

Severn Tidal Power
Review of “Interim Options
Analysis Report”

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Rev 1

Severn Tidal Power

Review of “Interim Options Analysis Report”

prepared for a consortium of NGOs including the WWF, WWT, National Trust, RSPB and the Wye and Usk Foundation

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Contents

Section	Page
1. Non-Technical Summary	1
1.1 Context	1
1.2 Aims of the IOAR	1
1.3 Aim of this Review	1
1.4 Conclusions on Phase 1 IOAR	2
1.5 Recommendations for subsequent Phases.	5
2. The IOAR Judged against its Aims	7
2.1 DECC's aims for the IOAR	7
2.2 Work required to meet stated aims	7
2.3 The work reported in the IOAR	8
3. Assessment Framework	10
3.1 IOAR Assessment Framework	10
3.2 Alternative Assessment Framework	11
3.3 Scope of work for next stage	12
3.4 Use of Existing Research	13
4. Power Calculations	14
4.1 Downstream sites and two-way generation	14
4.2 Taylor's analytical solution	15
4.3 Downstream sites	17
4.4 Two-way generation	17
4.5 Conclusions on power calculations	18
5. Recent Developments in Turbine Technology	19
5.1 Turbines	19
5.2 Importance of the MJ2 turbine	20
5.3 Feasibility of scaling up the MJ2 turbine	21
5.4 Environmental impact aspects of new turbine options	23
6. Construction Programming & and Cost Estimation	25
6.1 General Comments	25
6.2 Barrages B1, B2, B3	25
6.3 Outer Barrage B1	27
6.4 Tidal Lagoons	27
6.5 Tidal Reef	27

6.6	Questions & Answers	28
6.7	Conclusions on Cost Estimates	31
7.	Economic Analysis	33
7.1	Assessment methodology	33
7.2	Scope of analysis	33
7.3	Sensitivity testing	33
8.	References	34

APPENDIX – The optimum position for a tidal range scheme on the Severn estuary

1. Non-Technical Summary

1.1 Context

A coalition of NGOs, including the WWF, WWT, National Trust, RSPB and the Wye and Usk Foundation, have approached Atkins Ltd (Atkins) for a critical review of the *Technical Options Appraisal Report* (Vols 1 & 2), henceforth referred to as the IAOR, recently published by the Department of Energy and Climate Change (DECC) as part of the public consultation exercise on Severn Tidal Power. The review provided is to inform the respective responses of the individual NGOs to the Phase 1 consultation process for the Severn Tidal Power Feasibility Study.

1.2 Aims of the IOAR

DECC's stated aims on the Severn are:

- A. *to generate electricity from the renewable tidal range resource of the Severn Estuary with acceptable impact on the environment and economy both locally and nationally*
- B. *to deliver a strategically significant supply of renewable electricity, which is reasonably affordable compared to other sources of supply and represents value for money, in the context of the UK's statutory obligations under the forthcoming Renewable Energy Directive and Climate Change Act and our goal to deliver a secure supply of low-carbon electricity [Ref Initial Options Appraisal Report, Executive Summary, page v]*

The aims stated do not differentiate in "weight" between the environmental acceptability of any scheme and the strategic significance of the scale of the renewable energy to be generated. For the purposes of this report we have assumed that equal weight should be applied to both objectives.

The aim of the IOAR is stated by the authors as:

To undertake the assessment of options and provide an option-neutral report which could be taken into account by ministers when they determine the draft shortlist [pers.comm. Kydd/Rainey, April 09]

This indicates that the authors of the report consider that their role in this phase of the Severn Estuary studies is to provide an assessment of long-listed options for renewable energy generation, the results of which would inform any decision to be made by ministers about a short list. Despite this reported position, the IOAR does present a process whereby some of the long-listed options are discarded following an "initial screening", thereby taking a decision on viability of schemes before ministerial assessment.

1.3 Aim of this Review

This Review concentrates on the assessment process described in the IOAR, with particular reference to the economic assessment presented of the various tidal power

options on the Severn (both the energy produced, and its cost), and the outline assessment of environmental impacts. In particular we comment on the parameters and consistency of application of the assessment framework and consider how the application of the framework might alter the results reported in IOAR.

It is accepted that the IOAR is only seeking to provide an option-neutral assessment, i.e. an assessment of the relative energies, costs, and environmental impacts of the various options, and not an absolute assessment (which would enable tidal power to be compared with wind power, for example). This Review is based on the information provided in the IOAR which, in particular in respect of the cost estimates remains for comparative purposes only. Future phases of the DECC sponsored study are expected to develop more detailed information to support decision making.

1.4 Conclusions on Phase 1 IOAR

Equal consideration has not been given to the study aims of acceptable environmental impact and providing a significant amount of renewable energy at an affordable price. There has been no attempt to modify the long listed options to reduce environmental impacts.

The Phase 1 IOAR assessment framework was based on quantitative measures, largely: power output, construction cost, and cost and amount of energy. The qualitative measures included: impact on energy markets, environmental impact, technical risk, affordability, and economic and social impacts. A fair basis methodology was used to apply a consistent set of cost rates and assumptions across all options. A number of options including the tidal reef, tidal fence and some lagoons were then dismissed based on cost of energy. No options were dismissed based on environmental impact.

The quantitative measures assessed are in our opinion open to more potential bias than the IOAR team acknowledges. We have significant questions over both the energy estimates for some of the newer schemes and over the cost estimates and construction risk, where the same basis has been used for both small and large schemes. The difference in risk and environmental impact between small and large projects means that these “quantitative measures” are not truly and directly comparable and, in our view, risks discarding some schemes which might in reality be viable when environmental aspects are weighed appropriately in the balance.

There is no explanation of what constitutes a “significant” quantity of energy and the omission of any discussion of this parameter means that there has been less focus than is merited, in our view, on the potential of “in-combination” schemes (eg a group of tidal lagoons or lagoons with an inner barrage for example). The IOAR proposes to review the in-combination schemes only in subsequent phases with reference to options which have made it to the short-list. This presents the risk that some discarded options might be significant and suitable in combination whereas they have been assessed as unsuitable as stand-alone schemes.

The assessment approach seems, in our view, to eliminate options before sufficient work has been done on optimising arrangements for generation and management of environmental impacts. Our view is that the level of detail given in the IOAR is only sufficient to dismiss options that are clearly unreasonable.

1.4.1 Power calculations

There are several serious shortcomings in the IOAR' power calculations which bias the short-listing process. The IOAR does not discriminate between ebb-only generation schemes and two-way generation schemes, which are potentially less environmentally damaging, and gives the false impression that two-way generation schemes produce much less power. The calculations in our Review demonstrate that:

- Two-way generation, which is potentially less environmentally damaging, produces more power than ebb-only generation, provided suitable turbines are available. The maximum power available increases steadily as tidal power schemes are moved downstream in the Estuary. This negates the findings of the Bondi committee, which were that the power does not increase with reservoir area, but peaks at Minehead-Aberthaw, and then begins to fall if the barrage is moved further downstream (see the calculations in the Appendix).
- Because the IOAR bases its conclusions on the 30-year-old findings of the Bondi committee and fails to undertake new power calculations, it seriously under-estimates the potential of sites downstream from Cardiff-Weston. While the IOAR concludes that the power is only 25 TWh/yr for the Minehead-Aberthaw route, the calculations in this Review show clearly that that this route could produce up to 31 TWh/yr (see section 4.4).
- It is not satisfactory to rely on other sources, i.e. the Bondi Committee's conclusions, in this way, given the importance of the short listing process. The IOAR should have investigated these matters more thoroughly, and carried out its own independent calculations, e.g. with computer models. This would have been perfectly feasible given the resources available, which we understand were 10 man-years of engineering time, or £1 million, for the production of the IOAR. The IOAR is in error in abandoning its empirical relationship between power and reservoir area, in favour of the findings of the Bondi committee.
- The Tidal Reef was found to produce only half the power of a barrage with ebb-only generation at the same site (13 TWh/yr rather than 25 TWh/yr). This appears to be the result of some very sub-optimal assumptions about the operation of the Tidal Reef, and gives the false impression that two-way generation gives less power than ebb-only generation.

1.4.2 Recent developments in turbine technology.

In recent years the hydro-electric turbine industry has begun building very-low-head (VLH) turbines, albeit only on a small scale. Our Review concludes that:

- These new developments are highly relevant to the Severn because they suit two-way generation schemes, which can be much less environmentally damaging than ebb-only schemes. In particular, two-way generation may limit loss of inter-tidal habitat by allowing the pre-barrage tidal regime to be more closely matched during generation. In addition the small scale VLH turbines used to date have low blade speeds (which would remain the case even when

scaled up) which ought to have benefits of reduced migratory fish mortality. The IOAR dismisses such turbines as irrelevant, because the turbines built to date would have to be scaled up. We disagree in principle – it appears feasible to scale them up in the timescale of a major generation project in the Severn, although undoubtedly there would need to be some incentive for the turbine manufacturers to tread this path.

- Atkins have had conversations with senior representatives of a major technology manufacturer in this field, and they have expressed their strong interest in developing a scaled up prototype over the next 2 years for these operating conditions.

