The North Wales offshore tidal impoundment scheme: a preliminary study of requirements, constraints and opportunities

S E Evans **MEng(Hon)**
Cardiff University School of Engineering, UK
J E P Poole **MA(Hon), MSc (Hon)**
Environment Agency Wales & Cardiff University School of Engineering, UK
K P Williams **BSc(Hon), PhD**
Cardiff University School of Engineering, UK

SYNOPSIS

The concept of an offshore tidal impoundment (OTI) for generating electricity has been described, with water passing back and fore through turbines in the impoundment wall. Tidal cycles are predictable allowing accurate estimation of long-term power output. Such a scheme has been proposed for a site in North Wales, close to the existing North Hoyle offshore wind farm. The present paper scopes out this proposal as a prelude to any formal assessment. It considers the theoretical maximum power generation capacity and compares this with likely operational performance. The size, shape and siting of the structure are examined in relation to cost, and the likely impact on tidal currents and coastal flood protection. Three options are proposed for particular attention. Appropriate power generation devices are identified. Construction methods and materials are discussed, including the use of geomembrane bags, filled with material from the adjacent seabed. Costings for a single option are prepared and the overall sustainability of the scheme is assessed from economic, environmental and social perspectives. The likely power output is compared with that of an offshore wind farm covering the same area.

INTRODUCTION

Tidal Electric Ltd[1] have put forward the concept of an Offshore Tidal Impoundment (OTI) for generating electricity. Water flows into the impoundment through turbines at high tide and is stored until low tide when it is released, again through the turbines. Low-head hydroelectric turbines and equipment are proposed, as for tidal barrages.

Conditions for effective application of this technology include: a substantial tidal range; a flat shallow seabed; proximity to electricity demand; and suitable infrastructure. The coastline of Northeast Wales is suitable. The scheme considered here would be situated roughly between Colwyn Bay and Rhyl (Figure 1). The purpose of this paper is to look at the proposed scheme in the round to help scope a more detailed appraisal. The views expressed are those of the authors and not the Environment Agency.

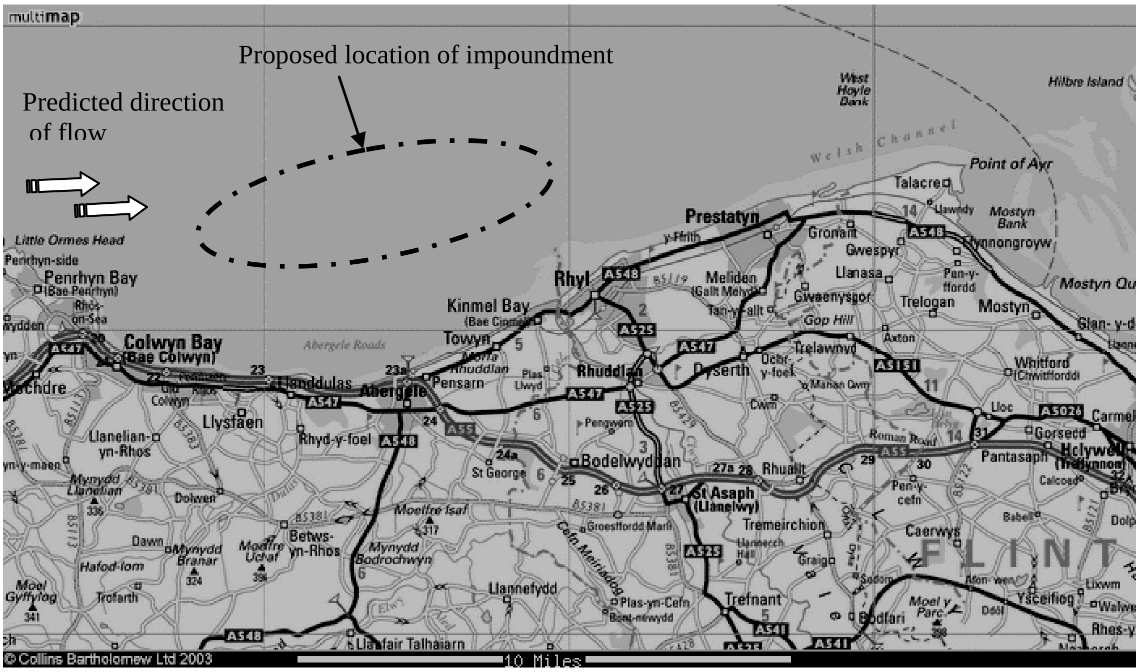

Fig 1 Proposed Location of impoundment (Source Multimap). This is illustrative – the precise location and shape are to be determined.

