Tidal Energy – Lessons Learnt from the United Kingdom and Opportunities for the Netherlands

Deltares

12 November 2009
Final Report
9V1913.A0
Deltares

A COMPANY OF

ROYAL HASKONING

HASKONING NEDERLAND B.V.
COASTAL & RIVERS

George Hintzenweg 85
Postbus 8520
Rotterdam 3009 AM
The Netherlands
+31 (0)10 443 36 66 Telefoon
+31 (0)10 443 36 88 Fax
info@rotterdam.royalhaskoning.com E-mail
www.royalhaskoning.com Internet
Arnhem 09122561 KvK

Document title	Tidal Energy - Lessons Learnt from the United Kingdom and Opportunities for the Netherlands
Document short title	Tidal Energy
Status	Final Report
Date	12 November 2009
Project name	Tidal Energy
Project number	9V1913.A0
Client	Deltares
Reference	9V1913.A0/R0003/CVH/SSOM/Rott

Drafted by	Nick Cooper, Martin Bailey, Leslie Mooyaart, Joost Lansen, Bas Jonkman, Cathelijne van Haselen	
Checked by	Leo Korving, Henk Altink, Bas Jonkman	
Date/initials check	12-11-2009	B. Jonkman
Approved by	Cathelijne van Haselen	
Date/initials approval	12-11-2009	

CONTENTS

GLOSSARY

Habitats Directive	Build around two pillars: the Natura 2000 network of protected sites and the strict system of species protection. All in all the directive protects over 1,000 animals and plant species and over 200 so called "habitat types" (e.g. special types of forests, meadows, wetlands, etc.), which are of European importance.
Birds Directive	Providing long-term protection and conservation of all bird species naturally living in the wild within the European territory of the Member States.
NNR	National Nature Reserves (NNR) is a United Kingdom government conservation designation for a nature reserve of national significance for biological or earth science interest.
pSAC	Special Area of Conservation (SACs) are strictly protected sites designated under the EC Habitats Directive.
Ramsar	The Ramsar Convention on Wetlands of International Importance is an intergovernmental treaty that provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources.
REP	Renewable Energy Package. European Commission's legislative proposal to achieve agreed EU objectives in the fight against climate change. Committed to reducing overall EU emissions to at least 20% below 1990 levels by 2020. It has also set itself the target of increasing the share of renewables in energy use to 20% by 2020.
RES	Renewable Energy Strategy (RES). UK's overall strategy for tackling climate change and to meet the EU target to source 20% of the EU's energy from renewable sources by 2020.
SPA	Special Protection Area's are strictly protected sites classified in accordance with Art. 4 of the EC Birds Directive. Classified for rare and vulnerable birds and for regularly occurring migratory species.
SSSIs	Sites of Special Scientific Interest (SSSI) is a conservation designation denoting a protected area in the United Kingdom. SSSIs are the basic building block of site-based nature conservation legislation and most other legal nature/geological conservation designations in Great Britain are based upon them, including National Nature Reserves, Ramsar Sites, Special Protection Areas, and Special Areas of Conservation.

1 INTRODUCTION TO THE PROJECT

1.1 Background

There has been major interest in the development of several sources of sustainable / renewable energy over the past years. One of the main sources of this type of energy is water power. This report focuses on tidal (range) energy, one of the potential water power sources.

In the United Kingdom there is a long history of tidal energy studies. A number of tidal energy projects have been under consideration in the United Kingdom since the 1980's. None of these tidal projects has been realized yet. The most well-known locations are the Mersey and Severn estuaries. The estimated peak power potential for the Severn project ranges between 1 GW and 15 GW depending on the location of the proposed barrage location. A new feasibility study on the generation of electricity from the Severn Estuary has been initiated in 2008.

Although the tidal ranges in the Netherlands are relatively limited, opportunities may arise as several plans are being developed to re-open estuaries that have been closed in the past.

This report starts with an overview of the majority of tidal energy projects in the UK, followed by the principal issues and lessons learnt. Then, the focus changes to the Netherlands. An investigation of the opportunities for tidal energy in the Netherlands will be presented and it will be evaluated how these findings for the UK can be transferred to the Netherlands in order to support the development of tidal energy in this country.

1.2 Aim of the project

The aim of the project is to present:

- A summary of the majority of tidal energy projects in the UK based on literature;
- Summary of principal issues and lessons learnt from the United Kingdom;
- Investigation of the opportunities for tidal energy in the Netherlands;
- Evaluation how these findings for the UK can be transferred to the Netherlands in order to support the development of tidal energy in this country.

1.3 Set up of the report

The set up of the main report is as follows:

Chapter 1: Introduction to the project	Chapter 5: Investigation of opportunities for tidal energy in the Netherlands
Chapter 2: Introduction to tidal (range) energy	Chapter 6: Lessons learnt for realization of tidal energy in the Netherlands
Chapter 3: Case studies in the United Kingdom	Chapter 7: References
Chapter 4: UK: Principal issues and lessons learnt	

In the Annex Report the following information can be found:

Annex A: Details of selected UK case studies	Annex D: Results from the interviews
Annex B: Case study summary – potential environmental issues and effects	Annex E: Results from the workshop
Annex C: Information from the Netherlands	Annex F: Determination of economic energy and power

2 INTRODUCTION TO TIDAL (RANGE) ENERGY

2.1 Introduction

Tidal energy is derived from the movement of waters in the oceans. These movements are governed by the gravitational effects of the sun, moon and earth and typically result in the rise (flood) and fall (ebb) of the tide twice a day (known as a ‘semi-diurnal’ tide). The difference between the high water level at the peak of the rising tide and the low water level at the peak of the falling tide is known as the ‘tidal range’.

The lunar cycle also causes a variation in the height of the high and low tides at any given location, resulting in ‘spring tides’ (with the highest tidal range) and ‘neap tides’ (with a smaller tidal range). During the rise and fall of the tide, currents (sometimes known as ‘tidal streams’) are generated. These are effectively the flow paths taken by individual particles in the water column, as measured by their velocity (i.e. speed and direction) at a given point in time.

Since the above effects are astronomically-influenced and have been studied for centuries, they are predictable to high degrees of accuracy, in terms of the level of the tide and the timing of high and low water, as well as the direction and magnitude of the tidal streams. This makes harnessing the power from the tidal energy a potentially favorable approach. Whilst meteorological effects, such as storm surges and winds, can influence the absolute high and low tide water levels or tidal currents experienced on any given day, it is the underlying astronomical tidal effects that are the most dominant component of a given tidal level or stream.

As tides propagate from the deeper oceans into narrower, shallower areas such as estuaries or bays, they can become accentuated. This results in the largest tidal ranges in the world being within areas such as the Bay of Fundy (17m) and Ungava Bay (17m), both in Canada, and the Severn Estuary (15m) in the UK.

Despite considerable concept development and investigations into both tidal barrages and tidal lagoons, no scheme has yet been constructed anywhere in the UK using either type of technology. The few ‘on the ground’ examples that do exist are from elsewhere in the world, including La Rance (France) and Annapolis Royal (Bay of Fundy in Canada). A few much smaller schemes also exist in Russia (Kislaya Guba) and China (Jiangxia), although information about these is scarce.

Table 2.1: Characteristics of existing tidal energy schemes.

Country	Location	Mean tidal range [m]	Installed Power [MW]
France	La Rance	8,5	240
Russia	Kislaya Guba	2,3	0,4
Canada	Annapolis	6,4	18
China	Jiangxia	5,1	3,9

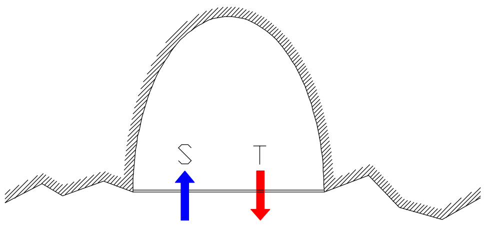
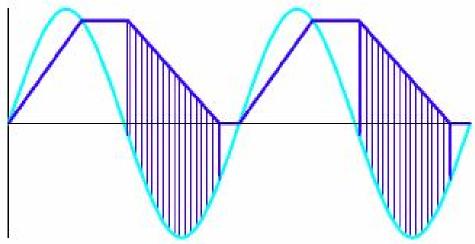
2.2 Tidal range energy

This report focuses on tidal range technology, including barrages and lagoons, which operate by impounding a large volume of water on the high tide and then releasing it through low-head turbines once a height difference is created on either side of the impoundment (i.e. during the ebbing tide).
Other related techniques, such as the generation of tidal stream energy (tidal stream generators draw energy from currents in much the same way as wind turbines) in coastal areas and water power generation in rivers are not considered in this report.

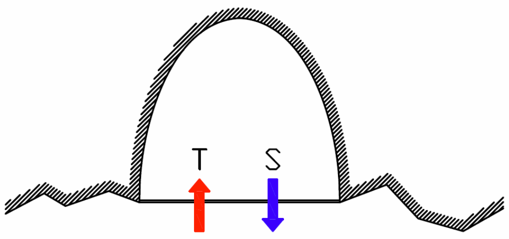
2.2.1 Tidal barrages

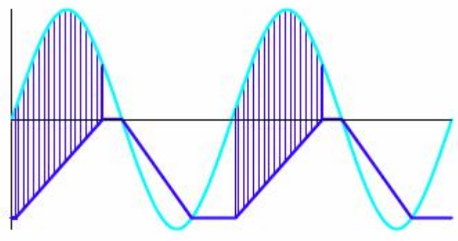
Tidal barrages are solid structures placed at strategic points within estuaries with a very high tidal range, thus creating an impoundment on the upstream side in conjunction with the banks of the estuary. As the tide rises, the estuary basin fills with water. Around the time of high tide, sluices or gates within the barrage are closed, impounding water upstream of the structure and allowing natural drainage downstream of the barrier during the ebbing phase of the tide. When a sufficient difference in water level (or 'head') has been created either side of the barrage, the sluices or gates are re-opened to release the impounded water through turbines contained within the barrage to generate electricity as the water flows through them. Whilst most schemes and proposals harness the tidal range energy during the ebbing tide only, it is also possible to do so on the flooding tide by keeping the sluices or gates closed as the tide rises and releasing the head of water into the empty basin, although this could affect the extent of basin infilling by limiting the flood tide.

Table 2.2: Single basin : ebb and flood generation and with double effect.