1.4.3 Cost estimation.

Our Review identifies several significant weaknesses in the IOAR's costing work:

- The IOAR's cost estimates take no account of the scale of the project, because they are all based on per-unit costs (cost per tonne of concrete, cost per MW of generating capacity, etc.). Since large projects tend to distort markets and inflate costs, this means that the cost estimates in the IOAR can only be considered as giving correct relative costs (which was the aim of the IOAR), if the overall project size is similar (i.e. several of the smaller schemes are built simultaneously, to give a project of similar size to one of the larger schemes). The absolute costs could be significantly under-estimated, taking other large projects as a guide.
- The larger schemes also appear to be significantly riskier than the smaller ones, because the caissons are bigger and more exposed, and thus more difficult to install. We estimate that this risk factor could double the caisson installation costs given in the IOAR, for the larger schemes.
- The construction programme for Cardiff-Weston has not identified a location for the caisson construction facility. We suspect that a new deep water port facility may be required on the Severn, which could have a significant impact on cost.
- The construction programme for Cardiff-Weston is inadequately described. If required, the planning and construction of new port facilities on the Severn would significantly extend the proposed construction and implementation programme.
- The caissons for the "outer barrage" between Minehead and Aberthaw (about a third of its total cost) are assumed in the IOAR to require 65% more concrete than those for the Cardiff-Weston barrage. This is only an educated guess.
- The turbines for the Tidal Reef between Minehead and Aberthaw (about two thirds of its total cost) are assumed in the IOAR to cost four times as much per MW as conventional turbines. This again is only an educated guess, as is the caisson cost (assumed to be 45% of the cost of the "outer barrage", which is again only an educated guess). It is discussed in Section 4.

1.4.4 Economic analysis

The IOAR only seeks to provide guidance on the relative economics of the various tidal power options on the Severn. The assessment methodology comprised the calculation of an average annual energy cost derived from discounting capital and annual costs at a variety of discount rates and then calculating a cost of energy. This is standard practice for assessing and comparing energy generation projects. Various discount rates were used to reflect either public or private ownership. A second phase of work will now follow, in which it is clearly essential that:

- some absolute cost figures be produced (addressing the points above, especially those in 1.6) – otherwise a misleading impression may be given of the cost of Severn tidal power compared with other renewable energy options, such as wind.
- The analysis in Phase II also include the cost of other environmental mitigation measures (aside from compensatory habitat). In particular, the impact on fisheries and the cost of mitigation or reduced turbine performance is not priced.

1.4.5 Assessment framework adopted in IOAR

The IOAR's short-listing assessment framework does not achieve a fair basis in its evaluation of energy, cost and environmental impact criteria and therefore gives some schemes unfair advantages over others. This is because the different schemes have different risks and environmental impacts.

Our review of the IOAR demonstrates that the assessment's methodology and outcomes are insufficient at this stage to adequately identify a short-list of tidal power options for the Severn Estuary. Moreover, given the objectives of the Feasibility Study, which are to produce a reasonably affordable and strategically significant supply of renewable energy with acceptable environmental impacts, short-listing should logically take place only after schemes are optimised to increase energy, reduce cost and avoid environmental impacts.

Section 3 of this report proposes an alternative assessment framework where only unreasonable options would be discarded at this stage.

1.5 Recommendations for subsequent Phases.

1.5.1 Assessment framework & short-listing

1. Equal consideration should be given to the study aims of acceptable environmental impact and providing a significant amount of renewable energy at an affordable price. The assessment framework should be amended to reflect this in Phase 2 and include a detailed assessment of the available technology that can be used to reduce environmental impact.
2. Short-listing schemes at this stage of the Feasibility Study is premature. The overarching objective of the Feasibility Study, which is to produce a reasonably

affordable and strategically significant supply of renewable energy with acceptable environmental impacts, may not be met by adopting an assessment framework that short-list schemes at too early a stage. Moreover, premature short-listing has the potential to introduce bias in the cost and energy production estimates. The next phase of work will 'optimise' schemes to increase energy, reduce cost and avoid environmental impacts – it seems more rational to short-list options only after the completion of this step.

3. We remain unclear as to the role assumed for the SEA. The attempt to short-list options prior to an SEA seems illogical and may fail a legal test. We recommend that tidal power options should be short-listed within the SEA process.
4. The £0.5 Embryonic Technology Fund provides limited funding for potentially less environmentally damaging schemes such as the tidal reef and tidal fence. We recommend that investment in potentially less environmentally damaging schemes must be proportional to the scale of the challenge and that these schemes should be evaluated within the Feasibility Study.
5. Combined schemes should be considered in the next phase including multiple lagoons and barrages.
6. of the Phase 2 studies should clearly define what constitutes a “significant” quantity of energy.

1.5.2 Power calculations

7. The power calculations are seriously flawed. We recommend that Phase 2 should re-investigate the power generation potential downstream of the Cardiff-Weston alignment, e.g. at Minehead-Aberthaw, and carry out its own independent calculations prior to short-listing options. The power estimates for some schemes, in particular the tidal reef, seem to be significantly underestimated.

1.5.3 Turbine technology

8. The Study should not dismiss existing low-head turbines and the potential to scale these up and fit them to two-way generation schemes. A major tidal power scheme would seriously incentivise manufacturers to research new turbine options.

1.5.4 Cost estimation

9. More precise costing of schemes is necessary. It is clearly essential that some absolute cost figures be produced; otherwise a misleading impression may be given of the cost of Severn tidal power compared with other renewable energy options, such as wind. A consistent approach to assessing risk and pricing would help to make evaluation more objective.
10. The next phase of the work should quantify unit costs taking account of the risks associated with the scale of the project otherwise the cost of larger projects, such as the Cardiff-Weston barrage, may be seriously underestimated.

2. The IOAR Judged against its Aims

2.1 DECC's aims for the IOAR

On their website, DECC clearly defined their aims for the Severn Tidal Power Feasibility Study as:

- *to generate electricity from the renewable tidal range resource of the Severn Estuary with acceptable impact on the environment and economy both locally and nationally*
- *to deliver a strategically significant supply of renewable electricity, which is reasonably affordable compared to other sources of supply and represents value for money, in the context of the UK's statutory obligations under the forthcoming Renewable Energy Directive and Climate Change Act and our goal to deliver a secure supply of low-carbon electricity*

As noted above these two aims are not formally weighted so that one can be assumed to be more important than the other. We have therefore assumed that equal weighting in any decision or decision-making process should be adopted at this high-level, strategic stage, particularly in the absence of any definitive new scientific work which would allow greater discrimination between competing objectives and options.

The aim of the Parsons-Brinkerhoff work covered by the IAOR was stated by them (e-mail Kydd/Rainey, 19th March) as being:

- *To undertake the assessment of options and provide an option-neutral report which could be taken into account by ministers when they determine the draft shortlist*

2.2 Work required to meet stated aims

To meet these aims, the work required in our view was:

1. Calculation of energy generated by the various options on a "fair basis". Energy generation is one half of the economic calculation (the other is cost), so the energy from the various options needs to be calculated in an unbiased way, at a sufficient level of detail to allow one option to be compared with another. It is thus relative energy output which counts – the analysis need not produce absolute numbers, but needs to do sufficient to ensure that no option has an unfair advantage over another. Options should include both stand alone and in-combination schemes in the absence of any formal definition of what a "strategically significant" supply of energy might amount to.
2. Calculation of the costs of the various options on a "fair basis". This is the other half of the economic calculation, and exactly the same comments apply. The

analysis need not produce absolute numbers, but needs to do sufficient to ensure that no option has an unfair advantage over another.

3. Assessment of environmental and socio-economic impact. This is the third factor mentioned in the aims. Since unfavourable impacts need to be weighed against energy generation, it is in our view logical to consider the impacts per unit of energy generated. Once again, the level of detail required is set by the requirement that no one option is given an unfair advantage over another.

2.3 The work reported in the IOAR

Set against these three requirements, our comments on the work reported in the IOAR are respectively:

1. Energy calculations. The IOAR calculates energy simply from reservoir area, which is a suitable method for giving the required comparative figures. However, the results of this method are apparently not used in some cases, in favour of more questionable methods. This, in our view, may unfairly bias the results. More detailed computations, and extra options, are included in cases where they are not needed, and omitted in cases where they are. This may not in the final analysis matter much since many options which are credible from the perspective of the two main objectives remain in the screened list, but it represents a risk that a bias is introduced early in the process.
2. Cost calculations. The IOAR calculates costs in a very simple way, on a per-unit basis (e.g. per unit of concrete volume, or per unit of rated power). This is in principle well suited to generating comparative figures, provided the scale of the project is not changed (i.e. several of the smaller schemes are undertaken simultaneously, to give a project of similar size to the larger schemes). This is because large projects may distort markets and inflate costs, which must be addressed during the next phase of the work, when absolute costs will be required. The IOAR methodology also gives questionable results when the units are changed (e.g. unit of conventionally-generated power vs unit of unconventionally-generated power), and it largely ignores the extra cost margin which is required when the risk is greater (e.g. of large offshore installations rather than small inshore ones).
3. Environmental impact. The IOAR largely ignores the reduced environmental impact of some options compared with others – notably, the Tidal Reef is given no credit for its reduced environmental impact, compared with a conventional barrage. The way in which environmental and social impacts may be judged is a matter of opinion for such a high level assessment. The assessment framework chosen in the IOAR examines a large number of aspects of the potential impacts which gives the impression of allowing a comprehensive assessment, although it is acknowledged in the report that there is a great deficiency of sound, accepted science in many of the areas and that the judgements made are therefore qualitative. We agree that this is the case and also agree that it is reasonable not to discard any options at this stage where there is such a deficiency of information. We comment later on the work which will need to be undertaken during subsequent phases of the study to throw

sufficient light on the environmental aspects to allow reasoned and publicly acceptable judgements to be made.