GENERATING CAPACITY

The power generated is related to the potential energy stored and released during each tidal cycle. Potential energy is the energy required to raise the weight (m.g) of the water by a particular height (H).

$$\text{Potential Energy} = mgH \qquad (1)$$

In a column of liquid of constant cross sectional Area A, and height H, the potential energy, taking account of the fact that elements of the liquid are present at heights ranging from zero to H, is derived as:

$$\text{Potential Energy} = \frac{\rho g A H^2}{2} \qquad (2)$$

For maximum power generation on the ebb tide, water would be retained in the impoundment until low tide. Similarly, for maximum generation on the flood tide, water would be excluded from the impoundment until high tide. Taking T as the tidal range, i.e. the height difference between high and low tide, and assuming that levels are equalised inside and outside the impoundment at high and low tide, equation 2 becomes:

$$\text{Potential Energy} = \frac{\rho g A T^2}{2} \qquad (3)$$

There are two tidal cycles every 24.813 hours. During this time, the impoundment would fill and empty twice. The maximum potential energy available during this time period is thus:

$$\text{Potential Energy} = 2\rho g A T^2 \qquad (4)$$

The maximum power, P_{max}, averaged over two cycles can therefore be calculated:

$$P_{max} = \frac{2\rho g A T^2}{24.813 \times 3600} \qquad (5)$$

At Llandudno, the mean tidal ranges of spring and neap tides are 6.7m and 3.5m respectively[2]. The overall mean tidal range may therefore be estimated at 5.1m. Taking, as an example, a rectangular impoundment 12 km long and 5 km wide, and this tidal range of 5.1m:

$$P_{max} = \frac{2 \times 1000 \times 9.81 \times 60000000 \times 5.1^2}{24.813 \times 3600} \qquad (6)$$

$$P_{max} = 343\text{MW}$$

In practice, however, it may not be feasible or desirable to pass all the water through the turbines at high and low tides. A more realistic mode of operation is presented in Figure 2, showing how the period of electricity generation is extended over more of the tidal cycle.

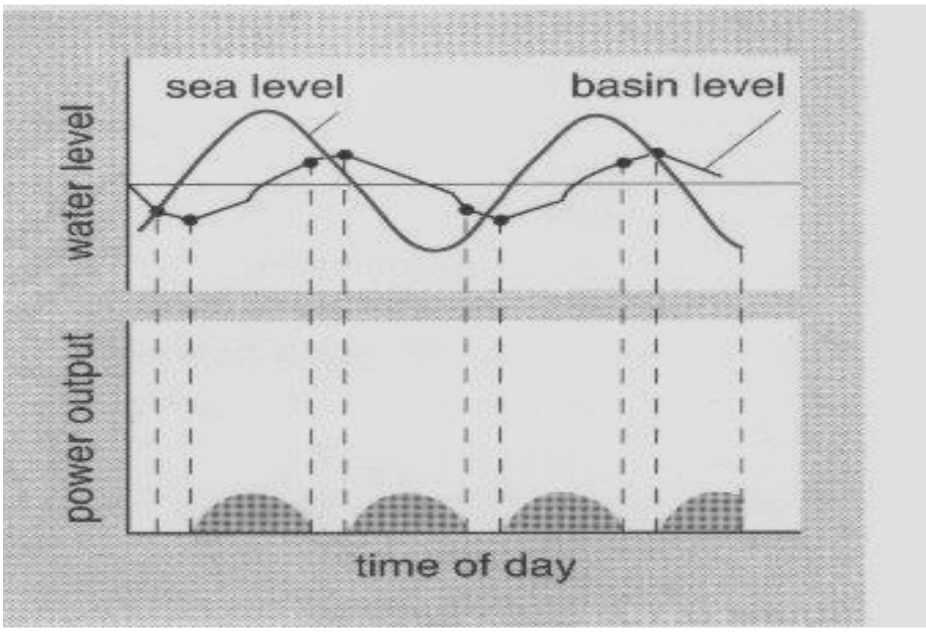

Fig 2 Profile for a two-way generation scheme

(Sourced from Boyle[3])