Single basin: ebb generation	
	
With this method energy is gained from the tide using sluices to fill the basin during flood and using turbines when ebb to produce energy. (Head ~66% of tidal range, 50% of time energy production)	

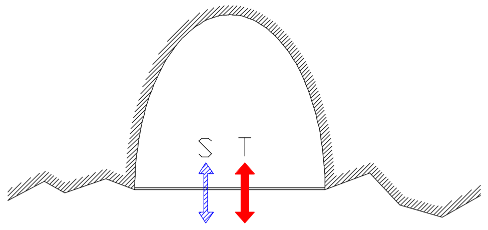
Single basin: flood generation

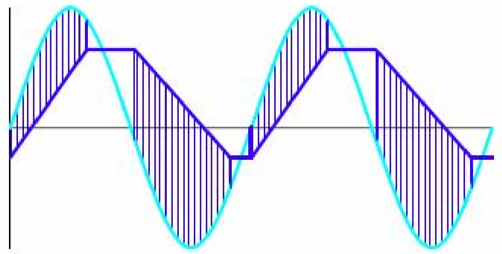




Flood generation works opposite of ebb generation. Sluices are used to empty the basin at ebb and turbines to fill at flood. As the water surface decreases with the water level, the volume processed is smaller and thus the energy gain is smaller. (Head ~66% of tidal range, 50 % of time energy production)

Single basin: Double effect





Turbines are used to gain energy during flood and ebb. As a result, the turbines are more expensive as they have to be able to turbine in both directions. When an attempt is made to gain as much energy during ebb as during flood, the average level of the basin has to be equal to the mean sea level. The advantage of this option is that sluices are not needed. It is also possible to gain more energy during ebb than during flood. In this case sluices are needed. In La Rance this kind of tidal power plant was built. The water levels in the right figure are an example of an double effect power plant with sluices.

The world's first, and to this date only large-scale, 240 MW tidal barrage was constructed between 1963 and 1966 in La Rance, Bretagne, France (Figure 2.1). The Bulb-turbine was developed for this tidal power plant. These turbines have the ability to gain energy in both flow directions, pump in both flow directions and sluice in both flow directions. The turbines have a higher efficiency than other turbines. From that moment on the Bulb-turbine was build in many low head run-off river plants and used for almost all plans for tidal (range) power plants.

Figure 2.1: La Rance tidal barrage, France.

In Canada, Annapolis a pilot tidal power plant was built of 20 MW in 1984. Straflo-turbines were placed instead of Bulb-turbines. As the concrete structure is much smaller than with Bulb-turbines the investment cost were relatively low. The disadvantage is the lower efficiency and therefore lower energy output. Also, the turbine did not have the ability to gain energy in both directions and to pump in any direction as the Bulb-turbines. Besides that there were problems due to the fact that it was placed in a marine environment. Although these problems were solvable, this type of turbine was never chosen in designs for tidal power plants anymore.

2.2.2 Tidal lagoons

Tidal lagoons similarly comprise solid structures used to impound tidal water, but the main difference between lagoons and barrages is that they do not span the entire width of an estuary or bay, but rather just impound a section of it. Lagoons can be either shore-attached impoundments or entirely detached from the estuary or coastal shore, and are often proposed in relatively shallow water. The electricity generation technology is similar to that previously described for barrages, including preferences for harness the tidal range energy during the ebbing tide only, but also having the potential – perhaps more so than with barrages – to do so on the flooding tide. See Figure 2.2 for further details.

The energy generation technology used in both tidal barrage and tidal lagoon systems is similar to that used in hydro-power dams and therefore is relatively mature. Despite this, the worldwide application of both tidal barrages and tidal lagoons is scarce and therefore the concepts remain unproven, despite the core technology itself being well proven.

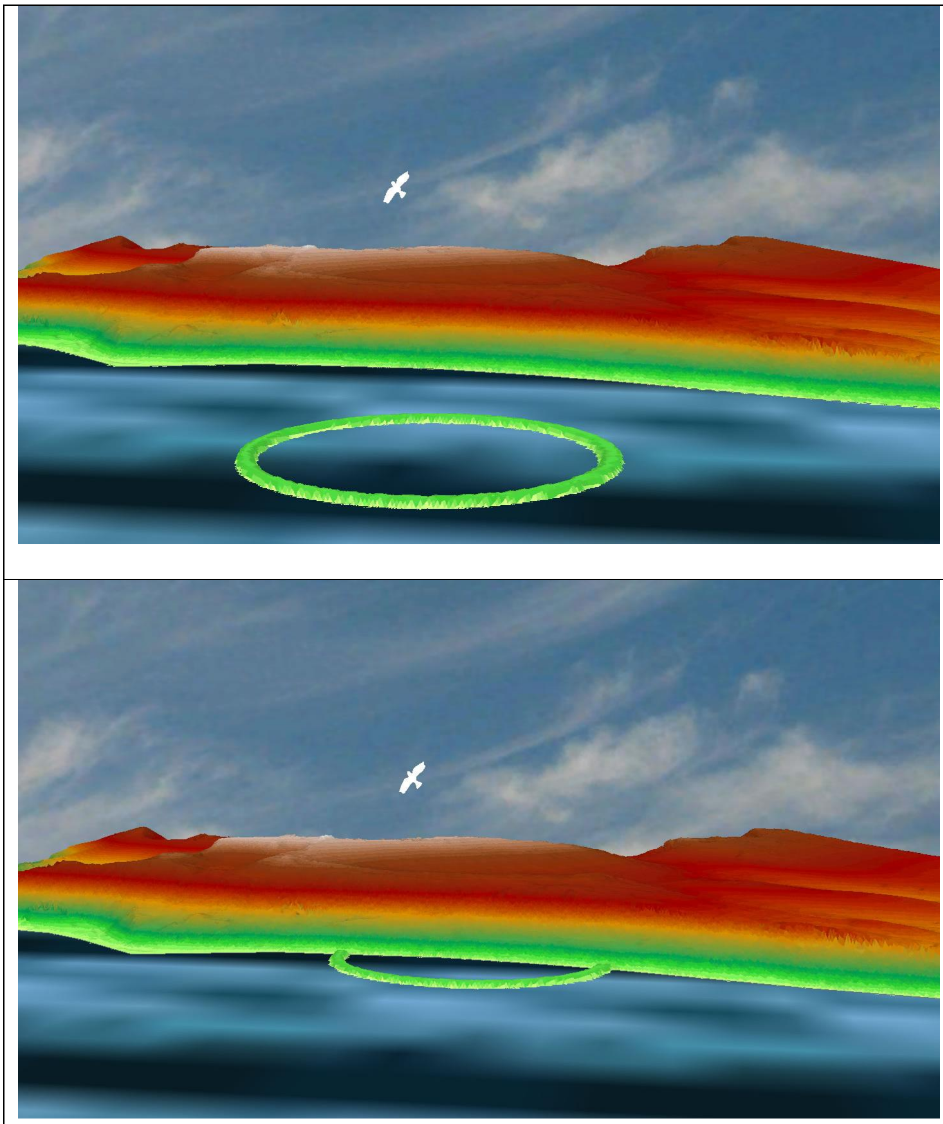


Figure 2.2a: Detached (top) and Shore-attached (bottom) Tidal Lagoons.

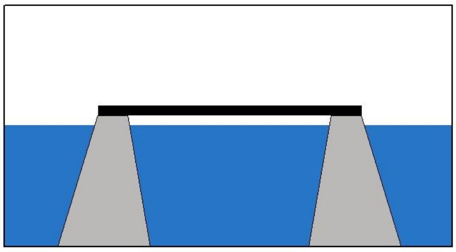
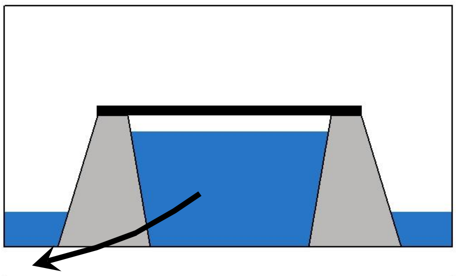
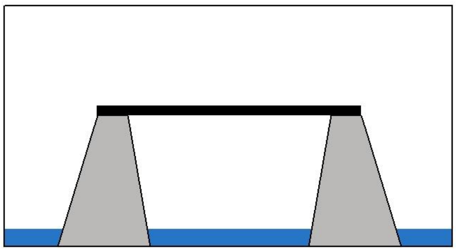
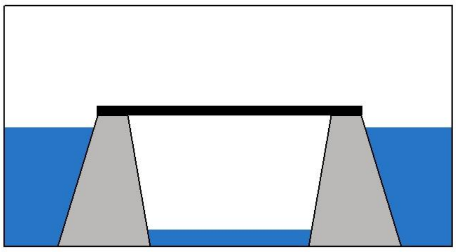
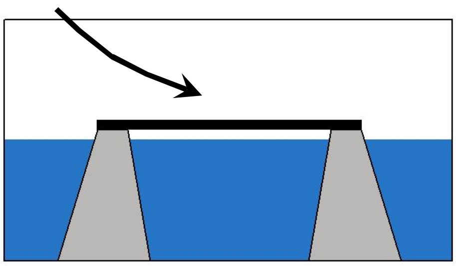
	**1**	Sluices open, so lagoon fills during flooding tide. Lagoon fullest at high tide.
	**2**	Sluices closed at high tide to retain impounded water and head created on ebb tide. Lagoon then discharges head through turbines.
	**3**	Lagoon empty at low tide.
	**4**	For two-way operation only: Sluices closed during flooding tide and head created. Head discharged through turbines to fill lagoon.
	**1**	The cycle is then repeated. Sluices open, so lagoon fills during flooding tide. Lagoon fullest at high tide.

Figure 2.2b: Operation of Tidal Lagoons.

2.2.3 Extra benefit when using turbines as pumps

The use of turbines as pumps in tidal power plants can lead to extra benefits without a large increase of the investment cost. In the largest operational tidal power plant of La Rance the turbines have the ability to pump in both directions. These pumps can then be used to store extra water in a basin or to empty it more rapidly.

Though using pumps costs energy, it can become beneficial when pumping with a low head and turbining the pumped water with a high head. In this way the costs for the energy to pump are smaller than the benefits gained when turbining. An example of the water level variation with the use of the pumping mode of turbines is shown in figure 2.3.