These points are expanded on in the following Sections.

3. Assessment Framework

3.1 IOAR Assessment Framework

The Assessment framework was undertaken on a “fair basis” approach where consistent energy and cost calculations were applied to the options. Options were then discarded based on estimated cost of electricity generated and were then compared on a qualitative basis in terms of environmental impact and risk.

As discussed later in this report no risk pricing was undertaken despite the different risk profiles for the lagoon and barrage options. Moreover, a sensitivity analysis has not been undertaken to explore how the costs of the options would vary depending on the pricing of risk. When considering a complex range of options, best practice would be to use a more quantitative approach to risk and sensitivity.

What is evident from the interim options study is that there is a balance to be struck between output, cost and environmental impact. The assessment framework has not recognized this basic fact. In simple terms, different modes of generation would produce differing losses of intertidal area. This relates directly to the impact on bird populations and the requirements and cost for compensatory habitat.

There is also a balance between turbine efficiency and fish mortality that has not been explored in any meaningful way. There are a variety of means of reducing fish mortality including providing so called fish friendly turbines, and providing screens and fish diversions measures. These measures would have an impact on efficiency and cost. Mitigation and compensation measures for fisheries impacts have not been priced.

The fair basis assessment of energy output has been undertaken on the basis of an ebb generation scheme output being applied to all of the options, with the exception of the tidal fence and tidal reef. It is questionable whether this mode of generation is optimal for tidal lagoons. Unlike barrages, it is possible to put more turbines into the walls of tidal lagoons. More turbines mean more energy.

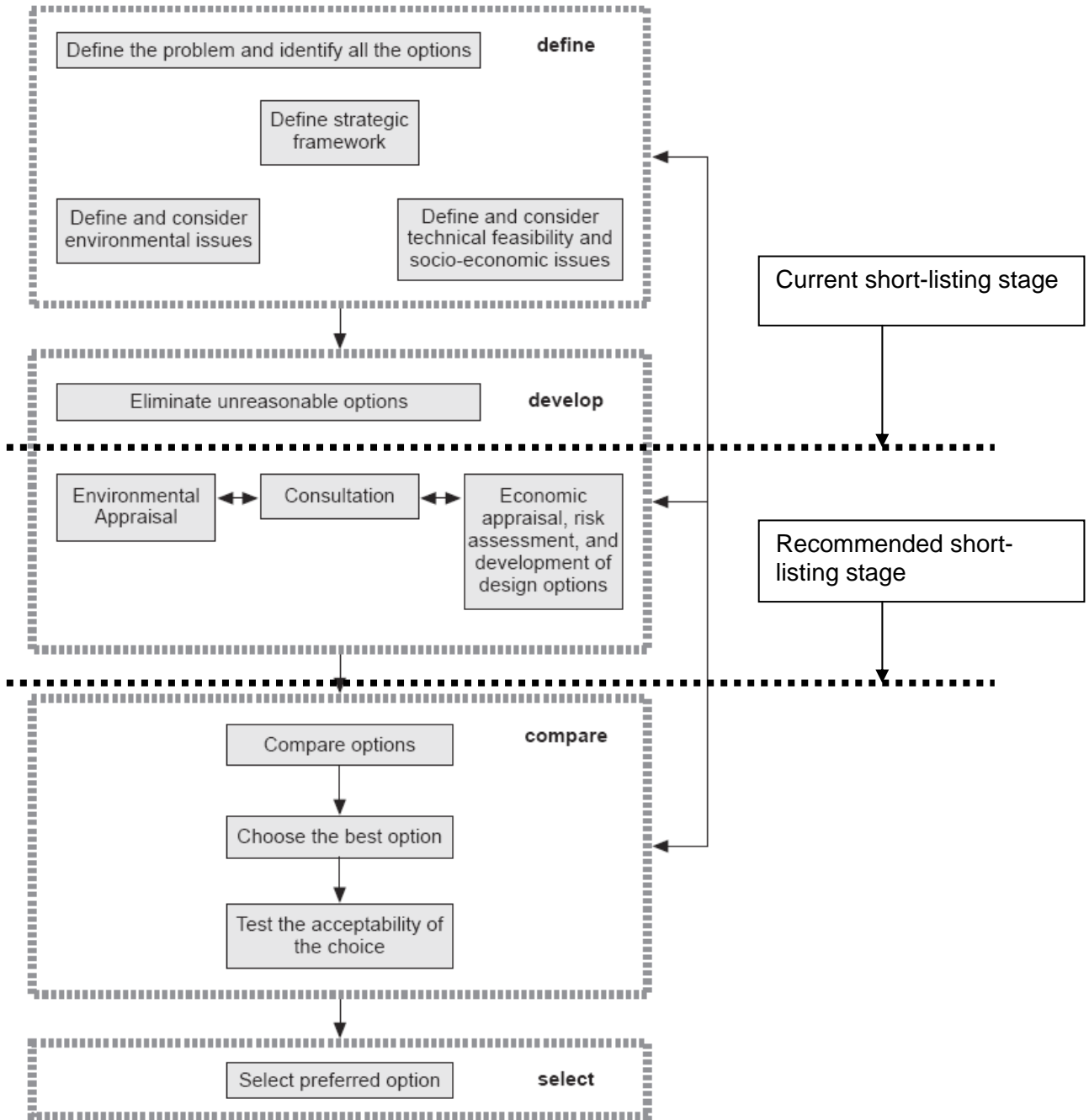
Our concerns with the assessment framework are that:

- No account was taken of how different technologies and modes of generation that could reduce environmental impact;
- There was no quantitative assessment of risk;
- Ebb mode generation may not be optimal for all options.
- there was not equal consideration of all assessment criteria, leading to bias towards schemes that meet “quantitative” criteria.

3.2 Alternative Assessment Framework

The Government Project Appraisal Guidance documents¹ for flood and coast defence provides a best practice example of how complex options should be assessed on the basis of economics, environmental impact, and risk. The figure below is taken from FCPPAG4.

Figure 1.1 Relationship between environmental and economic assessment and schen development



¹ <http://www.defra.gov.uk/Environ/Fcd/pubs/pagn/default.htm>

We think that this assessment framework has a lot of merit and note that it does not require short listing of options. However, if options are to be shortlisted this should be done at a later stage as shown above.

Using this assessment framework, the IOAR has reached but not completed the “develop” stage. FCDPAG4 also recommends that for projects in SAC/SPA designations there should be a stage where the options should be modified where possible to avoid or mitigate any adverse effects. The IOAR has not done this and furthermore has not developed the options to sufficient detail to allow a quantitative assessment of risk. Therefore, only unreasonable options should be eliminated at this stage.

An example of an unreasonable option would be the Severn Lakes proposal because it clearly does not meet the scheme objectives and because the cost is so much higher than the other options.

Using this assessment methodology, the outer barrages, tidal reef, tidal fence and the lagoons that did not make the shortlist recommended by DECC would not be dismissed at this stage. The costs of these options are not so much higher that they could be considered as “unreasonable” when considering the variation and uncertainty associated with the power output estimates, cost estimates, and risk described in the IOAR.

3.3 Scope of work for next stage

The assessment framework for the next stage should include a detailed assessment of the available technology that can be used to reduce environmental impacts. The two main features of this should be the mode of operation and fish survival.

The objective of looking at the mode of operation would be to reduce the impact on the loss of intertidal habitat. Potential modes of operation include:

- Ebb mode with sluicing at low water;
- Ebb and flood mode with 2 to 3 times number of turbines used for ebb only;
- Ebb and flood mode with sluicing and pumping.

Two dimensional flow modelling should be used to investigate the energy output and environmental impacts of these schemes.

A level of acceptable fish mortality need to be assessed and all options need to be designed to this figure.

In terms of practical design features, the following options need to be assessed in detail:

- Fish diversions/pass technology;
- Turbine intake screening and fish bypassing;
- Fish guides;
- Turbines designs that reduce fish mortality.

A combination of these measures may be required.

3.4 Use of Existing Research

The next stage of this study should make best use of existing research. In particular, we would draw attention to the following:

- Liverpool Universities 2d model of the Irish Sea and the results of their NERC funded research project on “Tapping the Tidal Potential of the Irish Sea”. <http://www.liv.ac.uk/engdept/tidalpower>.
- American research into hydropower and the reduction of fish mortality for hydro power projects. Extensive research is listed at <http://hydropower.inel.gov/turbines/>.

4. Power Calculations

4.1 Downstream sites and two-way generation

The IOAR calculates power in a very simple way, based on an empirical relationship to the reservoir area. See IOAR Vol 1, Fig. 4.1 – the power is taken as proportional to:

$$(\text{reservoir area})^{0.97}$$

In our view this approach is well-suited to an initial assessment of the various options, which is the object of the IOAR.