Inspection of Figure 2 shows that the volume of water exchanged during any given filling or emptying is only half that of the impoundment. The mean head during water transfer is approximately 0.35 times the tidal range. The maximum potential energy converted by the turbines into electricity can be calculated:

$$\text{Potential Energy} = \text{Mass Throughput} \times g \times \text{head} \qquad (7)$$

$$= A.(0.5T).\rho.g.(0.35T)$$

$$= 0.175A\rho gT^2 \qquad (8)$$

Comparison with Equation 3 indicates that the potential energy is only 35% of the theoretical maximum. Applying this mode of operation to the impoundment under study indicates that the mean power output over two cycles would be only 35% of that given by equation 6, or 120MW. Assuming 90% efficiency of the turbine-generator sets, the mean power output would be 108MW, equivalent to an overall energy conversion efficiency of 31.5%.

Modelling would be required to calculate the daily power generated. The tidal variation associated with the lunar cycle can be predicted very accurately. However, there is additional, irregular, variation associated with high and low atmospheric pressure and wind direction.

THE SIZE, SHAPE AND SITING OF THE IMPOUNDMENT STRUCTURE

Much of the coastline between Rhyl and Colwyn Bay lies below the higher range of Spring tide level, and is therefore vulnerable to flooding from the sea. In February 1990, storms, high winds, tidal surges and high wave heights combined with one of the highest tides of the year to produce the kind of flooding then expected to occur only once in 500 – 1000 years[4]. Sea defences protecting Towyn were breached and the town suffered catastrophic flooding, leaving thousands homeless. The defences have since been strengthened. However, the risk may be expected to increase with global warming and rising sea levels.

Ideally, any impoundment built for power generation should also offer coastal protection by reducing storm surges and the energy of waves before they reach the mainland shore. Several factors will influence the optimum size, shape and siting.

First, the scheme needs to be cost-effective. The bulk of the cost lies in the construction of the embankment itself (see below). Other economies of scale apart, the cost of the embankment is broadly proportional to its length, whereas power generation capacity is proportional to the area enclosed (or the square of its length). There is therefore a break-even size, below which the project is uneconomic, and above which it becomes progressively more economic.

Second, as the seabed shelves away from the shore, the height (and therefore cost) of the embankment becomes progressively greater, whereas the additional generation capacity per unit area added (determined by the tidal range) remains unaltered. There will be a distance from shore, beyond which the profitability of the scheme declines.

Third, the size and shape of the impoundment would affect prevailing tidal flows, which are form West to East (Figure 1). Eddies generated near the impoundment (depending on the shape) could cause sediment trapping, creating offshore beds and disrupting navigation channels. Streamlining the impoundment would minimise this effect.

Fourth, for protecting the coast against wave action, the structure should presumably run parallel to the shore. The further inshore it is sited, the greater protection might be expected. However, the speed of currents running through the intervening channel might then increase, leading to greater sediment transfer along the shore. This could be countered by constructing groynes at right angles to the shore.

Determining the optimum size, shape and siting of the impoundment would require sophisticated modelling. Options might include:

- A *"minimum environmental impact"* option, streamlined and located some 5 km from the shore.
- A *"maximum power generation"* option, brought closer to the shore and extended seaward to follow a particular depth contour.
- A *"climate change"* option where the impoundment is brought onshore as a long-term response to rising sea-levels. This could be achieved in a phased manner, with an offshore impoundment constructed first, and the area between it and the shore incorporated later.

MECHANICAL AND ELECTRICAL COMPONENTS

The principal mechanical and electrical components of the scheme would be the turbines, generators, sluice gates, gearboxes, electrical control system and connections to the grid (both land and sea). The power generation devices would be based on traditional hydroelectric technology. For a low head (5.1m) large-scale scheme, a large number of axial turbines would be appropriate (Figure 3). A combined efficiency of 90% is assumed for a turbine and alternator (Novak et al[5]). Materials would need to withstand marine conditions. Properly maintained, bulb turbines have a design life of 30 – 50 years.