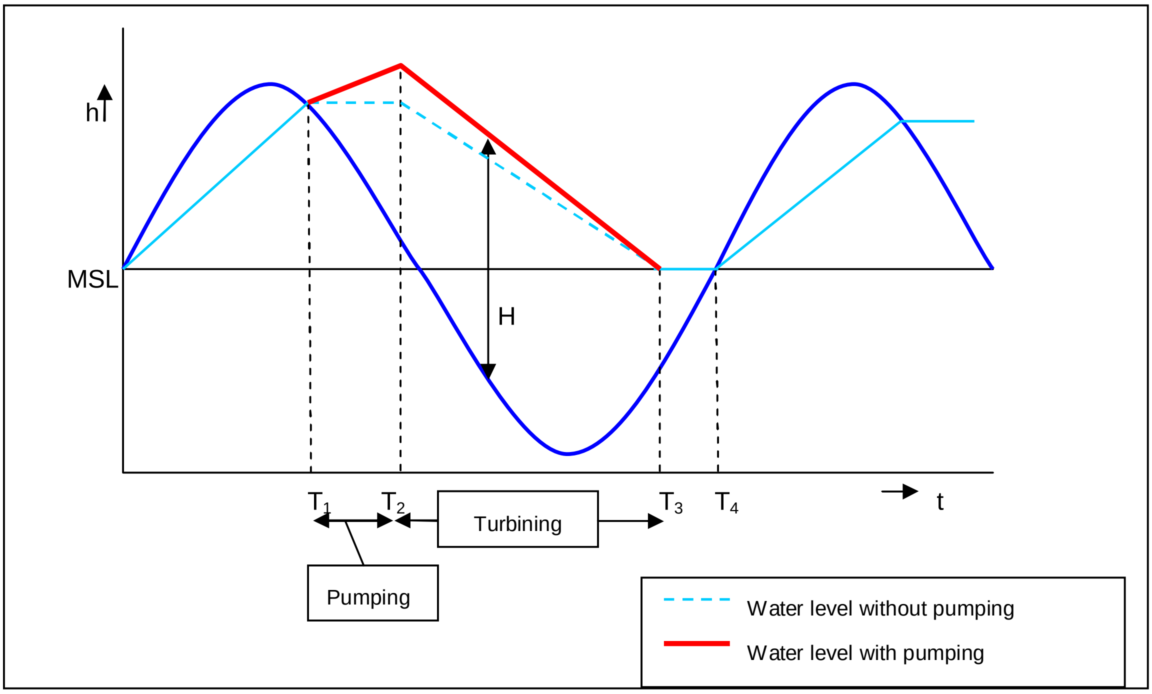


Figure 2.3: Water level variation in basin when using the pumping mode of turbines.

Filling the basin with pumps, as is shown in figure 2.3, is called flood pumping. In La Rance the benefits of using this mode of the turbines was 10% more than without using the turbines as pumps (report Severn).

Using pumps becomes extra beneficial in two situations:

- During pumping the energy price due to the daily fluctuation is lower than during turbining;
- With extreme neap tides the head during turbining is that low that the efficiency is reduced drastically when pumps are not used.

In the same way pumping becomes less beneficial when the energy price is high during pumping and low during turbining, and when pumping causes a large efficiency reduction during spring tides. In these cases it can be decided not to use the pumping mode.

3 CASE STUDIES IN THE UNITED KINGDOM

3.1 General history of the development of tidal range energy

The concept of exploiting the tidal range energy potential of parts of the UK through construction of an impoundment barrage has been around for a considerable time. The most favourable location has been the Severn Estuary, since this possesses the second largest tidal range in the world. Indeed, since as long ago as the 1920s, various government-commissioned studies have considered alternative sites in this estuary. The issue has been revisited again over recent years as the awareness of the consequences of climate change has increased and the need to secure alternative sources of energy generation has become more manifest.

Consideration of tidal lagoons does not have such a long running history as tidal barrages and probably was initiated in the 1981 Bondi Committee Report. This considered a concept known as the Russell Lagoons in the Severn Estuary, where three such shore-connected lagoons were planned to enclose specific reaches of the estuary, leaving a narrow channel running in between and therefore not completely obstructing the estuary to navigation. Subsequent developments of this concept have been for impoundments completely separated from the shore. Swansea Bay is the most commonly cited proposal for such a lagoon in the UK.

3.2 Recent UK Reviews

As part of a wide ranging review of the UK's tidal energy potential the Sustainable Development Commission (SDC) commissioned a series of reports to evaluate various aspects of tidal power.

- **SDC Turning the Tide – Tidal Power in the UK** (Sustainable Development Commission, 2007) laid out a series of recommendations for UK Government on how to develop the UK's tidal power resources.

- **SDC Research Report 1** (Sustainable Development Commission, 2007a) provided an overview of the UK's tidal resource.

- **SDC Research Report 2** (Sustainable Development Commission, 2007b) provided an overview of tidal technologies.

- **SDC Research Report 3** (Sustainable Development Commission, 2007c) investigated various barrage proposals on the Severn Estuary.

- **SDC Research Report 4** (Sustainable Development Commission, 2007d) investigated non-barrage proposals for the Severn Estuary.

- **SDC Research Report 5** (Sustainable Development Commission, 2007e) provided a review of a number of UK case studies (both tidal stream and tidal range).

Overall, the report series examined the UK tidal resource, the status of the technology, and potential environmental impacts. Due to this, it provides the most current and comprehensive review of its type.

3.3 UK Tidal Range Energy Potential

The *UK Atlas of Offshore Renewable Energy* (Department of Trade and Industry, 2004) identifies the optimum conditions for tidal range technologies to be where mega-tidal ranges exist (i.e. tidal range >8m) and the tide is semi-diurnal in character (i.e. the tide floods and ebbs twice a day).

Figure 3.1 shows optimum locations to be restricted to the Irish Sea, the Severn Estuary/Bristol Channel, the Wash, the eastern English Channel and the Channel Islands. Around 90% of the UK tidal range energy output is estimated to be in the Severn Estuary, with another 7.5% in the Mersey Estuary, adjacent to the Irish Sea (SDC, 2007b).

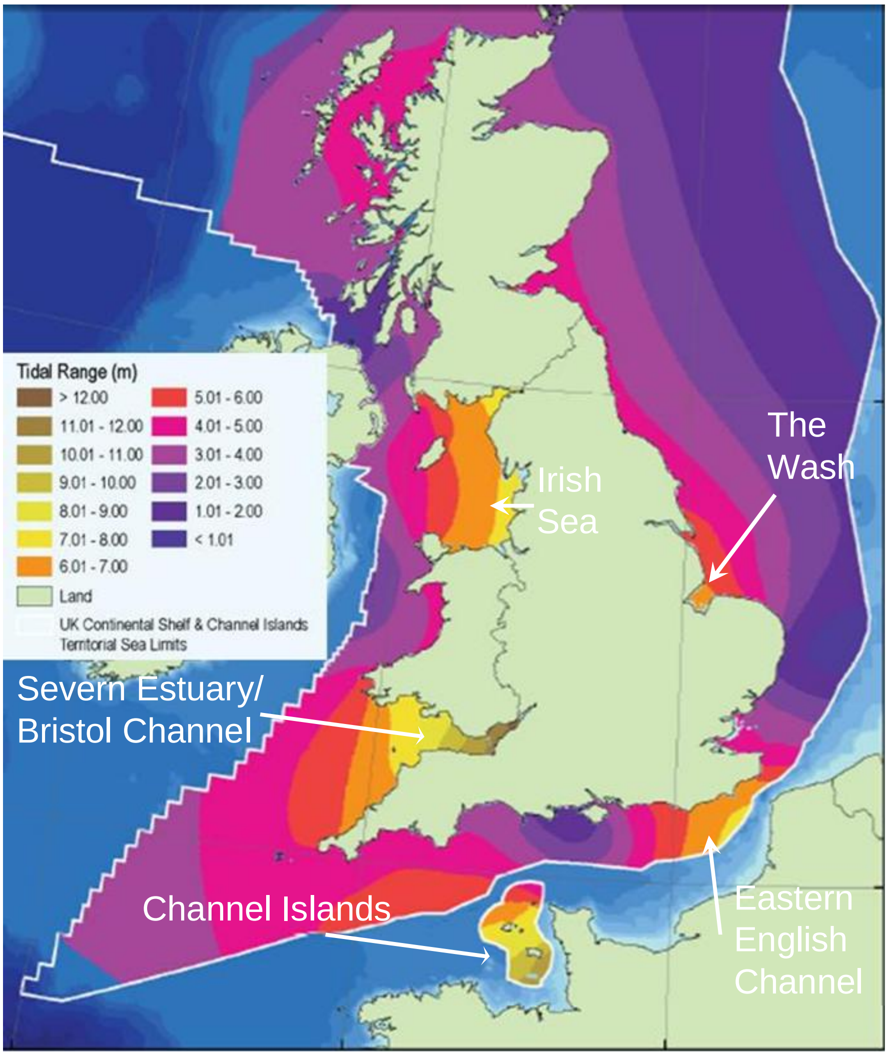


Figure 3.1: Tidal Range Energy Potential in the UK (after DTI, 2004).

The selection of case studies in the SDC studies was designed to provide a series of examples of tidal energy concepts and their impacts. In each case, specific features were highlighted and the implications of development in addition to the generation of renewable energy were reviewed.
These impacts include marine spatial planning, navigation and commercial shipping, regional benefits including employment and flood defence, potential effects on

designated sites (nature conservation), recreational use and impact on the seascape. The selection of case studies also took into account different technologies, comparative size and location.

The following case studies have been carried forward from the SDC series into this report:

- Severn Barrage. Up to 8640 MW capacity barrage;
- Mersey Barrage. 700 MW capacity barrage;
- Liverpool Bay / North coast of Wales. 340 MW capacity tidal lagoon;
- Loughor Estuary. 5 MW capacity barrage;
- Duddon Estuary. 100 MW capacity barrage;
- Wyre Estuary. 64 MW capacity barrage.

The Lower Thames estuary lagoon has been carried out from the Metrotidal Tunnel report:

- Thames Estuary.

The case studies described are indicated in red in figure 3.2.

Due to its physical size and energy capacity, the Severn Estuary has attracted most attention. A number of tidal range energy developments have been proposed on the estuary; and those of a non barrage design were reported in Sustainable Development Commission (2007d) and included the Russell Lagoons and the Swansea Bay Lagoon

Most of the examples selected as part of the SDC study were previously investigated as part of the UK's tidal energy R&D programme between the early 1980s and 1994. The primary interest of the current UK programme is the development of tidal energy barrages principally across the Severn Estuary and the Mersey Estuary.
A number of smaller estuaries also attracted interest from both local authorities and industry and were the subject of initial feasibility studies. These estuaries included the Loughor, Duddon and Wyre.

Tidal energy projects built in estuaries would be harnessing one of the major forces responsible for shaping and controlling the estuarine environment. As a consequence the pattern of the tides would be altered, which would, in turn, be expected to influence the estuarine environment and its surroundings. In the case of the Severn Estuary the natural accentuation of the tidal range will mean that any changes to the open estuary will need careful and rigorous assessment so that the changes caused by development can be accurately predicted (Sustainable Development Commission (2007d).

Further information on the civil engineering, capital cost, energy generation and carbon balance aspects associated with these case studies is provided in table 3.1 below and in Annex A of the Annex report.

Figure 3.2: Overview of case studies in UK.