However, the IOAR departs from this method in two cases:

1. **Downstream sites (Minehead-Aberthaw and further west).** Since the reservoir area of a Minehead-Aberthaw barrage is $1060/504 = 2.10$ times that of a Cardiff-Weston barrage (IOAR Vol. 1 Table 4.2), if the above formula is adhered to the power should be $2.10^{0.97} = 2.06$ times greater, according to the formula above. So if the Cardiff-Weston power is taken as 17 TWh/yr, the Minehead-Aberthaw power will be $17 \times 2.06 = 35$ TWh/yr. By the same token, much more power should be available at sites further downstream than Minehead-Aberthaw. This is a very important point, because of DECC's stated objective of producing "strategically significant" quantities of power (see previous section). However, the IOAR departs from the reservoir area method for Minehead-Aberthaw, and concludes that the power is only 25 TWh/yr (IOAR Vol 1 p.35 and p.38), apparently based on the findings of the Bondi committee and an impression that the calculated outcome is less likely due to declining tidal range. This may be the case but should be sensitivity tested at an economic level. Sites further downstream are not considered at all.
2. **Two-way generation.** The reservoir area method gives the relative powers between two sites. It is silent, however, on the relative power between two-way and ebb-only generation at the same site. This question is important because two-way generation can be less environmentally damaging than ebb-only generation, and reducing environmental damage is DECC's other stated, and equally weighted, objective (see previous section). The conventional view, expressed for example on p.30 of Ref. [1], is that two-way generation in principle gives more power, but it is often not achieved in practice because of lower turbine efficiency. Two way generation is considered in the IOAR in respect of the Tidal Reef at Minehead-Aberthaw. Here it is concluded from other sources (Vol 1, p.29) that the two-way Tidal Reef will only produce 13 TWh/yr, compared with 25 TWh/yr for an ebb-only barrage (see (1) above). The IOAR thus concludes that the latter is much more economic.

In our view it is not satisfactory to rely on other sources in this way, given the importance of the questions. The IOAR should have investigated these matters more thoroughly, and carried out its own independent calculations, e.g. with computer models. This should have been perfectly feasible given the resources available, which we understand were considerable, for the production of the IOAR.

Computer simulations were carried out for small lagoons and barrages (IOAR, Table 4.1), where they were not needed (the smaller the lagoon the more closely is the power proportional to reservoir area, because the tidal range is increasingly unaffected), but were omitted in cases (1) and (2) above, where they were needed because the power/area relationship could be modified.

4.2 Taylor’s analytical solution

As an alternative to computer modelling, there is in the literature an analytical solution for the tidal flow in the Severn estuary, devised nearly a century ago by the famous English scientist G.I.Taylor. This can be extended to include a barrage with two-way generation, and allows the power at a number of sites in the Severn estuary to be calculated. This is done in Appendix 1, for Taylor’s original locations E-A shown in Figure 3.1 below.

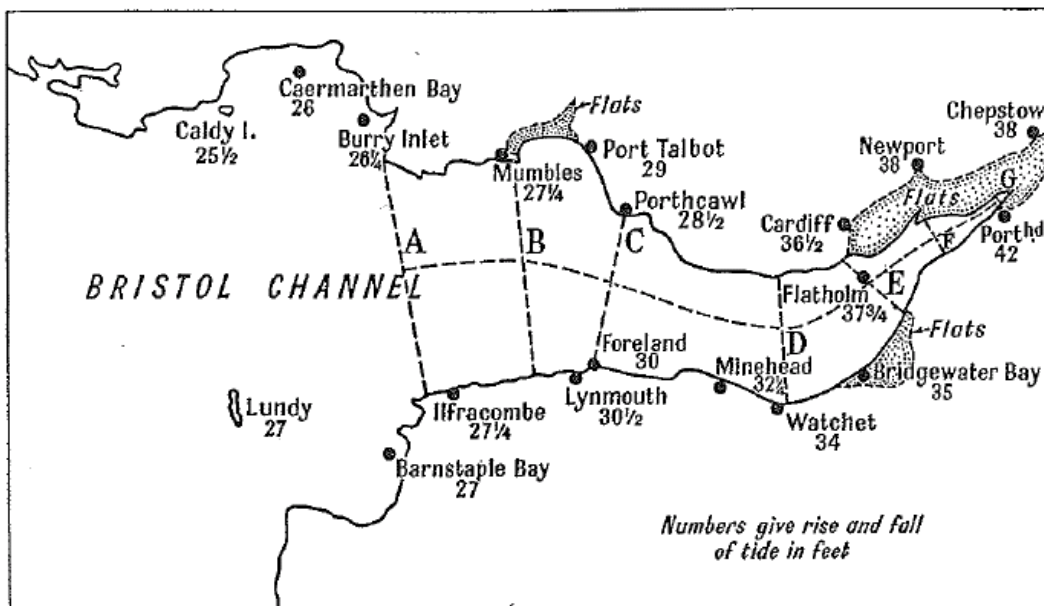


Figure 3.1. Taylor’s model of the Severn estuary

The annual-average power available (before conversion losses) with two-way generation at these sites is shown in Figure 3.2, taken from the Appendix. They are plotted against the level difference across the barrage, expressed as a fraction of the original tidal range (measured the same way, so for example 0.5 means the head across the barrage is $\pm 2.5\text{m}$, when the tidal range is $\pm 5\text{m}$).

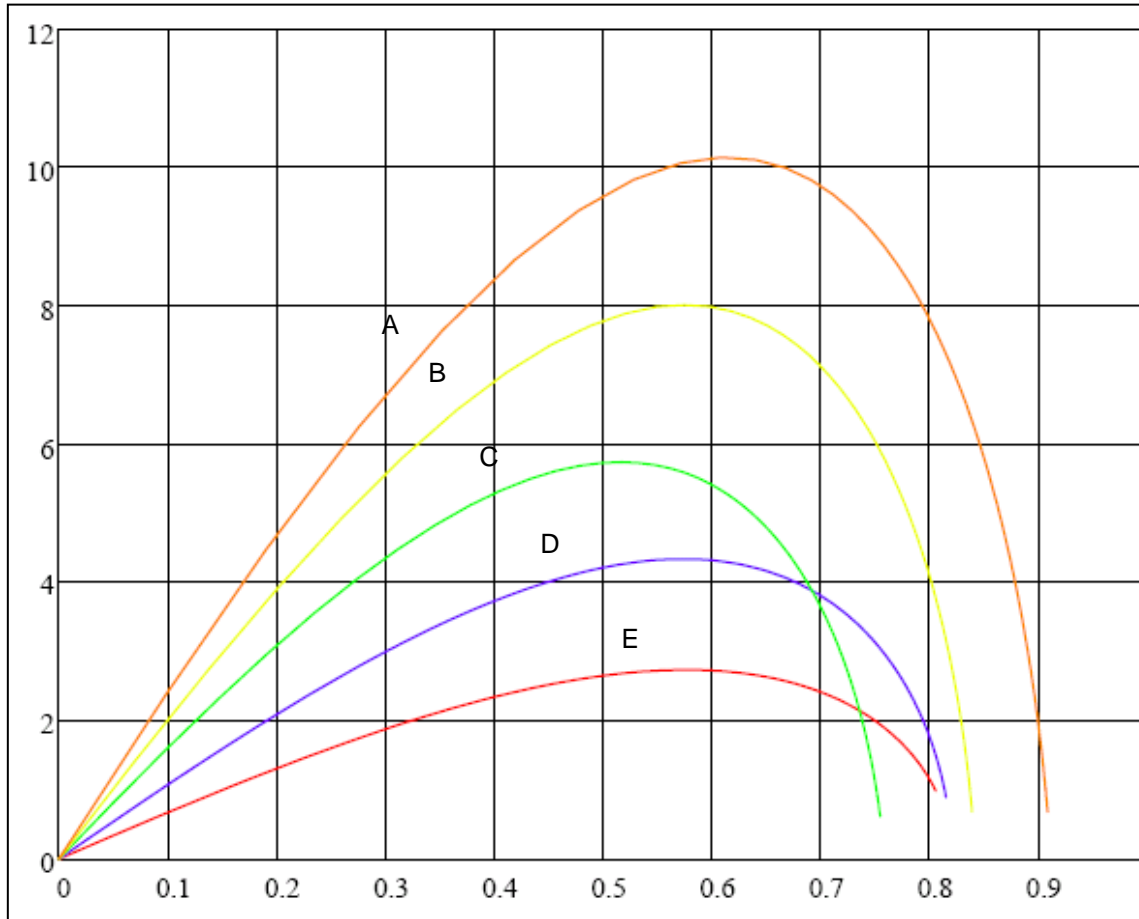


Figure 3.2. Annual-average power (GW) v. fraction of original tidal range seen across barrage. Curves are for Taylor’s sites A-E in Figure 3.1

These results throw light on the two questions of downstream sites and two-way generation, raised in Section 3.1 above.

4.3 Downstream sites

It may be seen from Figure 3.2 that the theoretical maximum power available increases steadily as the barrage site is moved downstream. The maxima from Figure 3.2 are plotted against reservoir area, in Figure 3.3 below.