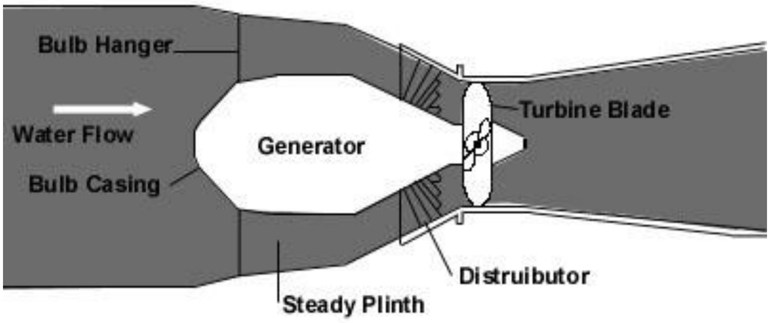

Fig. 3 Bulb Turbine (Source Australian Renewables Website, Copyright Boyle)

Adopting a large number of relatively small turbines would bring advantages. Flow rates across the impoundment could be finely regulated. Single units could taken out of use for maintainance with minimal impact on overall power output. The associated generators are also cheaper as smaller turbines have a higher speed. (Wavedragon[6]). The tidal barrage at La Rance, Brittany, has 24 bulb turbines each with a rating of 10MW. The proposed Severn Estuary barrage would have had 216 turbines, each with a rating of 40MW. For the current scheme close discussion would be required with manufacturers to arrive at the best design.

The siting of the turbines requires particular care, as they would cause local scouring. One view [7] is that they should be located on the seaward side of the structure, to minimise coastal disturbance. Another view suggests they should be on the landward side for protection from waves and presentation with calmer water.

Cables to shore would be required. The neighbouring North Hoyle Wind Farm has two cables, each buried 1.5m deep, with the cable landfall and grid connection point in Rhyl[8].

CONSTRUCTING THE IMPOUNDMENT

The choice of construction method and materials will significantly affect the viability of this scheme. Construction would take place in the wet and scheduling should therefore recognise tidal cycles and likely weather conditions. The construction period is estimated at approximately four years. The durability of the structure is of great importance given that failure to supply contracted power to the national grid would presumably lead to cost penalties.

Shaw[9] recommends that selection of construction method should be based on topographic studies, seismic surveys, trial bores, material sources, working sites, preliminary design studies and estimated time and cost of construction. Potential methods include:

- Traditional embankment dam.
- Embankment dam, but constructed with geo-membrane bags.
- Concrete caissons

Tidal Electric advocate a traditional embankment dam. Where possible, materials such as loose gravel, sand and secondary aggregates would be used, instead of more expensive rock fill and rock armour. The inward and outward facing walls would require varying degrees of protection from local wave action. The dam would have a sand/clay core to restrict permeability and rocks on the outer part for protection (Figure 4). The core fill would be dumped into the sea using split barges. Sand would come from the local seabed or from licensed dredging sites. A geo-membrane layer might be needed to prevent seepage through the walls, which would damage the structure and might lead to failure.

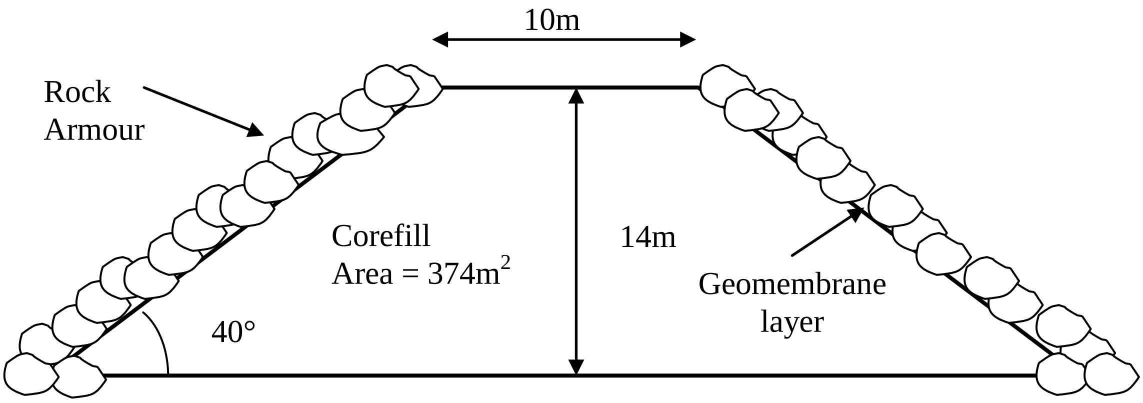

Fig. 4 Cross-section of embankment dam

A variation on the traditional embankment dam would be to use hydraulically filled geomembrane bags. Barr et al[10] discuss this method in relation to land reclamation. It may also be suitable for a marine impoundment. Impermeable bags would be specially designed with strengthening grids in their walls to help retain their shape. They would hold the core of the dam in place and improve its overall consistency.