Table 3.1: Information on civil engineering, costs etc. of different todal energy schemes

SCHEME	**Details** Status	Mean Spring Tidal Range (m)	Energy output (TWh/y)	Installed Capacity (MW)	Capital Cost (million€)	Lifespan (years)	**Civil Engineering aspects** Construction
Severn Barrage (Cardiff-Weston)	Detailed Assessment Stage	10,5	17,0	8640	1600	120	16km barrage (>70m wide where turbines are housed) comprising embankments, ship locks, turbines and sluices (both housed in caissons). Caissons built in dry-dock and floated. Towed to site and ballasted into position. There would be 216 no. 40 MW turbines and generator sets in the power-house. Ebb generation with reverse pumping at high water.
Severn Estuary (Shoots)	Feasibility Stage	11,5	2,8	1050	13700 – 18600	120	4km barrage, comprising embankments, ship locks, turbines and sluices (both housed in caissons). Caissons built in dry-dock and floated. Towed to site and ballasted into position. There would be 30 no. 35 MW turbines and generator sets in the powerhouse. Ebb generation only
Swansea Lagoon	Feasibility Stage	8,5	0,1 – 0,2	60	1600 – 1900	120	9 km of sand-filled core embankment, with an outer containment rock bund during construction and rock armour protection during operation. The structure would be exposed to relatively high wave energy in the Bristol Channel due to its more westward location than other proposals in the Severn Estuary. Rock armour would help dissipate the wave energy. The powerhouse would be contained within six concrete caissons (each 40m long by 30m wide) set in deeper water as an extension to the lagoon on its seaward side. Caisson built in dry-dock and floated. Towed to site and ballasted into position. There would be 24 no. 2,5 MW low-head hydroturbines and generator sets in the powerhouse. There is potential for generation during both the flood and the ebb tide. In contrast to other schemes, one design was for a lower crest and shallower slope gradient for the embankment. This would allow overtopping of water at high tide. Another option is to have a more 'conventional' embankment. Some 2,3m of settlement could occur due to compaction. Dredging of the navigation channel into Swansea would be required to enable transportation of the caissons.

SCHEME	Details						Civil Engineering aspects
	Status	Mean Spring Tidal Range (m)	Energy output (TWh/y)	Installed Capacity (MW)	Capital Cost (million€)	Lifespan (years)	Construction
Russell Lagoons (assumed 3 No.)	Bondi Commision Report	14,0	6,48	2,835	87,3	120	Up to 3 no. lagoons, formed by sand-filled embankments (each with a circumference length of between 20-30 km) with rock debris protection and then covered by concrete blocks, slabs or stone-filled mattresses. Pre-fabricated powerhouse (concrete or steel) containing turbines, generators and sluices built in dry-dock and floated. Towed to site and ballasted into position.
Mersey Barrage	Feasibility Stage	8,0	1,45	700	7500	120	1,9km barrage constructed of pre-fabricated concrete caissons built in artificial enclosures adjacent to the barrage landfall. Towed to site and ballasted into position. Two ship locks incorporated into the design, to be constructed in-situ. Most of the barrage length would consist of sluices to maximize flow into the impounded reach on the flood tide. A shorter section would contain turbines, operating during ebb tide. Single generation on the ebb tide only was deemed the most efficient and economic mode of operation.
Liverpool Bay Lagoon	Pre-feasibility Stage	6,7	0,94	340	712	120	Sand-filled embankment (constructed from locally-dredged sand and protected by rock armour) built to enclose an area of 60 km^2. The turbines and generators installed along 1 section within a pre-cast RC caisson powerhouse. Caisson built in dry-dock and floated. Towed to site and ballasted into position. Power plant could potentially be operated in reverse (i.e. on flooding tide) as well as on ebb tide for 2-way power generation. Serviced from local base (such as Rhyl, Mostyn or Connah's Quay). Extensive dredging probably required during construction. Likely to be 20 no. 17 MW turbines
Loughor Barrage	Feasibility Stage	3,9	0,015	5	25	120	Cofferdam and in-situ construction
Duddon Barrage	Feasibility Stage	5,8	0,21	100	443	120	Sand-filled embankment with a short central section of pre-fabricated RC caissons. Towed to site and ballasted into position. Dredging of a navigation channel to allow the caissons to be floated into position. Dredged spoil used to make the embankment
Wyre Barrage	Feasibility Stage	6,6	0,13	64	148	120	Pre-fabricated structure placed across entrance estuary. Small ship lock and embankment.

In addition to the above, the authors, through their work in the industry, are aware of historic and current proposals for barrages in other areas of the UK. The following additional case studies have therefore also been included:

- Morecambe Bay Barrage;
- The Wash Barrage;
- Solway Firth Barrage

3.4 The Severn Estuary

A cross-government group led by the Department of Energy and Climate Change (DECC, formerly BERR) has initiated the Severn Tidal Power (STP) Feasibility Study to consider whether the UK Government could support a barrage project which exploits the major energy generation potential of the Severn Estuary's tidal range, and if so, on what terms. At present two potential locations are under prime consideration; Shoots Barrage and Cardiff-Weston Barrage (Figure 3.3).

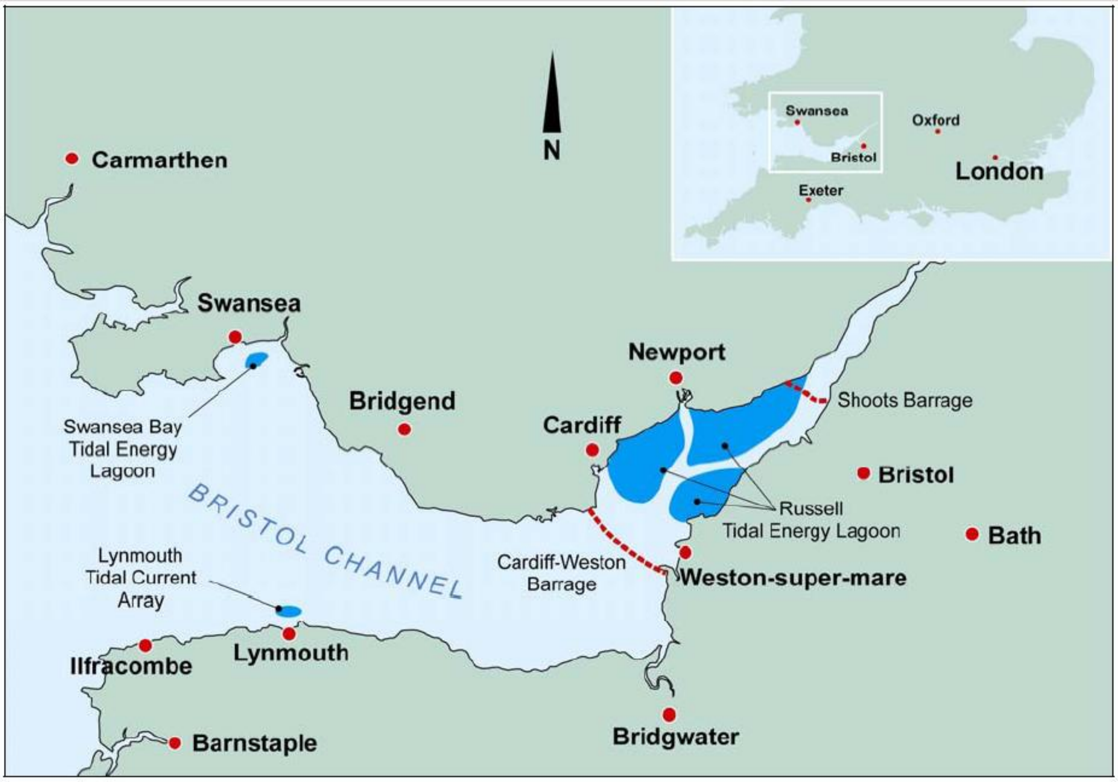


Figure 3.3: Indicative Location of the Shoots Barrage and Cardiff-Weston Barrage. (reproduced from: Tidal Power in the UK. Research Report 4 – Severn Non-Barrage Options. SDC, 2007d).

Note: The indicative location of the Russell Lagoons and the Swansea Bay Lagoon is also shown in this figure.

A Strategic Environmental Assessment (SEA), which will be compliant with the requirements of the EU SEA Directive 31, is being undertaken to assess the significant environmental effects of proposals to generate electricity from the renewable tidal range energy output of the Severn Estuary; and, if the Government can support a tidal power project in the Severn Estuary, then to inform the development of a preferred alternative or alternatives.

The Severn Estuary lies on the south-west coast of the UK between Wales and England. Its potential as a source of tidal power has been the subject of studies for over 90 years and it has been shown to contain a significant tidal energy energy output with the potential to release an annual average energy output in the region of 17000 GWh/year (almost 12 times that of the Mersey Estuary). The estuary has the second highest tidal range in the world and the highest spring tides at Avonmouth can exceed 14m, with the mean tidal range at this location being around 8,5m. Approximately 200km^2 of inter-tidal habitats support a wide variety of flora and fauna.

A prominent feature of the tide on the Severn Estuary is the Severn bore. The tide curve at the entrance to the Bristol Channel is a sine curve and, as the flood tide propagates up the estuary, the shape of the estuary causes the curve to be modified; the flood tide rises more steeply and the ebb tide falls more slowly. Ultimately, upstream of Avonmouth, the rise is so steep that a bore forms.

The entire area of the Bristol Channel and the Severn Estuary is recognised as being internationally important in terms of its ecological function and biodiversity and much of the estuary is now protected under the European Habitats Directive, Birds Directive and Ramsar Convention. The Convention on Wetlands of International Importance, called the Ramsar Convention, is an intergovernmental treaty that provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources.

The estuary has been designated a possible Special Area of Conservation (pSAC), Special Protection Area (SPA), and Ramsar site. The region contains 157 Sites of Special Scientific Interest (SSSIs), 5 National Nature Reserves (NNRs), 2 SPAs (including the Severn Estuary) and significant areas of Heritage Coast and Areas of Outstanding Natural Beauty.

Depending on the barrage location and mode of operation, changes to the hydrodynamic regime, particularly upstream of a barrage, would have an impact on water quality; e.g. changes in dissolved oxygen levels. There would be a significant reduction of inter-tidal area in the upstream basin and a similar area increase of calmer sub-tidal areas.

Such environmental changes in intertidal and in water quality areas may have significant adverse effects upon the species they support. Whilst compliance with all environmental requirements would be an important requirement for any estuarine barrage proposal, the specific requirements of the Habitats Regulations are likely to present the most significant challenges in seeking approval for a project. It must be remembered that the Natura 2000 network comprises all European sites and direct effects on one interest feature may indirectly affect another on a distant site.

This is especially true where species migrate between sites, or are displaced from one site to another.

For a barrage proposal to proceed in accordance with the requirements of the Habitats Regulations, it would need to demonstrate that there were no less damaging alternatives, that the project met the grounds for IROPI (Imperative Reason of Overriding Public Interest) and that all necessary compensatory measures could be delivered to secure the overall coherence of the Natura 2000 network.

Aside from the requirements of the Habitats Regulations, the requirements of other existing environmental legislation and policies are not considered to pose such significant challenges, although the requirements relating to the Water Framework Directive have yet to be applied to development projects. Marine environmental legislation and policy will continue to evolve, particularly with the expected implementation in the UK of the Marine and Coastal Access Bill.