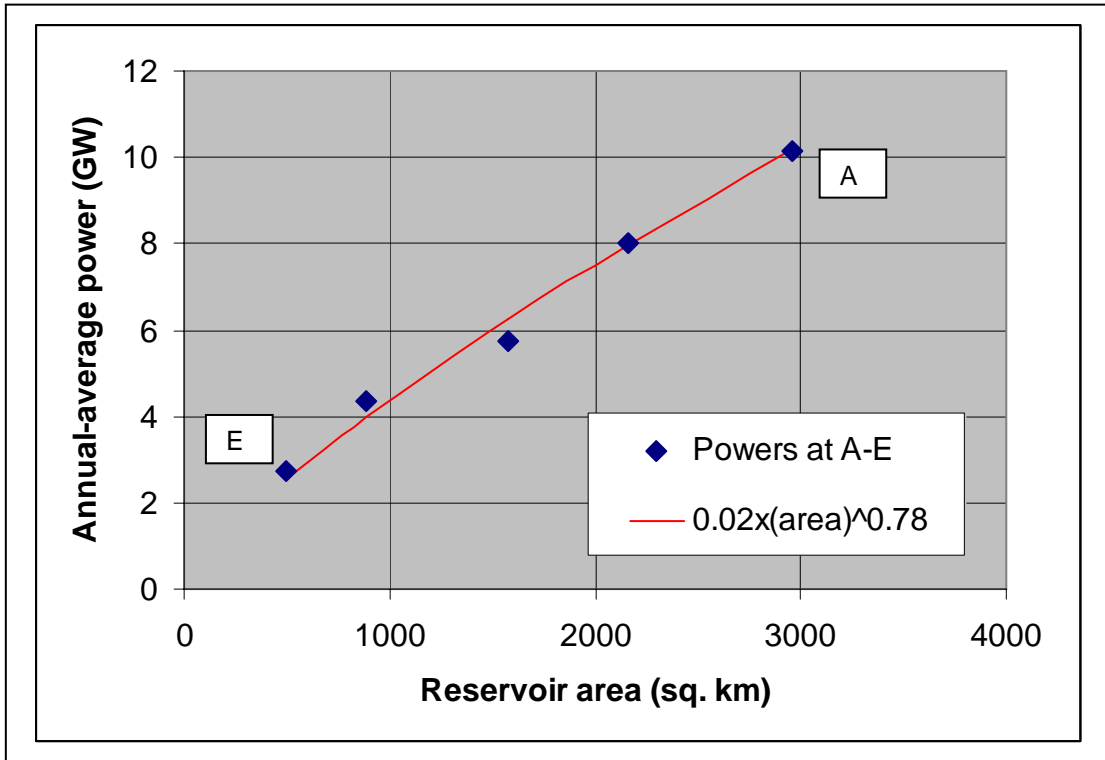


Figure 3.3. Maximum powers from Figure 3.2, plotted against reservoir area

In the style of Fig. 4.1 in Vol 1 of the IOAR, an empirical relationship may be fitted to the data – the power is evidently proportional to:

$$(\text{reservoir area})^{0.78}$$

This is in reasonable agreement with the relationship proposed in the IAOR (see Section 3.1 above), given that it is based on a different part of the estuary.

It is very different from the findings of the Bondi committee, which were that the power does not increase with reservoir area, but peaks at Minehead-Aberthaw, and then begins to fall if the barrage is moved further downstream. This conclusion appears to be in error, for the reasons discussed in the Appendix.

We may conclude that the IAOR is in error in abandoning its empirical relationship between power and reservoir area, in favour of the findings of the Bondi committee, without any significant investigation of this apparent anomaly.

4.4 Two-way generation

From Figure 3.2, the annual-average power available at Taylor’s site E, which is close to the Cardiff-Weston barrage, is 2.7 GW. Assuming an overall conversion efficiency of 75% (see next Section – this figure relies on very large turbines), this is $2.7 \times 24 \times 365 \times 0.75 = 18$ TWh/yr, which is slightly in excess of the figure of 17 TWh/yr quoted in the IOAR (Vol 1, Table ES1) for a barrage with ebb-only generation. This is consistent with the conventional view, cited in Section 3.1, that two-way generation gives more power, if turbine efficiency can be maintained.

The results in Figure 3.2 assume the simplest-possible “linear” turbine characteristic (i.e. flow directly proportional to pressure head across the barrage), which is convenient mathematically, see Appendix. It is well-known, however, that more power is available with a non-linear characteristic, which is readily achieved in practice. For example, it is clearly advantageous not to allow flow through the turbines at very small pressure heads, but to wait until the pressure builds up, and then let the same volume of water through at a higher head, so obtaining more power. Our experience from other tidal power studies is that a significant power increase can be expected – of the order of 25%. Extensive optimisation of this kind was carried out by the STPG on the Cardiff-Weston barrage, as described in Ref. [3], and is built into the figure of 17 TWh/yr quoted for that barrage in the IOAR. For the purposes of an initial assessment of options, it is arguable that a similar benefit should be allowed for two-way generation.

By contrast, however, the IOAR gives (Vol 1 p.29) a figure of only 13 TWh/yr for the tidal reef scheme. This is much less than the figure from Figure 3.2 for this site, which is approximately 4.7 GW (it is approximately 25% of the way between Taylor’s sections D and C). Assuming an overall conversion efficiency of 75% (see next Section), this is $4.7 \times 24 \times 365 \times 0.75 = 31$ TWh/yr. The IOAR figure of 13 TWh/yr is also much less than the figure given in the IOAR for an ebb-only barrage at this site, which is 25 TWh/yr (see Section 3.1). The IOAR appears (Vol 1 p.28) to be making some very sub-optimal assumptions about the operation of the Tidal Reef, which gives the misleading impression that two-way generation necessarily gives less power than ebb-only generation.

4.5 Conclusions on power calculations

There appear to be two serious shortcomings in the power calculations in the IOAR:

- The maximum available power from barrages below Cardiff-Weston has apparently been underestimated, because in those cases the IOAR uses a different calculation method from that used at all the other sites. This other method appears to be erroneous.
- The only two-way generation scheme considered (the Tidal Reef) is found to produce only half the power of a barrage with ebb-only generation at the same site (13 TWh/yr rather than 25 TWh/yr). This appears to be the result of some very sub-optimal assumptions about the operation of the Tidal Reef, and gives the impression that two-way generation gives less power than ebb-only generation. Our calculations support the contrary (and conventional) view, which is that two-way generation will produce more power rather than less, provided suitable turbines are fitted.

5. Recent Developments in Turbine Technology

5.1 Turbines

Tidal barrages and other hydropower generation schemes rely on turbines to convert the energy available from the water into electrical power. Hydro-generation schemes convert the pressure (head) of the water and/or flowrate (m³/sec) of the water. There are many different types of turbine which have been developed over the years including Pelton wheels, Francis turbines, axial-flow turbine, cross-flow turbines, bulb turbines, kinetic flow turbine and others. These have been developed with particular characteristics to maximise the energy conversion from particular water sources. Some reservoir based systems have high pressure head and relatively low flows (of the order of <5m³/sec), whilst run of river or tidal schemes have relatively low pressure head but markedly larger water flow rates in the order of thousands of m³/sec. Different turbine types will be selected for these different duties.

Given the economics of hydro-generation schemes, which tend to have high initial capital costs much of which is in the mechanical and electrical equipment and relatively low on-going costs, the selection of the right turbine, with the optimal efficiency, is crucial to the viability of the scheme. Modern turbines have adaptable guide vanes and other systems to allow the turbine to cope, within a sensible range, with variations in flows and heads and still to produce energy at a high efficiency. Development work by manufacturers is on-going all the time to bring more potential hydro schemes into a viable state by extending the range of each type of turbine to meet different operating conditions. Manufacturers will be prepared to spend development money if they can see a new market area available to them, but their preference will logically be to adapt existing equipment to extend the available market rather than to invest in completely new technology unless they can see a significant new worldwide market to aim for. We have had a conversation with a large technology manufacturer which is interested in developing a scaled up version of the MJ2 turbine described below and believes it will be possible to have a working prototype within 2 years. The manufacturer believes there is a significant potential market and has estimated that the cost of such a turbine, for a large order such as for the Severn tidal generation options, would be of the order of £2m/MW.

The mechanical bits of the turbine apart, efficiency is also a function of the management of the flow through and around the turbine blades. Design of the orifice, often a concrete structure in which the turbine is located and through which the water flows onto the blades, through the blades and on downstream, is also a sophisticated process and good design can add significantly (+2-3%) to efficiency of energy

conversion. Conventional turbines are more efficient in energy conversion when the water flows one way. Two way generation is possible but often carries a penalty in one flow direction at least.

5.2 Importance of the MJ2 turbine

The cost of a hydro-electric scheme, per kW produced, generally increases as the head is reduced. Historically, therefore, the high-head hydro-electric resources have been exploited first. Turbine manufacturers have accordingly addressed the high-head market first too. Only in the last few years has the first turbine been developed for a head of 2m or less, by MJ2 Technologies in France. The first one was installed at Millau in the south of France two years ago, see Figure 4.1 below.



Figure 4.1. The MJ2 turbine at Millau

This development is important because:

- Two-way generation, with its potentially-superior power output, and reduced environmental damage, typically involves a head of 2m on the Severn. See Figure 3.2, where the optimum head across the barrage is given as about 0.6 of the tidal range, so between $\pm 1.5\text{m}$ and $\pm 3\text{m}$, in typical Severn tides of $\pm 2.5\text{m}$ (neaps) and $\pm 5\text{m}$ (springs). This exactly suits the optimum operating range of the MJ2 turbine, which is 1.4m – 3.2m, see references cited in Ref [2].
- Low-head turbines are inherently less damaging to fish, which is a major issue on the Severn, as the blades rotate relatively slowly. The MJ2 turbine has been optimised for minimum fish damage.
- The Severn barrage is too large a project for the existing turbine supply chain, in our view (see next section). New turbine options therefore need to be considered anyway.