The bags would be carried out to sea with floats. The sand could be directly dredged from the centre of the impoundment into the bags. Barr[11] estimates that each bag would be 1.5m high and 50m long. The top one would be 5m wide with an angle of 40° to the lowest bag (Fig. 5). The bags' behaviour in a completely submerged environment and their resistance to puncture by rocks would require investigation. Two layers might be required. The likelihood of the structure surviving if built directly on to the seabed, as opposed to being grouted on to the underlying rock, would also need to be examined.

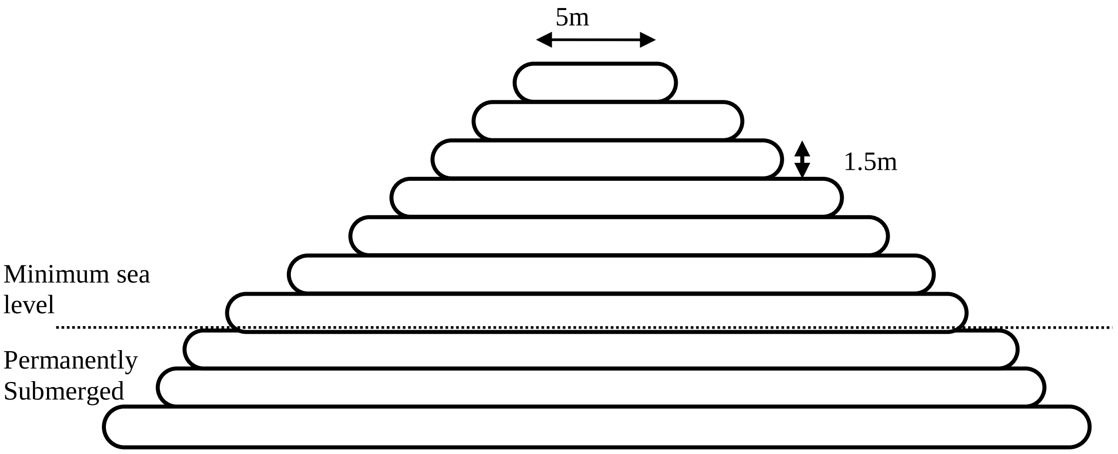

Fig. 5 Cross-section of impoundment wall using geomembrane bags

The proposed Severn Barrage was designed for construction with hollow concrete caissons, prefabricated in a shipping yard and floated out to sea. Given the size of the proposed impoundment, it is considered that construction entirely in concrete would be uneconomic. The turbines and sluice gates would, however, require a concrete frame and foundations, and secure holdings.

MATERIALS

Construction of an impoundment 12 km long and 5 km would require 10 million cubic metres of rock and aggregates. The cost analysis presented below assumes 10 million tonnes of rock armour and 10 million tonnes of dredgings. Rock armour could be imported from Scandinavia, though this would increase costs.

There is a permitted sand-dredging site north of Liverpool Bay that could be used to supply core fill relatively cheaply. The quantities needed may not be available from licensed sites and additional consent may be required. Another option would be to dredge the top layer of seabed within the future impoundment. Surveys carried out for the adjacent North Hoyle wind farm[12] found that the prevailing material was gravely sand with some fine sand, gravel and clay.

Alternatively, secondary aggregates might be appropriate. The National Assembly for Wales commissioned a report by Ove Arup[13] Consultancy into the potential use of slate waste from Gwynedd. The report estimated that 270-371 million tonnes of slate waste around Bethesda and Blaenau Ffestiniog might be suitable for use as secondary aggregate, but concluded that remoteness from markets gave a cost disadvantage. Transport by rail would be possible if the Conwy Valley line was upgraded and new loading and unloading facilities provided. The cost of improving rail links to the quarries was estimated as £15-£21 million. There are connections to sea near the proposed impoundment.