In addition to the Severn Barrage option, two options for Tidal Energy Lagoon projects have been assessed for the Severn Estuary: the Swansea Bay Lagoon, and the Russell Lagoons (three lagoons in the upper Severn Estuary). The location of these proposals is shown in the earlier Figure 3.3.

Sustainable Development Commission (2007a) concludes that the Russell Lagoon concept for three land-bordered tidal lagoons is unlikely to be viable when compared to the barrage proposals on the grounds of energy efficiency. Although the Russell Lagoons could theoretically capture up to 6480 GWh per year, this is less than 50% of the annual production of the largest barrage scheme (17000 GWh per year) proposed for the Severn Estuary. It was concluded that the lagoons would have a similar or greater environmental impact due to the channeling effect on tidal currents passing by the three lagoons. Such impacts would place the Russell Lagoons in a similar category to a Severn Barrage in terms of environmental legislation; i.e. imperative reasons of over-riding public interest (IROPI) would have to be demonstrated in order for the project to go ahead. It would be very difficult to mitigate the loss of the large areas of protected, internationally important intertidal habitats that currently exist and are protected within the estuary. The coexistence of a barrage and a large lagoon development within the Severn Estuary is therefore even less likely to receive approval.

The much smaller 50 MW proposal for Swansea Bay is potentially more realistic as its scale suggests that habitats lost could by mitigated regionally through provision of compensatory habitat, although a key concern raised by the Countryside Council for Wales (in 2006) relating to the Swansea Bay Lagoon is the potential impact on sedimentary processes.

3.5 The Mersey Estuary

The Mersey Estuary has been the subject of a number of studies looking into potential for a tidal barrage. Initial concepts were conceived in the 1980s and developed into the early 1990s but were not progressed.

Renewed impetus has more recently been generated by funding from the Regional Development Agency, and further investigations are currently ongoing, looking at a variety of alternative locations for a barrage. The prime location under consideration is shown in Figure 3.4.

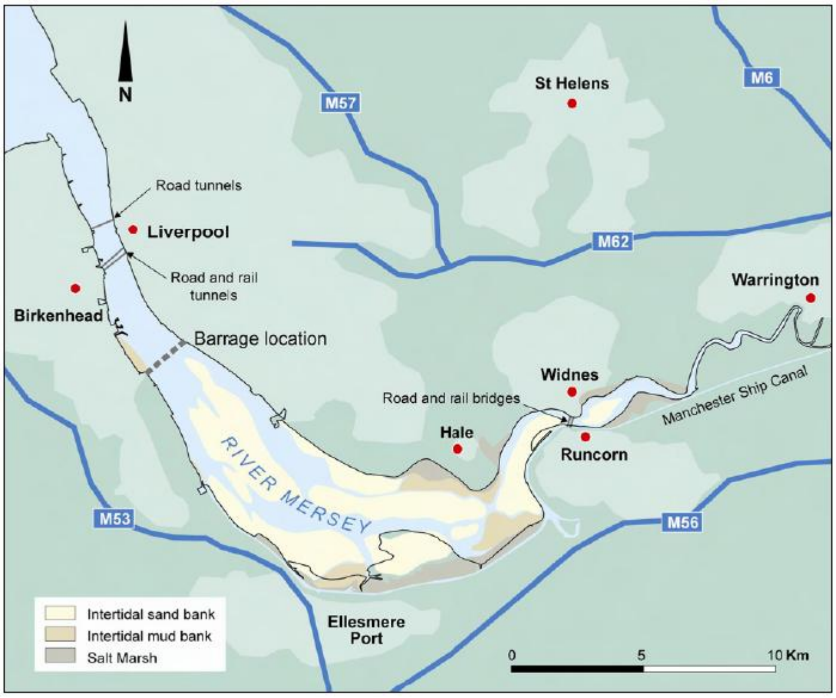


Figure 3.4: Indicative Location of the Mersey Barrage (reproduced from: Tidal Power in the UK. Research Report 5 – UK Case Studies. SDC, 2007e).

The Mersey Estuary is a large tidal estuary in North West England. It is one of the largest estuaries in the UK with a mean spring tidal range of approximately 8.0 m. It receives drainage from a catchment area of approximately 5000km^2 which extends from the Pennine hills of England to the Irish Sea including the conurbation of Greater Manchester and Liverpool (Langston et al. (2006)). The Mersey Estuary is unique in terms of its geomorphology and hydrology. From the upper to middle reaches, the inner estuary gradually widens to a maximum width of 5km before narrowing to about 1km at the Mersey Narrows and flowing into the outer estuary which forms part of Liverpool Bay.

Extensive areas of intertidal sand and mudflats exist in the upper and middle estuary, and also around the mouth of the estuary. Much of the estuary and the surrounding coastline of Liverpool Bay is designated for its internationally important populations of migratory waders and waterfowl. Similarly, its intertidal habitats are also protected as Natura 2000 sites under the European Birds and Habitats Directives respectively.

The estuary is an important and busy shipping route, with large volumes of traffic passing through the estuary to Manchester via the Manchester Ship Canal that enters the estuary on its south shore at Eastham. Several large industrial sites are located along the shores of the estuary; e.g. Ellesmere Port and Birkenhead.

In the past, the estuary received environmentally damaging quantities of organic effluent and inorganic contaminants; for example, previous industrial chemical operations around the upper estuary at Runcorn and Widnes in particular were poorly controlled during the nineteenth and early twentieth centuries. Recent initiatives, coupled with changing industrial practices, have led to improved water quality. However, given the long term legacy of pollution and the repository held in fine sediments, chemical impacts and resultant biological effects are monitored closely by UK regulators.

- The large tidal range of the Mersey estuary (MHWS 8,0 m) is an important factor determining its physical and biological characteristics.
- The annual average energy output is expected to be in the region of 1450 GWh/year from an installed capacity of 700 MW.
- Seabed sediments are generally mobile with low benthic species diversity.
- Intertidal sand and mudflats of the inner estuary support internationally important numbers of water birds throughout much of the year.
- Much of the estuary is developed and there is a legacy of pollution of water, sediments and biota although there have been significant improvements of recent.
- Tourism is important, and the coastline and waters of the estuary are used for a variety of recreational activities.

A significant area of the middle Mersey Estuary is designated a Special Protection Area (SPA) under the EC Birds Directive. The estuary is also identified as a Ramsar site under the Ramsar Convention. The north Wirral coastline is also a possible SPA and Ramsar site (pSPA/ pRamsar), while all the waters of Liverpool Bay below mean low water to approximately 10-20 km offshore are also a pSPA. The coastline north of the mouth of the estuary is designated a Special Area of Conservation (SAC) for habitat and species features under the EC Habitats Directive, and an SPA/ Ramsar.

The principal constraints associated with implementation of a barrage across the Mersey Estuary are:

- High capital costs (around £1,5B estimated) making the unit cost of output yield commercially non-viable;
- Adverse environmental impact on an estuary of highly and internationally designated nature conservation importance;
- Adverse impacts on navigation access, including to Garston Dock, Eastham Locks, the QEII Oil Lock, and the Manchester Ship Canal. This would require the inclusion of lock gates in the barrage and would increase operating costs of shipping companies due to increased transport times;
- Increased dredging costs to clear navigation channels of accumulated sediment following increased sedimentation due to the effects of the barrage.

The most relevant ancillary benefits and opportunities beyond the low-carbon energy generation are the:

- Potential to combine the barrage scheme with a new road crossing of the estuary, linking key economic centres to both north and south, and the boost generated to the local economy during fabrication;
- Construction and operation activities, including temporary and permanent job creation.

3.6 Liverpool Bay

Liverpool Bay is noted for its large tidal range and the case study presented in Sustainable Development Commission (2007b) is based on the 340MW scheme proposed by Evans et al. (2007) for a potential offshore tidal impoundment site situated between Colwyn Bay and Rhyl off the north coast of Wales (Figure 3.5); an area that is particularly vulnerable to flooding from the sea.

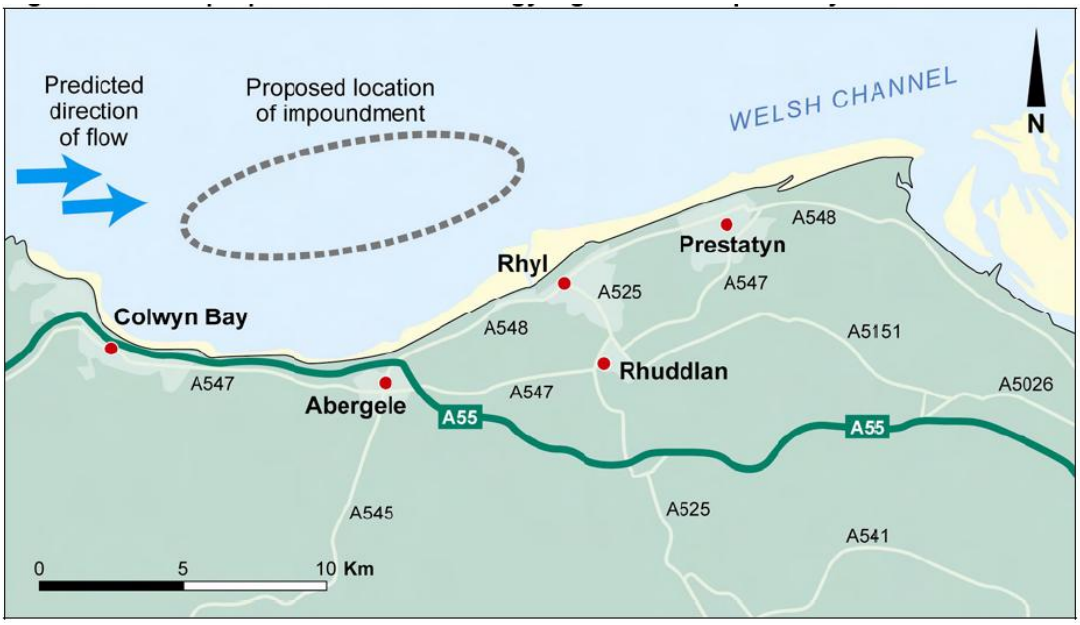


Figure 3.5: Indicative Location of the Liverpool Bay Lagoon (reproduced from: Tidal Power in the UK. Research Report 5 – UK Case Studies. SDC, 2007e).

This case study addressed the energy potential, cost and value of energy for a tidal energy lagoon. It also evaluated the embedded carbon and carbon savings that the scheme could offer as well as its potential economic benefits and environmental impacts.

The north coast of Wales is primarily low and sedimentary with few rocky headlands; with the exception of north Anglesey and the Great Orme to the west. Long sandy beaches, sand dunes, two shallow estuaries and shallow offshore sand banks are the primary features of the area. The coast is also much influenced by a well developed tourist industry, the Mersey Estuary outflow, the Dee Estuary and the presence of many industrial activities in Liverpool Bay.