The fish-friendliness can be better appreciated from Figure 4.2 below, which shows the inner structure of the turbine. The outer bars visible in Figure 4.1 are merely a fixed screen to prevent large debris (e.g. logs) from entering the turbine. Behind it is a row of fixed blades, shown in white in Figure 4.2, and then finally, some way further back, the rotor, which is coloured red which is stated by the manufacturer to be visible to fish.



Figure 4.2. Internal structure of MJ2 turbine

The blade area is made as large as possible, so that the blade speed can be as low as possible. The turbine typically rotates at 40 rpm, see references cited in Ref [2], at which the blade speed is about 9 m/s at the tip, and 4 m/s at the root. This is slower than the equivalent bulb turbine and should be beneficial in terms of fish survival.

5.3 Feasibility of scaling up the MJ2 turbine

In our earlier Report, Ref [2], we proposed scaling up the MJ2 turbine at Millau by a factor of 5 in diameter, to suit a two-way barrage on the Severn. This option is considered in the IAOR (Vol 1 p. 28) but is dismissed because:

- The Millau turbine is not bi-directional; and

- It would require a “fundamental change in the turbine concept”.

The MJ2 turbine is easily made bi-directional, by rocking its frame (already on bearings) to allow retraction for maintenance, see Figures 4.1 and 4.2) like a see-saw, see Figure 4.3 below (based on the caisson design proposed in Ref [2]).

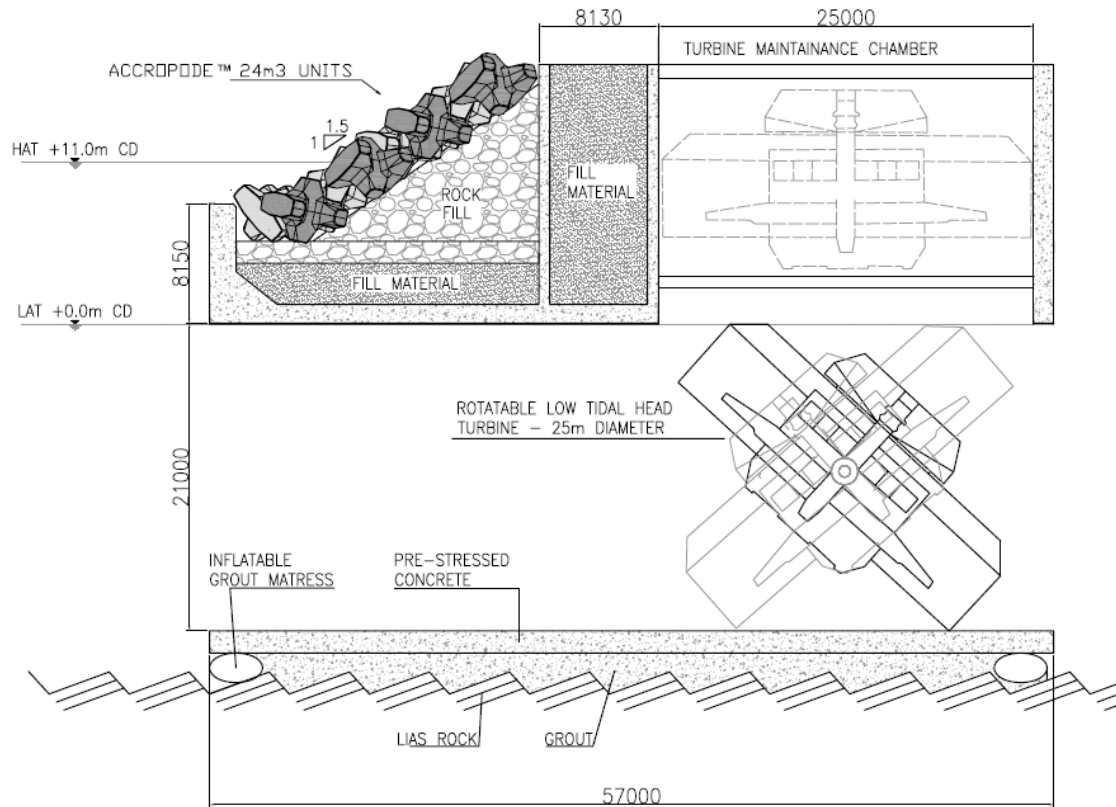


Figure 4.3. Cross-section of caisson with scaled-up MJ2 turbine, mounted for two-way operation

In our earlier Report (Ref. [2]), the overall efficiency is given as 75% (i.e. 90% each from turbine efficiency, kinetic energy losses and power take-off efficiency, giving $(90\%)^3 = 75\%$ overall). From the estimated annual-average absorbed power of 4.7 GW at the Minehead-Aberthaw site, given in the previous Section, this gives an annual-average power of $4.7 \times 0.75 = 3.5$ GW. The peak power during an average power cycle will therefore be $2 \times 3.5 = 7$ GW. A Minehead-Aberthaw barrier would be approximately 20 km long, giving space for 700 turbines, so the peak power of a single turbine in an average power cycle is $7,000\text{MW}/700 = 10$ MW.

This is equivalent to full power from the Millau turbine, operating at the same head and flow velocity, because the power is then proportional to the cross-sectional area, and so reduces to $10\text{MW}/5^2 = 400$ kW, which is its rated power. In the spring tides, the peak power is about 60% higher (a factor $(10/8)^2 = 1.56$, see Appendix 1), or 16 MW. This implies a 60% higher water velocity through the turbine that at Millau.

Structurally, there should be no problem in scaling the Millau turbine up, since the same head means the same pressures, and thus the same stresses in the blade material. The challenge is the drive-train to the generator, because of the very high torque implied by the low rotor speeds. At 10 MW, the rotational speed is $40/5 = 8$ rpm

= 0.8 rad/s. The torque is thus $10/0.8 = 12.5$ MN-m. At 16 MW, it will be same – only the rotational speed will increase.

The problem of high-torque transmissions has been studied intensively in recent years, because they are needed in wind turbines. The standard solution is a gearbox, which is feasible, but expensive and prone to damage if overloaded. A minority of large wind turbines have direct-drive electric generators (as on the Millau turbine), but these are very large and arguably at their limits in large wind turbines, at only a few MN-m. The best option appears to be an hydraulic transmission, which has recently been developed for wind turbines, see Ref [3], and which would readily scale up to 12.5 MN-m. Figure 4.3 below shows a 1 MN-m hydraulic wind turbine transmission developed by Artemis Intelligent Power Ltd., under test at their factory in Edinburgh.



Figure 4.3. 1 MN-m hydraulic wind turbine transmission under test

The remainder of a scaled-up Millau turbine is conventional marine engineering, as in a controllable-pitch ship's propeller, or a ship's stabiliser fin. The conventional marine supply chain is large enough to supply the requirements of a Severn barrage, and thus gives a guide to the likely price for a very large turbine order.

We therefore disagree with the conclusion in the IOAR (Vol 1 p.28) that it is not feasible to scale up the Millau turbine, at any rate in the timescale of the Severn Barrage Project (IAOR Vol 1 p. viii).

5.4 Environmental impact aspects of new turbine options

Another criticism of the IOAR is that it gives little or no credit in the relevant sections (Vol 1 p.vii, Table ES1, Table 5.1, p.58) for the potential reduced environmental impact of two-way generation, for example when it considers the Tidal Reef.

The loss of inter-tidal habitat is stated as “unquantified due to insufficient data” in Table 5.1 of Vol 1 the IOAR, but the figure of 74% of the previous tidal range was available from Ref [2] (and indeed ought to have been calculated independently in the IOAR, for energy reasons, see Section 3.1). A cursory examination of the relevant Admiralty

Charts shows that for such a reduced tidal range impact the loss of inter-tidal habitat is therefore of the order of one tenth of that with the conventional “outer barrage” (B1) at the same site. Such an order-of-magnitude guide would have been helpful, in our view, given the importance of environmental damage to DECC’s objectives (Section 2.1).

There is also no mention on p.58 of Vol 1 of the IOAR that the low-head two-way turbines of the Tidal Reef might be less damaging to fish than conventional turbines. A scaled-up Millau turbine would never exceed the head, and rarely exceed the flow velocity, through the original Millau turbine, see Section 4.2. The very low fish mortality of the original Millau turbine will thus be preserved – and moreover will now apply to fishes 5 times longer, which will include Salmon. By contrast the turbines in the Cardiff-Weston barrage (see Ref [2] p. 32) are 9m diameter (rather than 4.5m at Millau) and rotate at 50 rpm (rather than 40 rpm at Millau), and the blades are thus travelling $(9/4.5) \times (50/40) = 2.5$ times as fast, i.e. 25 m/s at the blade tip and 10 m/s at the root. 25 m/s is 50 mph, which is clearly a danger to fish. Again, some approximate guidance along these lines would have been helpful, in our view, given the equal importance of environmental acceptability in DECC’s objectives (Section 2.1).

6. Construction Programming & and Cost Estimation

6.1 General Comments

For smaller schemes such as the lagoons and inner barrages, the size of the project is analogous to an average sized thermal or nuclear power station. While these are major projects, local materials and labour can be used with the provision of offloading facilities to bring in bulk materials by sea.