Slate waste generally comes in small particle sizes. If it were used for the core fill of the dam, it might need to be augmented with larger-sized material to support the structure and offer protection against the waves.

COSTINGS AND ECONOMIC CONSIDERATIONS

The Exponential Cost Estimating Method (IChemE[14]) has been used to estimate the cost of the proposed scheme, by comparing it with the cost estimates by AEA[15] for the Swansea Bay scheme and examining the difference in capacity of the sites. This is common practice in the process industry.

$$\frac{Cost1}{Cost\,2} = \left(\frac{Size1}{Size2}\right)^n$$

The n value is assumed to be 0.7; this gives a cost for the North Wales Scheme (60 km^2, 343MW) of £224 million.

The minimum and maximum costs have also been calculated from basic principles. The costs given in Table 1 are for a rectangular impoundment 12km by 5km with an installed maximum power capacity of 340MW.

Table 1 Cost Estimates

Investment Cost	**MINIMUM**	**MAXIMUM**
Capital and installation costs:	**£ MILLION**	**£ MILLION**
Civil engineering works:		
Dredgings / Waste (10 million tonnes)	**20**	**30**
Armour/Waste Rock (10 million tonnes)	**50**	**100**
Road Transport to Sea Loading site 10p/tonne/mile	**50**	**100**
Placement	**20**	**40**
Turbine houses (20 @ £50,000 / 75,000 each)	**1**	**1.5**
Geomembrane Bags	**70**	**140**
Sub Total Civil Works	**211**	**411.5**
Turbine generators (Assuming £2.4-4M per turbine and 20 turbines in total)	**48**	**80**
Labour		
Construction Period 4 years; 20 – 40 people full time (£50k/y)	**4**	**8**
Offices	**2**	**3**
Others (E.g. Feasibility studies, parliamentary, planning and approval)	**20**	**40**
TOTAL INVESTMENT COST	**285**	**542.5**

The payback period for this scheme has been calculated based on a mean generation capacity of 110MW. The Royal Academy of Engineering has published a commentary[16] on the cost of generating electricity by different means. Costs ranged from 2.2p/kWh for combined-cycle gas turbine plants to 5.5p/kWh for offshore wind farms. Assuming a price of 3p/kWh, the income generated by the impoundment would be £28.9 million per year.

Assuming an annual recurring cost for operation and maintenance of £3 Million/year, the minimum net income would be £25.9 Million/year. Based on the total investment costs in Table 1 the payback period ranges from 11 years to 21 years.

This scheme has a projected design life of around 100 years, so a long-term view is necessary. Barring unforeseen maintenance problems, and allowing for the replacement of the turbine/generator sets after 40 years, the operating costs should remain relatively constant. In contrast, the cost of fossil fuels seems set to rise.

SUSTAINABILITY OF THE SCHEME

This scheme should be considered on the basis of its local and strategic impacts. Sustainable development involves making environmental, social and economic progress simultaneously. Taking local environmental issues first, the developers would require a licence from DEFRA under the Food and Environmental Protection Act 1985 Part II, to *"deposit any article or substances in the sea or under the seabed"*. This would need an Environmental Impact Assessment (EIA). The EC EIA Directive requires the EIA to *"identify, describe and assess the direct and indirect effects of a project on the following factors: human beings, fauna and flora; soil, water, air, climate and the landscape; material assets and the cultural heritage; [and] the interaction between these issues"*.

Initial guidance from the Environment Agency and Countryside Council for Wales has identified a range of relevant issues (Table 2). As the details became clearer, the developers would have to seek further guidance regarding any necessary authorisations. Where data did not exist, the developer would have to fund surveys.

Table 2 Issues for the Environmental Impact Assessment

- Impact of structures, and changes in flows and waves, on coastal accretion and erosion, and geomorphological features.
- Impact of construction, decommissioning and removal on the seabed.
- Impact of lighting, disturbance and habitat change on bird behaviour and feeding grounds.
- Impact of underwater disturbance and noise on marine mammals.
- Impact of cables to shore, construction and maintenance on intertidal habitats.
- Impact of exclusion areas, displacement and electrical interference on fish and fisheries, including shellfish.
- Impact of exclusion area and collision hazard on navigation, amenity and water use.
- Impact of discharges during construction and maintenance on water quality, and on the amenity status of beaches nearby.
- Impact of onshore structures on coastal habitats.
- Overall impact of the scheme on designated sites, such as Sites of Special Scientific Interest (SSSI's) and Special Areas of Conservation (SAC's).
- The visual intrusion on the seascape, historic landscape and coastal character, depending on the structure's size, location, visibility, layout and lighting.