There are several conservation sites of international importance in the vicinity, including the sea cliffs at Great Orme's Head, the Dee Estuary Special Protection Area (SPA) and Ramsar and Dee Estuary draft Special Area of Conservation (pSAC), the proposed Liverpool Bay SPA, and the Menai Strait and Conwy Bay SAC.

SDC (2007a) identifies that the impact of a large offshore structure on the scale envisaged for a tidal energy lagoon in Liverpool Bay would need careful assessment. One of the key concerns would be the potential impact on sedimentary processes. Assessing impacts on sediment movement is important not only because of potential changes to intertidal and subtidal habitats, but also coastal processes. To predict changes to sediment erosion, movement and accretion a sediment transport model would need to be developed over an extensive area of the eastern Irish Sea and Liverpool Bay and linked to a hydrodynamic model of water flows over different tidal ranges and related current strengths. It is also considered likely that regulators would request that any EIA would include an assessment of potential coastal processes at all stages of development from pre-construction to operation and decommissioning together with likely cumulative effects with other plans and projects; e.g. extensive offshore windfarm developments (two operational, one other consented, and one proposed) in the region. The EIA would also need to take account of climate change, particularly sea level rise and increasing storm frequency and intensity.

Changes to substrate linked to lagoon construction and operation could potentially affect inshore fisheries and benthic fauna. Consequently, surveys of these habitats would be a requirement. The Countryside Council for Wales (2006) also expressed concern over the potential loss of habitat especially intertidal feeding areas frequented by waders and wildfowl. Any EIA must also take account of dredged areas as well as the permanent loss of habitat caused by the large lagoon footprint (Countryside Council for Wales (2006)).

3.7 Loughor Estuary

The Loughor Estuary is located within Carmarthen Bay in Wales. Feasibility studies were undertaken in the late 1980s into the creation of a barrage across the narrow restriction by Loughor Bridge (Figure 3.6) for both energy generation (around 5MW capacity) and amenity purposes, with the latter issue relating to the creation of a new marina upstream of the barrage.

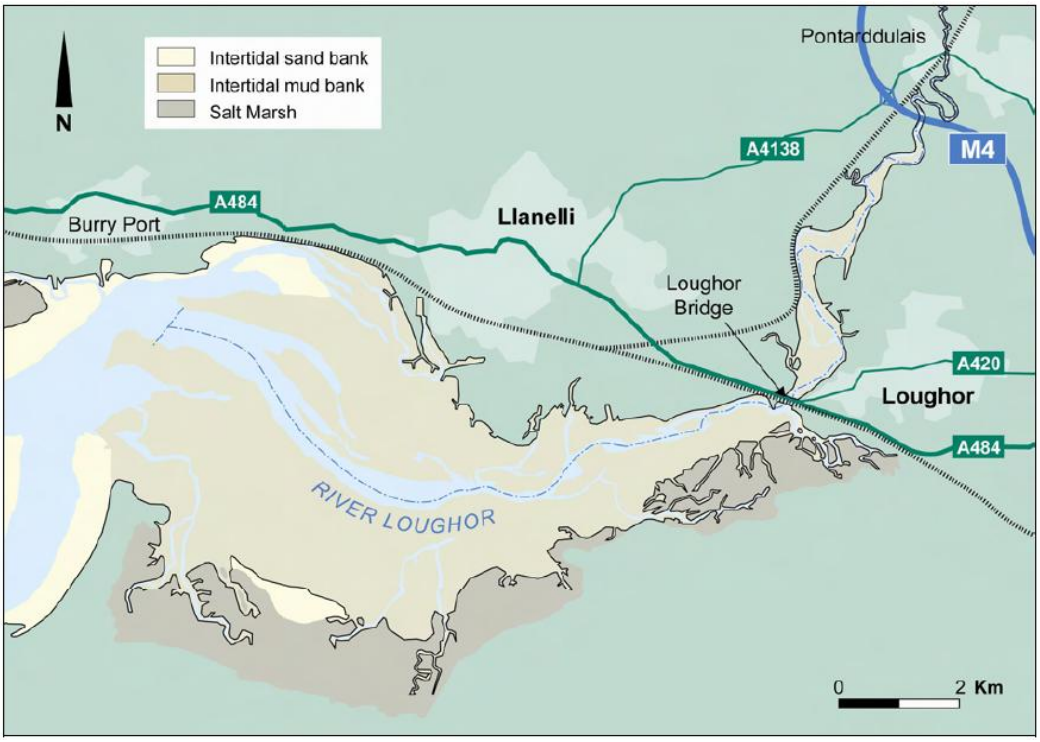


Figure 3.6: Indicative Location of the Loughor Barrage (reproduced from: Tidal Power in the UK. Research Report 5 – UK Case Studies. SDC, 2007e).

The initial studies highlighted major concerns associated with sedimentary issues. First, there was an identified potential for increased sedimentation behind the impoundment which would require extensive dredging if the existing morphology was desired to be retained. Second, there were concerns that historic contaminants from previous industrial activity could be re-mobilised by changes in the hydrodynamic regime, causing far-field pollution.

In addition, there were also concerns relating to the potential adverse impact of the barrage on areas of internationally, nationally and locally designated nature conservation value.

3.8 Duddon Estuary

The Duddon Estuary is located along the North West coast of England. In the early 1990s a feasibility study was undertaken to investigate the potential for a barrage at, or just upstream of, the estuary mouth. Three alternative locations considered are shown in Figure 3.7.

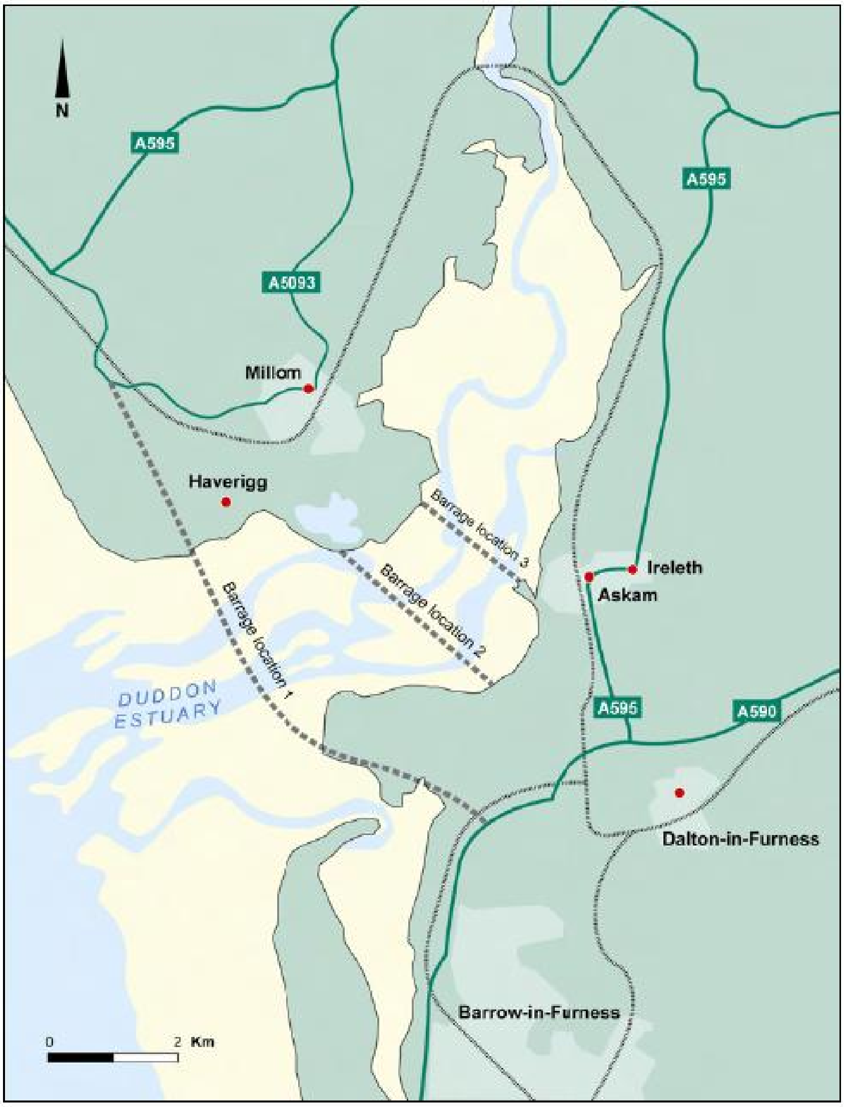


Figure 3.7: Indicative Location of the Duddon Barrage (reproduced from: Tidal Power in the UK. Research Report 5 – UK Case Studies. SDC, 2007e).

One of the added advantages of this proposal was that it was intended to also create a road crossing of the estuary to improve this remote and largely rural region's transport infrastructure.

Due to the very shallow bathymetry of the estuary, combined with the high tidal range, the intertidal areas are extensive. This brings intrinsic nature conservation value and the potential adverse impact on the natural environment was one of the major concerns associated with the proposals. This related not only to the barrage itself, but also to the impact of the temporary works, most notably including estuary dredging along the low water channel to improve navigation to enable the import of materials.

3.9 Wyre Estuary

The Wyre Estuary in North West England flows into the North Sea to the south of Morecambe Bay. A feasibility study was undertaken in the early 1990s to investigate the potential for a barrage just upstream of the estuary mouth (Figure 3.8) to both generate energy from the large tidal range and to provide a new road crossing. The latter aspect was seen as a critical component of regenerating the town of Fleetwood, located to the west of the estuary. The principal issues related to this proposed were the potential adverse effects on the hydrodynamic regime and the 'knock-on' consequences of these on the natural environment.