This is not the case for a Cardiff-Weston Barrage (B3). This is a “mega” project that, using the same analogy, would be like building 5 power stations all at once and all in the same place – as indeed would building several lagoons and an inner barrage simultaneously, to produce a “strategically significant” amount of renewable energy. To further put the Cardiff-Weston scheme into context, it would have a similar cost and construction programme to the Three Gorges Dam in China (£25billion) and is twice the size of a Channel Tunnel (£10billion).

The unit rate approach used to estimate the costs for the different options does not recognise the fundamental difference between a single scheme of about 1 GW size compared with an >8 GW barrage. The very much larger schemes will overwhelm local markets and suppliers and require special provisions to import labour and materials from national and international locations. This is a significant limitation of the cost estimation methodology, which could increase costs by a factor of two, to judge by other large projects (e.g. the Channel Tunnel, or the recent Finnish nuclear plants, which have suffered a cost over-run of this size).

Only if the overall size of the scheme is kept constant (i.e. the smaller schemes are built simultaneously, to give a similar sized project to the larger schemes like the Cardiff-Weston barrage) will the costs be likely to be correct in relative terms.

Construction risk has not been specifically priced. This may under-estimate the cost of the larger barrages that require the use of marine construction plant in exposed conditions. Government guidance on the scheme appraisal of coast and flood defences recommends risk pricing as best practice. Best practice for the comparison of Severn tidal power options would have been to price risk. It is recommended that the next stage of work should include detailed risk pricing.

6.2 Barrages B1, B2, B3

The IOAR has little detail concerning the construction methodology and refers to work that is now 20 years out of date (Vol IIIA and Vol III B of 1989 STPG Report). This may still be state of the art but some commentary in respect of new developments and risk profile would have been helpful.

A high level review in the IOAR identifies key issues that require further study. The primary issue is the construction methodology and provision of dry docks to construct the caissons.

The B1, B2, and B3 barrages would require coastal sites with deep water access and good road and rail links. The STPG report states that 4 sites in the vicinity of the barrage and two in Scotland were used in the cost estimate.

Each of 4 the sites would require 3 basins with a total area of about 140 ha.

The only existing facility in the Bristol Channel that would be suitable is Port Talbot because it has access for large vessels and is under utilised. In fact the STPG report has used the Port Talbot layout to demonstrate the construction of dry dock basins, as shown in the figure below:

Port Talbot has good road and rail links and could be used to import basic raw materials such as aggregates, armour rock, and cement. This makes it ideal for the barrage construction. The figure below shows that it could provide three dry docks. This still leaves a requirement for further dry dock capacity both within the Severn and further afield. Furthermore, even Port Talbot will only just have the draft to construct the largest turbine caissons. This is demonstrated as follows:

The required draft for floating a caisson = 20.5 (trimmed draft) + 2.1 under keel clearance = 22.6m draft requirement. Port Talbot dock has a stated draft of 20.84m at MHWS at the Dock entrance. This means that caissons will only be able to float out on spring tides higher than the mean, or that some dredging will be required. These problems are not insurmountable, but do demonstrate a lack of any detailed planning behind the cost estimates.

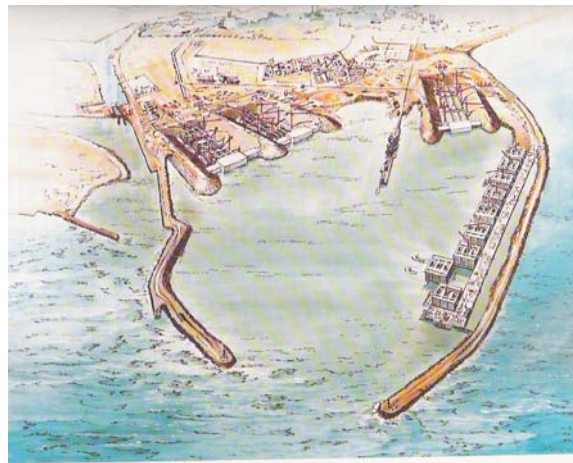


Figure 5.1: Caisson Construction Port Facility

Regardless of the use of Port Talbot, a second facility will be required on the Severn. The Ports of Barry, Cardiff, and Avonmouth are all restricted by the size of lock gates and various draft restrictions and could probably not accommodate the size of caissons required.

In comparison, the smaller caissons required for the B4 and B5 inner barrages and the lagoons options could be fabricated in just one facility such as Portbury Dock at Avonmouth or Port Talbot.

The outer barrage projects would actually required the construction of a whole new port the size of Port Talbot. This fact is recognized in the STPG work. However, the design and construction of a new port is something that can take a decade to achieve, and this does not seem to be reflected in the implementation programme.

The interim options analysis includes a cost of £96m for the construction of dry docks. It is assumed that this is the price for constructing dry docks within existing facilities. It is noted that the previous STPG work included a cost of £339m (1989 prices) for “caisson construction yards”. If there has been some new work to support this significant change, it is not explained in the options report.

6.3 Outer Barrage B1

This barrage has a similar length to the Cardiff-Weston barrage, but the IAOR gives it a significantly higher cost. It is understood that this is because it is located in deeper water and therefore has larger caissons – which have been scaled in volume from the B3 (Cardiff-Weston) caissons (see 5th Table of Appendix A.1, IOAR Vol 1) by a factor $40,872/24,684 = 1.66$.

This is a rather simple assumption, apparently an educated guess, and it could be expected that this option would have warranted rather more investigation of the best means of building a barrage on this line. It is noted that engineering details such as caisson cross sections are entirely absent from the report.

6.4 Tidal Lagoons

Four tidal lagoons shore attached lagoons are considered. Two of these lagoons: Peterstone Flats & English Grounds have higher construction costs due to higher cost for the caissons and lagoons walls. In the interim options reports it is not clear why this is the case. Again, there is very little detail concerning the engineering of these schemes – caissons are scaled from the B4 (Shoots barrage) caissons (see 5th Table of Appendix A, IOAR Vol 1).

6.5 Tidal Reef

The IOAR takes the structural cost of the Tidal Reef to be 45% of that of the B1 barrage on the same site (IOAR Vol 1 Appendix A.5). The B1 barrage volumes are scaled from the B3 barrage by a factor 1.66 (see Section 5.1 above), and thus the volume of concrete in the B1 caissons (see IOAR Vol 1 Appendix A.1 3rd Table) appears to have been taken as $7,513,000 \times 1.66 = 12,500,000 \text{ m}^3$. Thus the volume of concrete in the Tidal Reef caissons appears to have been taken as $45\% \times 12,500,000 = 5,625,000 \text{ m}^3$. This compares with the $3,000,000 \text{ m}^3$ given in our earlier Report (Ref. [3]).

This shows the level of approximation in the IAOR – the figure of 45% is no more than an educated guess, as indeed is our figure in Ref [3] of 25,000 tonnes per caisson (hence $3,000,000 \text{ m}^3$ of concrete overall), although the latter is perhaps based on more recent relevant experience (of concrete oil rigs) and is at least based on some calculations of loads and strengths.

The caisson cost is however small compared with the cost of the turbines, which the IAOR finds to be two thirds of the total (IOAR Vol 1 Appendix A.5). The figure for the turbine cost relies entirely on the figure of £2.75m per MW compared with £0.676m per

MW for a conventional barrage (IOAR Vol 1 Appendix A1.4 1st table), which is another educated guess, discussed in Section 4.

6.6 Questions & Answers

With reference to the specific questions raised in the Client's brief, our comments are:

Q: Has there been appropriate consideration of access roads, berthing facilities and other temporary works needed for construction of the works?

A: This information is not provided in the report. For the small options these issues are not extraordinary. For the B1, B2, and B3 barrages, or for several small schemes built simultaneously, they could well be significant. The 1989 STPG report does not provide specific locations for the dry docks to build the caissons. These issues have not been considered in any significant detail.

Q: Has there been appropriate consideration of the location and outline design of facilities for the construction of caissons?

A: With reference to the general comments above on the B3 barrages, it is evident that no new work on this has been completed and that there are no firm locations for a caisson construction facility. This is a critical element of the construction methodology that could have a significant impact on cost and programme.

Q: Has there been appropriate consideration of the sources of construction materials, particularly aggregates and rock armouring?

A: The basis of the cost estimates has been made using traditional pricing techniques. No account has been made of the sources of materials. There are significant quantities of stone needed for most of the options and local sources may not be sufficient for the need (see below).

With regard to aggregates, the landings of dredged aggregates for the UK South West region is about 1.5 million tonnes.

South Wales is uniquely dependent on marine-dredged sand which accounts for 93 per cent of the market for all construction sand and 97 per cent of building sand supply.

A B3 barrage would require about 8 million tonnes of aggregate over a period of seven years, or 1.1 million tonnes per year. This is 70% of the present total local capacity of 1.5 million tonnes. The local capacity would therefore have to be temporarily increased, for example by leasing additional dredging barges, or the additional requirement could be imported from elsewhere. In either case this would increase the cost of concrete used in the caissons.

Armour rock is not available from UK and adjacent European quarries in the quantities required. The likely feasible option is to use Scandinavian quarries such as Larvic in Norway. Rock would be loaded onto 15,000t barges and towed into the Severn Estuary for unloading. The price of £70/m³ used in the interim options study may be an underestimate, but it is not unreasonable considering the economies of scale.

Q: Has there been appropriate consideration of the construction sequence and duration, taking account of tidal and seasonal conditions?