There are no designated protected sites within the proposed location of the offshore impoundment. However, Llanddulas Beach, Great Orme's Head, Little Orme's Head, Pensarn beach, Gronant Dunes, Talacre Warren and the Dee Estuary are all SSSI's. The Dee Estuary is also a Special Protection Area under the EC Birds Directive.

Environmental impacts can be both positive and negative. The potential impact on coastal flood protection has already been discussed. There may also be some ecological benefits. The impoundment would resemble an atoll, available for colonisation by animals and plants. Counting the inner and outer facing walls, it would create 68 km of rocky coastline. Sections could be designed with particular species, such as Little Tern, in mind.

Strategically, this scheme would help reduce global warming. Assuming an efficiency of 30%, and 85% utilisation, a coal-fired power station generating 110MW$_e$ would release around 1,000,000 tonnes of CO_2 annually[17]. An equivalent combined-cycle gas turbine plant would release around 400,000 tonnes. This scheme would contribute 1TWhr/annum to the Welsh Assembly Government's target of 4TWhr/annum of electricity from renewable sources by 2010[18].

Turning to socio-economic issues, the local area has relied heavily on tourism and day trips. Nowadays, these resorts are a shadow of their former selves. Rhyl West is the most deprived ward in Wales on the basis of Multiple Deprivation[19]. The scheme is seen as a means of economic regeneration. For example, a visitor centre on the impoundment is envisaged, with boat access from Rhyl Harbour. Marina facilities might also be provided, with substantial ongoing benefit to the local economy. Bringing the impoundment onshore would be preferred, since it would provide easier access with the mainland. If berths were located within the impoundment, locks would be required for access. These would be required in any case for maintenance purposes, such as to allow dredging.

COMPARISON WITH OFFSHORE WIND FARMS

Strategic allocation of coastal areas for renewable energy requires an understanding of the generating potential offered by different technologies. The North Hoyle Wind Farm, located 7 – 8km off the coast between Pretatyn and Rhyl, has 30 turbines with a maximum capacity of 2MW each[8]. Turbine separation is 800m East-West and 350m North-South. Based on these criteria, an area of seabed 12km by 5km could accommodate 240 turbines, with a total installed capacity of 480MW. The load factor (mean power output as a proportion of maximum installed capacity) for a typical UK offshore wind farm has been estimated as 0.35[20]. Based on this figure, the mean power output for the wind farm considered here would be 168MW – similar in magnitude to the tidal impoundment. The choice of option might then be based on:

- Relative costs per unit generated.
- The pattern of generation – particularly the reliability and predictability of supply.
- The range of other benefits and disbenefits offered – for example coastal protection.

It is possible to envisage schemes that combine technologies. Wind turbines might be built within the impoundment or on the wall.. For any scheme to be successful, the full range of benefits must be factored in from the start, rather than added as an afterthought. In the current scheme, for example, the area around the turbines would clearly be unsuitable for small craft. This holistic approach to scheme design requires consultation with all relevant stakeholders, who can then contribute to the best overall solution.

CONCLUSIONS

1. In assessing tidal energy schemes, distinction must be drawn between theoretical maximum generating capacity, installed capacity and the reliable output in operating conditions.
2. Extending the period of power generation within the tidal cycle reduces significantly the total amount of energy generated.
3. The size, shape and siting of the impoundment must be considered carefully in relation to potential benefits for coastal protection.
4. The technology for building the tidal impoundment already exists, in the form of traditional breakwaters. It is suggested, however, that the use of specially designed geo-membrane bags filled with locally dredged aggregate might offer a more cost-effective method of construction.
5. Matching energy generated to demand will have a critical impact on the profitability of this scheme. The payback period for the scheme is estimated as 11 – 21 years, based on an overall energy conversion efficiency of 31.5%.
6. The overall sustainability of the scheme will be enhanced if appropriate social and environmental benefits are incorporated.
7. The mean power generated is predicted to be similar to that from an offshore wind farm occupying the same area of sea bed.
8. Detailed physical, environmental and economic modelling is required if the assessment of the scheme is to be successful.

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