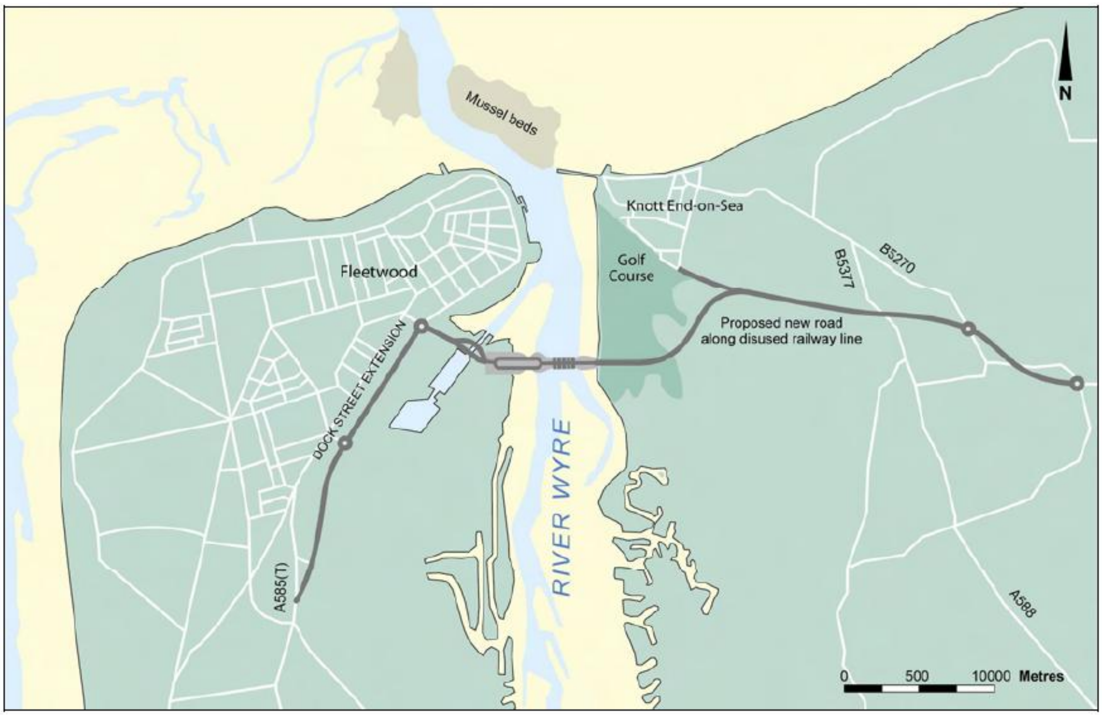


Figure 3.8: Indicative Location of the Wyre Barrage (reproduced from: Tidal Power in the UK. Research Report 5 – UK Case Studies. SDC, 2007e).

3.10 Morecambe Bay

Morecambe Bay is a large inter-tidal bay in the north west of England into which several smaller estuaries discharge. The Bay itself is characterised by a high tidal range and extensive areas of inter-tidal sand flats intersected by low water channels. The Bay is subject to numerous nature conservation designations, including SPA and Ramsar citations. Proposals for a barrage across the Bay have been ongoing for over 40 years, although initial proposals were to impound freshwater coming down the estuaries into the Bay for purposes of addressing a perceived water shortage in the mid 1960s and early 1970s. More recently, the concept of a tidal energy barrage has been considered, with a proposal to build a 12 mile long toll road and pedestrian route between Heysham and Barrow, across the mouth of the Bay. This was perceived as scheme which could harness power from both the wind (using wind turbines) and the tidal range, which it was estimated would save 87000 tonnes of CO_2 per annum.

Ancillary benefits included the potential to create 2000 jobs and regenerate the economy of West Cumbria. One of the concerns associated with the barrage proposal was the potential for 'red tide' bacteria, which could impact on the important shellfish industry and ecosystems of the Bay. More recently, the barrage concept has been dropped in favour of tidal stream technology which is perceived as less environmentally damaging to the intertidal area of the Bay. This latest proposal is being called a 'Green Bridge' since it would be combined with a road crossing of the Bay. The latest proposals remain at a very early stage of development.

Figure 3.9: Morecambe Bay.

The Wash

The Wash is an extensive tidal embayment on the east coast of England. It is subject to numerous nature conservations designations and accounts for approximately 10% of the UK salt marsh and mud flat total. Proposals for a barrier across the Wash extend back to 1949 when it was proposed to build such a barrage across the mouth of the Wash to form both a freshwater reservoir and a Europort. In 1972 a study was commissioned by the Government to asses the feasibility of building a barrage across half of the Wash to capture the freshwater from the four main entering rivers, to improve navigation through sea locks, to provide recreational facilities and to provide an area of land for development of a power station. This led to a circular trial bank/bund being built but ultimately the scheme was dropped.

Figure 3.10: The Wash.

The latest concept is for a barrage that would span the Wash from Hunstanton in Norfolk to just south of Skegness in Lincolnshire, a distance of approximately 18km, with an additional 5km of barrier in Lincolnshire in order to reach higher ground. The principal aims of the proposals are to create energy from the tidal range and to provide protection to the low lying land around the Wash against rising sea levels.

Estimate costs of the scheme are in the order of £2B and some of the ancillary benefits are claimed to be associated with flood protection, economic regeneration, and improved amenity facilities. The barrage would also provide a foundation upon which wind turbines would be located. The main impacts and issues associated with the proposals are recognized to be the adverse impacts on the natural environment, navigation and coastal processes.

Solway Firth

The Solway Firth is located on the UK's West coast, straddling the border of England and Scotland. It possesses extensive intertidal areas and numerous international designations for nature conservation importance.

Proposals for barrages across the Firth are documented as far back as the mid 1960s, with these early concepts intended to impound freshwater for water resource purposes. In the late 1980s a national study highlighted the Solway Firth as an area of tidal energy generation potential, but schemes were not progressed at that time. More recently, plans for a tidal range barrage were reignited, with the intention of combining this with a road link and with the barrage intended to also provide improved relief against the risk of sea flooding further up the estuary. It is understood that progress with further development of the concepts has not been rapid and no further information is available at the present time.

Figure 3.11: Solway Firth.

3.11 Lower Thames Estuary Lagoon

A prospectus was published in June 2008 for an independent private-sector initiative to develop a self-contained, multi-model tunnel in the lower Thames Estuary, integrating new orbital and circulatory rail and road infrastructure with renewable energy generation and improved flood alleviation for London city.

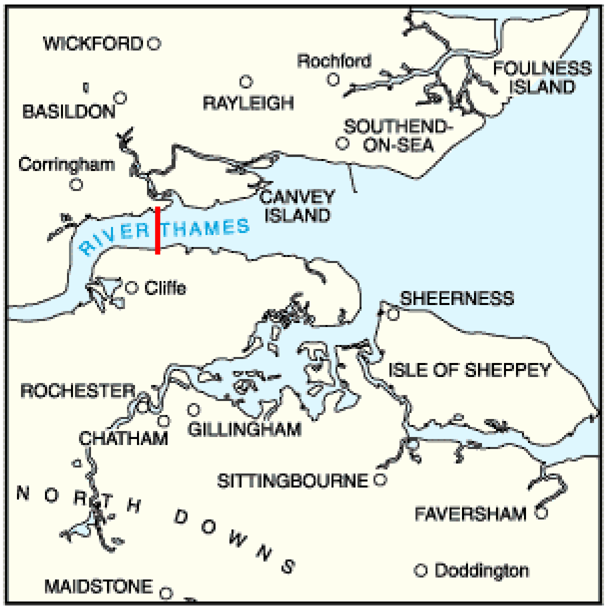


Figure 3.12: Indicative Location of the surge tide barrier and tidal power plant in the Thames estuary (reproduced from: An Integrated Lower Thames Tunnel solution for the Thames gateway, Metrotidal Ltd., 2008).

The initiative is being promoted by the Metrotidal consortium and is termed a 'tunnel-barrier-island system' that is intended to link the Medway coast (in the county of Kent) to

Canvey Island (in the county of Essex). The scheme is estimated to cost between £2B and £4B.

The proposals include a dual carriageway highway and twin track railway in an immersed tube tunnel. The renewable energy is generated from an elliptical-shaped tidal lagoon located between the navigation channel and the south bank of the estuary, impounding an area of some 4,75km^2. The lagoon is connected to shore by an embankment, within which the hydropower plant-house is constructed. This embankment forms part of the tide surge barrier which also extends across other reaches of the estuary, leaving the navigation channel open. The restrictions on tidal flow imposed by the barrier are claimed to reduce the tidal range upstream, thereby reducing flood risk further upstream. The estuary cross-section would be reduced by 80% in width during high tide conditions by these arrangements. It has been suggested that material requirements for the embankments could be 'beneficial use' of material that will be dredged from the estuary bed for the construction of the London Gateway Container Port. Proposals also include wind turbines within the tidal lagoon.

It is argued by Metrotidal that the revenues generated from road tolls, passenger and freight rail tariffs, tidal and wind power sales, and funding savings for equivalent alternative ways of providing the same standards of flood alleviation make the proposals economically viable.

4 UNITED KINGDOM: PRINCIPAL ISSUES AND LESSONS LEARNT

4.1 Introduction

In the UK, there appear to be two aspects that are of great relevance on tidal range technology:

- Economic and commercial viability;
- Environmental impacts.

These two issues will be described more in detail in paragraphs below.

4.2 Economic and commercial viability

4.2.1 General information

The main factors identified from the review which affect the economic and commercial viability of tidal range energy generation in the UK are:

- The size and accessibility of the tidal range energy output;
- The amount of electricity which can be generated by a scheme;
- The ability to transmit this electricity to consumers;
- The cost of constructing, maintaining and decommissioning the scheme;
- The actual cost of the electricity produced; and
- The competitive sale price of the electricity produced.

For some renewable energy schemes, such as tidal stream devices, wave converter devices, offshore wind farms, and tidal lagoons, the high capital and operational costs are, in part, due to the technology being relatively immature. Consequently, further centralised investment is required to develop pilot technologies, undertake laboratory testing, and enable field deployments at ‘demonstration site’ scales, particularly with respect to tidal lagoons.

However, the above is not really a valid reason for lack of uptake of tidal barrage technology where:

- The necessary maritime engineering works (such as caissons, turbines, cofferdams, scour protection, grouting, fish passes, locks/sluices/gates, sheet piling, mechanical and electrical engineering, embankment construction, dredging and so on) are highly conventional; and
- The turbine technology is similar to that which is well proven in hydro-power technology. Consequently, overcoming the cost barrier in relation to tidal barrage technology is likely to depend on Government-awarded concessions to encourage development and on maximising benefits from such schemes by drawing in other attributes and values, such as incorporated road links, amenity aspects and improved flood alleviation elsewhere in the estuary system.

In assessing the commercial viability of a scheme, the above factors are used in ‘conventional’ economic analyses.

However, the commercial viability of a scheme may be deemed greater if a wider range of economic benefits could be incorporated, such as:

- Temporary and permanent job creation through the construction and operation of the scheme;
- Wider economic benefits, such as regeneration opportunities and improved transport networks;
- Improved recreation and educational potential;
- Innovation and job creation throughout the supply chain.

A scheme would have positive regional economic and employment benefits, whilst additional impacts may also accrue within the UK and internationally. A larger scheme is centrally estimated to bring a net annual average of 1500 additional jobs during a construction period of up to 10 years; a smaller scheme would be closer to 500 jobs annually over 5 years. Operation of a scheme would create additional jobs both directly and indirectly, estimated to be up to an annual average of 200 for a large scheme and up to 50 for a small one. These figures are net of estimated negative impacts on, for example, employment in ports and fisheries in the Estuary and surrounding area.

It can be concluded that to encourage development and maximise benefits other attributes and values can be drawn in, such as incorporated road links, amenity aspects and tourism and improved flood alleviation elsewhere in the estuary system. Road links, tourism and improved flood alleviation are only interesting in the case of tidal barrage. Amenity aspects can be possible with tidal lagoons as well.

