific and hydrodynamic effects have been revealed from the 2-D modelling which alter the energy predictions significantly from the 0-D modelling counterparts, so demonstrating the necessity of the more rigorous modelling approach.

5. Further investigation is required, therefore, to determine how much of the substantial energy increases predicted from 0-D modelling of 3xDoEn installations (~80%) can be realised in the 2-D modelling of conjunctive operation of the barrages (together with the Severn). Presently, only a ~20% enhancement has been achieved, as a consequence, in part, of the reduction of tidal amplitudes at the barrage locations. The impact on unit electricity cost as a result of this disparity is likely to render the option financially unattractive relative to the base ebb-mode 1xDoEn case.

6. Whilst power production between the North West estuaries and the Severn is fully complementary in ebb-mode operation, dual-mode (two-way) operation would give rise to synchronised and higher peak power pulses for the electricity grid to handle.

7. Earlier studies (DoEn, 1989) reported the potential for an outer line for the Severn barrage producing an additional 6.8TWh, and barrages on the Wash, Humber and Thames capable of yielding 3.7, 1.65 and 1.37 TWh, respectively. Combining these with the 33 TWh obtained herein for the North West barrages and the Cardiff-Weston Severn barrage scheme (for similar 1xDoEn ebb-mode operation) would achieve at total of 46.5TWh. This should be capable of uplift to ~50TWh by addition of positive head pumping. This would represent 13% of the UK (2005) electricity consumption of 387TWh.

8. Further energy capture from other small barrage schemes on estuaries or embayments (DoEn, 1989, Anderson, 2008) would enable tidal range energy extraction to meet the 15% of UK energy consumption quoted earlier by DTi (2005).

9. Adding an extractable UK tidal stream resource of about 5% (SDC,2007), would uplift the potential for tidal energy to meet up to 20% of the nation's (present) electricity consumption.

10. Outline studies have been conducted to investigate modest tidal stream generator array deployments within the domain of the 2-D model, as a demonstration of this capability within the ADCIRC generic modelling framework developed in the project.

Recommendations

1. Further optimisations of the barrage configurations and operational controls (ie chosen time delays and use of pumping) are called for in the 2-D modelling studies, to obtain robust estimates of potential maximum energy capture, under both ebb-only and dual-mode generation and for up to 3xDoEn turbine installations.

2. Barrage schemes should be introduced individually in the 2-D modelling, also, to identify the influence of each on changes to the tidal regime in the Irish Sea.

3. Further refinement of the ADCIRC modelling routines is required to better explain and suppress the tendency for occasional instability and aberration in its outputs.

4. Sediment transport should be incorporated into the ADCIRC modelling routines, to enable understanding of likely morphological changes, both in the near vicinity of the barrage installations and in the far field.

5. Further study is called for on the case study barrages for the proactive management of extreme fluvial flows to reduce flood risk in the lower river reaches.

6. The full potential of tidal-stream farm resources in the domain of the Irish Sea warrants more extensive investigation.

7. The operation of the electricity grid under the injection of such large power pulses (~ 10GW) from these potential tidal resources requires urgent consideration.

8. Alternative turbine technologies, including single regulated bulb units but including possible 'fence' or 'reef' systems could be incorporated to investigate their behaviour in both the 0-D and 2-D modelling systems.

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