A: No new work appears to have been done on this for the interim options study which relies on previous work done by the STPG. The comments below on the use of marine plant in the exposed conditions of the Severn estuary refer to B3 barrage options:

Comprehensive closure studies for the Cardiff-Weston barrage have been developed. Caisson placing using tugs has been established as the preferred method of construction and over the years has been examined in some detail. Despite this work there remain many questions about the feasibility of the construction methodology.

The single largest concern is the ability to place caissons in the exposed conditions of the Severn estuary. In particular the proposed methodology of winching the caissons into place is untested and requires the use of anchors or anchor points requiring drilling into the seabed. This will require the use of jack up platforms to provide a base for a piling rig to drill the anchor points. An alternative method without winches is proposed in Ref. [3].

The caissons discussed in the IAOR (but not the caissons in Ref [3]) require a rock bedding layer. This operation will require the use of a work barge and rock grab, and work barges with excavators to trim the bedding.

The point of listing the marine plant requirements is that the construction methodology is not just about caisson placing on a neap tide at slack water. Other activities will be happening every day in tidal streams of up to 2m/s while exposed to the predominant southwesterly waves. A lot of marine plant is restricted by wave conditions. In particular, jack-up rigs require that wave heights be less than 0.5m when they are lowered for towing to a new location, and barges have similar restrictions. During the winter months the wave climate is not suitable for the use of marine plant and this will impose restrictions on the rate of construction progress. Based on the available information it is difficult to see that how this has been adequately reflected in the estimated construction programme.

Excavation of some 18million cubic metres of sand and rock is required. Some of the rock will require drilling and blasting again using marine plant such as jack up pontoons. Dredging would be undertaken using a cutter suction dredger. Large dredging plant has an impressive record of making short work of large volumes of material. However, this plant usually work 24 hours a day, seven days a week. Cutter suction dredgers have a spud leg and anchors that require a firm hold on the seabed. Can such a hold be maintained on a rocky seabed with a 2m/s tidal current? If not, there may be significant down time associated with the dredging works.

The cost of the marine works in the options report is £1037m for a B3 barrage. Given the uncertainty in the rate of production an optimism bias or risk contingency figure of 100% of the estimated marine works cost would not be unreasonable at the current level of knowledge. The fair basis approach cost estimation used in the interim options analysis does not recognise the greater risk of a large scheme that is more exposed compared with the smaller lagoon schemes that would use less marine plant and more land based construction techniques.

Q: Has there been appropriate consideration of existing capacity to manufacture turbines, generators and gates, and the need to strengthen such capacity?

A: No new work appears to have been done on this.

Yaver Abidi in his address to the Royal Academy of Engineers (Ref. [5]) addressed this point very well with respect to Barrage B3 option:

There are three or four major manufacturers of bulb turbines in the world – it is a cottage industry. This is manufacturer No. 1 – and I am not advertising anyone so I have not named them –and they claim to have 50% of market share, but I had never heard of them, and had been in the hydropower field for some time. I discovered that they are a massive conglomerate – they had bought all the cottage industries and put them together basically, so collectively they have done this. But look at the installed capacity since 1936 that they have delivered – 4,500GW. Half of this barrage has been done by them since 1936. They have done 170 generators, and we have 210 in this barrage – and they have done this over the last 70 years, with 300 turbines. Similarly, manufacturer No. 2 is a very well-respected and known continental manufacturer – whoopee, 118 machines installed since 1955. We have 210 to do in five years. So what will you do? Will you go out to competitive tender? There are only three of these guys and they do it in their garages. There are some really interesting challenges here.

The next phase of work needs to consider the options for procurement of turbines in some detail. As already mention in Section 5.1, the IOAR can only be considered to give relative costs, assuming that the same overall size of the project (i.e. several smaller schemes assumed to be built simultaneously, to give a similar project size to the larger schemes).

Q: Has the programme for construction of the works been prepared in sufficient detail, taking account of the issues above, to allow construction cost estimates to be built up appropriately?

A: The interim report has not provided detailed construction programmes. The cost estimates have been undertaken on a unit rate approach and have not been led by programming constraints. There is little consideration of risks to programme. For a B3 barrage option the following are considered to be the worst programme risks:

- Provision of compensatory habitat if this is required prior to construction;
- Design, construction and consenting of new port facilities could add 5 to 10 years to the programme.
- The exposed conditions in the Severn Estuary, particularly in winter could significantly extend the programme.

The next stage of the project needs to consider construction logistics in much more detail and in particular how port facilities could be provided in the Severn.

Q: Has the method of cost estimation been appropriate to take account of the unique nature and exceptional scale of the works and manufactured components?

A: No, the same cost estimating methodology is used for a small tidal lagoon and a large barrage. As already explained in Section 5.1, this means that the relative costs will only be correct if several small schemes are built simultaneously, to give an overall project of similar size. The absolute costs will not be correct, however. The next phase

of the work needs to use a methodology driven by programme and material supply constraints.

Q: Have appropriate cross-checks been made with the actual costs of comparable projects?

A: No. Suitable examples might have been the Channel Tunnel in terms of raw materials and labour prices, and the Three Gorges project in China for the hydromechanical equipment. The next stage of work should include a study of the economic impacts of large projects on labour and materials prices.

Q: Has appropriate allowance been made for costs associated with the risk assessment?

A: No: risks have not been priced. The options appraisal for the short listed options should be included a detailed assessment and pricing of risk.

Q: Have appropriate allowances been made for contingencies and optimism bias?

A: No. No optimism bias has been applied at this stage. Some construction contingency has been included.

6.7 Conclusions on Cost Estimates

Our most important conclusion on the cost estimates in the IOAR is that they take no account of the scale of the project, because they are all based on per-unit costs (cost per tonne of concrete, cost per MW of generating capacity, etc.). Since large projects tend to distort markets and inflate costs, this means that the cost estimates in the IOAR can only be considered as giving correct relative costs (which was the aim of the IOAR), if the overall project size is similar (i.e. several of the smaller schemes are built simultaneously, to give a project of similar size to one of the larger schemes). The absolute costs will be significantly under-estimated – by a factor of two, perhaps, taking other large projects as a guide.

It is very important that the next phase of the work quantifies this factor, because on conclusion the Severn Tidal Power Feasibility Study is intended to produce absolute costs, not just relative ones.

Other conclusions are:

- The larger schemes also appear to be significantly riskier than the smaller ones, because the caissons are bigger and more exposed, and thus more difficult to install. We estimate that this risk factor could double the caisson installation costs given in the IOAR, for the larger schemes, thereby affecting the unit costs.
- The caissons for the “outer barrage” between Minehead and Aberthaw (about a third of its total cost) are assumed in the IOAR to require 65% more concrete than those for the Cardiff-Weston barrage. This is only an educated guess and any reduction of this 65% figure could markedly change the unit costs.
- The turbines for the Tidal Reef between Minehead and Aberthaw (about two thirds of its total cost) are assumed in the IOAR to cost four times as much per MW as conventional turbines. This again is only an educated guess, as is the

caisson cost (assumed to be 45% of the cost of the “outer barrage”, which is again only an educated guess). It is discussed in Section 4 but if this multiple is only 2 this would markedly change the unit costs.

7. Economic Analysis

7.1 Assessment methodology

The assessment methodology comprised the calculation of an average annual energy cost derived from discounting capital and annual costs at a variety of discount rates and then calculating a cost of energy. This is standard practice for assessing and comparing energy generation projects. Various discount rates were used to reflect either public or private ownership.

7.2 Scope of analysis

A design life of 120 years has been used and minor and major refurbishment of structures has been included in the future costs. Decommissioning costs have not been included. However, when discounted from 120 years in the future these costs may become very small. The next stage of the project should consider whether some sort of a levy fund needs to be set up to pay for decommissioning.

The analysis includes the cost of compensatory habitat but does not explicitly include other environmental mitigation and compensation. In particular, the impact on fisheries and the cost of mitigation or reduced turbine performance is not priced. This should have been considered in much more detail as it is as least as important as the compensatory habitat issues in terms of satisfying the European habitats regulations. It also introduces further bias as the lagoon options may not be as damaging to migratory fish as the barrage options.

7.3 Sensitivity testing

Sensitivity testing was not undertaken. Best practice for project appraisal is to use sensitivity testing to test the variety of the scheme economics with respect to changes in key assumptions, risk pricing and material prices. Given that the difference in economics between the B1, B2, and B3 barrages are quite small, sensitivity testing could have been effective in helping ministers in making choices between these options.

The next phase of this study needs to consider sensitivity testing of the options carried forward against key assumptions and risks.

8. References

- [1] Baker, A.C. 1991 *Tidal Power* Peter Peregrinus Ltd. on behalf of the Institution of Electrical Engineers
- [2] Tidal Power in the UK: Report 3 – Review of Severn Barrage Proposals. Final Report. Black & Veatch, July 2007. Available for free download from <http://www.sd-commission.org.uk/publications.php?id=610>
- [3] Severn Barrage: Feasibility of the “Tidal Reef” Scheme. Atkins Report 5079276/RPT/01, available on the RSPB website <http://www.rspb.org.uk>.
- [4] Hydraulic Transmission for Large Renewable Energy Devices Including Offshore Wind. Artemis Intelligent Power Report prepared for the Carbon Trust, CT Ref. 062-181.
- [5] “The Severn Barrage”, Royal Academy of Engineering conference 22 May 2008, Transcript of Proceedings