Tidal energy schemes could also improve flood alleviation elsewhere in the estuary system by protecting against storm surge flooding from the sea. In the Severn estuary it has been considered but further investigation is needed.

The above aspects are all undoubted potential economic benefits associated with tidal range schemes, but would need a broader range of financial contributors (and benefactors) than the power generation company alone. For example, the commercial viability could be improved if a Regional Development Agency or Regional Governmental body part-funded the scheme to gain the short- medium- and long-term benefits from job creation, regeneration and improved transport links.

4.2.2 Cost of constructing and maintaining the scheme

The costs of a tidal energy scheme consist mainly of investment costs (constructing costs) and costs for operating and maintaining the scheme. The capital costs are dominated by the cost of the scheme itself. Table 5.1 summarises the capital costs and unit cost per kWh production from a selection of the case studies for which information is available. The capital costs of small schemes such as the Loughor Barrage is estimated 25 million Euro, the capital costs of realizing the Severn scheme will be higher, around 17000 million Euro or around 2 million euro per MW. The unit cost of generation for the Severn, with a discount rate of around 6% is estimated approx. 7,5 eurocent / KWh. For a smaller scheme such as Loughor Barrage around 12 eurocent/KWh (Sustainable Development Commission, report 5, 2007).

For offshore wind parks in the Netherlands the unit cost of generation are approximately 15 eurocent / KWh. The investment costs around 2 to 2,3 million euro per MW (EWEA, 2009).

Tidal barrages, such as the large schemes such as Severn and Mersey, give a competitive sale price of electricity. This is because it is possible to find a site for the barrage in the estuary where tidal difference and basin are large, increasing the energy gain and a small barrage length, reducing the cost. For the Severn and Mersey (the larger schemes), the private sector would not have the capacity to finance or build the scheme without Government sharing some of the risks (and costs) involved.

As the length of the barrage with tidal lagoons is relatively large, the cost of the barrage is large compared to the tidal barrage. As for smaller schemes are less viable because the potential energy output is less cost efficient. The sale price is not viable without subsidies.

For smaller schemes and lagoons, the private sector is likely to be able to own, finance and take on most, if not all, construction risk (i.e. one with a construction cost of <£4bn) but government can participate in providing subsidies.

Table 4.1: Capital Costs and Unit Cost of Generation of Selected UK Case Studies (Sustainable Development Commission, report 5, 2007).[1]

	Details		**Unit cost of generation (eurocent/kWh)**			
	Installed Capacity	Capital cost	Discount rate			
SCHEME	(MW)	(mill. €)	3,5%	8%	10%	15%
Mersey Barrage	700	1600	6,24	13,15	16,92	28,42
Severn Barrage (Cardiff-Weston)	8640	13700 – 19100	4,90	9,57	12,25	20,52
Severn Estuary (Shoots)	1050	1600 – 1900	4,32	7,59	9,42	14,92
Swansea Lagoon	60	87 **	2,20 (9,32)	4,45 (19,71)	5,50 (24,55)	8,22 (28,64)
Russell Lagoons (assumed 3 No.)***	2835	7500	5,43	12,69	16,64	28,64
Liverpool Bay Lagoon	340	712	3,33	6,43	9,26	14,74
Loughor Barrage	5	25	7,48	15,54	19,44	29,93
Duddon Barrage	100	443	8,04	16,53	20,69	32,04
Wyre Barrage	64	148	5,76	11,17	13,77	20,65

* Original table was presented in pounds. Exchange rate of 12-10-'09 was used for the determination of the presented values in euro's (exchange rate October 2009, 1 pound is 1,0717 euro).

** An independent review placed costs at 273 million euro. The figures stated are from Tidal Electric Limited. The figures in brackets are from an independent review.

*** The Bondi report considered only 1 of the 3 lagoons proposed by Russell. Other studies have simply multiplied the energy output capacity/costs etc. by a factor of 3 (as presented here)

4.2.3 Carbon payback

An advantage of implementing a tidal power plant would be the reduction of the amount of CO_2 produced per amount of energy. The embodied CO_2 values for materials have been taken from the "Inventory of Carbon and Energy" document from the University of

[1] As projects have different statuses (see table in chapter 3), some trends mentioned in the text (lagoon is more expensive, larger schemes are more profitable) are not visible.

Bath[2]. As the quantity of energy produced from the barrage is high, while the amount of carbon dioxide produced per kWh of energy during operation is low, subsequently a low carbon payback period is expected. The absolute accuracy of these figures is not considered essential as there is between one and two orders of magnitude between the lifecycle emissions of the barrage options and those of conventional power plants.

The carbon pay back period is calculated as follows:

$$T = \frac{I_{CO2}}{E \cdot (p_{con} - p_{tidal})}$$

T carbon payback period [year]
I_{CO2} CO_2 used during construction [ton CO_2]
E annual energy production [kWh/year]
p_{con} CO_2 production of conventional power plants [ton CO_2/kWh]
p_{tidal} CO_2 production of tidal power plants [ton CO_2/kWh] (assumed: 0)

The following tables provide the breakdown for the embedded carbon in the Cardiff-Weston barrage and the Shoots barrage.

Cardiff-Weston embodied carbon

Table 4.2(1): Cardiff-Weston Embedded CO_2

Cardiff-Weston		
	Quantity (tonnes)	**tonnes CO_2**
CAISSONS		
Concrete		
Cement	2,900,000	2,378,000
Fine Aggregate	5,000,000	26,500
Coarse Aggregate	9,200,000	73,600
Rebar	900,000	1,548,000
EMBANKMENTS & FOUNDATIONS		
Rock	16,300,000	342,300
Sandfill	29,100,000	154,230
Roadworks	400,000	56,000
Fabricated Steel	200,000	364,000
TOTAL CO_2 (tCO_2)		4,942,630
Total Energy production over lifetime (TWh)		2,040
CO_2 emissions gCO2/kWh		**2.42**

n.b Quantities taken from STPG 1989 report[28]

[2] The data that have been used to calculate the embedded carbon have been cross-checked by experts in the UK, and in general it has been found to be a good match with other sources.

The Shoots embodied carbon

Table 4.2(2): English Stones Embedded CO_2

English Stones		
	Quantity (m^3)	CO_2
CAISSONS		
Rock dredging for foundations	720,900	38,074
Rockfill mattress/foundations	46,970	2,481
Turbine/sluice caissons concrete (pre-cast)	171,240	88,360
Sluice caissons concrete (pre-cast)	38,660	19,949
Ship lock concrete	94,135	48,574
Grout (assumed motar)	61,563	35,301
Sand ballast	504,921	4,683
Concrete placed under water	116,952	60,347
Concrete placed between tides	104,698	54,024
EMBANKMENTS		
Rockfill	2,020,000	106,686
Sand fill	2,210,000	20,498
Armouring - seaward (assumed rock)	369,600	19,520
Armouring - basin side (assumed rock)	201,600	10,648
Filter membrane (assuming rock density)	667,800	13,436
TOTAL CO_2 (tCO_2)		522,581
Total Energy production over lifetime (TWh)		330
CO_2 emissions gCO2/kWh		**1.58**

The energy payback associated with the Severn Barrage can be calculated in relation to the amount of CO_2 that would otherwise be produced from using the energy that comes from the electricity grid (Option A represents a general mix of energy sources) or electricity generated from combined cycle gas turbines (Option B). Based on this the CO_2 payback period is shown in the Table below.

	Cardiff Weston	English Stones	units
Average Annual Energy	17.00	2.75	TWh/year
$CO_{2\ emissions}$	2.42	1.58	gCO2/KWh
CO_2 saved (assuming grid supply uses 430gCO2/KWh)	427.58	428.42	gCO2/KWh (saved)
CO^2 Payback (A)	**8.16**	**5.32**	**months**
CO_2 saved (assuming CCGT generated electricity 329gCO2/KWh)	326.58	327.42	gCO2/KWh (saved)
CO^2 Payback (B)	**10.68**	**6.96**	**months**

So the table shows that within a year after starting operation the cumulative CO_2 production of the UK is lower than it would be without the implementation of a Severn Barrage.

Carbon Payback of Severn Barrage 11/03/2009
http://www.european-waternews.com/news/id474-Carbon_Payback_of_Severn_Barrage.html#
The payback period of carbon costs induced by the production, transportation and construction of the materials to be used at the Severn Barrage would be less than six months, according to a recent study published in CIWEM's Water and Environment Journal.

The Severn Barrage project is the largest single source of renewable energy available to the UK, with the estuary providing one of the world's best opportunities to harness energy from tides. A barrage of 16km long would provide 5% of the UK's annual electricity demand, which is 25% of the UK target to cut emissions by 2020. This is similar to that of all other renewable energy projects currently operating in the UK. A major concern for all forms of electricity generation is their effect on carbon emissions. Renewable energy projects can be substantial in terms of the volume of equipment and land they require because they depend on low energy density sources, so the physical extent of this project is viewed by some as relatively demanding in materials and, by inference, in carbon content. The barrage would mainly be formed of reinforced concrete caissons constructed at many shore based yards and towed to the site. It would require over 200 large water turbines and electrical generators and 166 sluice gates. The carbon content of producing these materials, transporting them to plant fabrication yards, manufacturing and constructing the units of equipment, and transporting the products to site for final assembly and installation have been quantified by Charlie Woollcombe-Adams, Michael Watson and Tom Shaw FCIWEM.

In just over four and a half months the barrage can be expected to have paid back the carbon costs incurred from the sourcing of materials, manufacture of components and their transportation to the barrage site. When including the on-site works used to construct the barrage, this increases the payback period to five and a half months. Constructing the Severn Barrage would take about nine years but power generation could begin before the barrage is completed as long as it is 'closed'. Hence the barrage could begin its carbon payback when still incomplete and less than a year of operating at 85% annual output, it will have paid back the construction-related costs of the whole project. Compared with its construction, the annual carbon cost of its operation is nominal. No energy intensive activities are involved as it should need little more than low-intensity maintenance during its expected 120 year lifespan.

The authors say:
"The technical simplicity and reliability of tidal power schemes is dwarfed by the complexity of their political realisation, not least when environmental legislation is being tightened at a time of growing international concern about the security of energy supplies and, paradoxically, their predicted serious environmental effects. In time honoured fashion, the decisions that have to be taken must be based on facts and rational debate. This paper adds an important dimension to that process."

4.3 Environmental impacts

By default, the very environments best suited to tidal range technologies (e.g. high tidal range, semi-diurnal tides) are by virtue of these characteristics also the very environments with high intrinsic nature conservation value due to the presence of expansive inter-tidal landforms and associated habitats and species. There can be no doubt that construction of a tidal range device will have an adverse impact on these features. The key question is over what spatial scale.

For example, the application of tidal lagoon technology may, due to its (likely) smaller ‘footprint’ of deployment, have a lesser impact than a tidal barrage, principally because the natural system is not entirely truncated as it is by a barrage and can at least still partially function.

Once the type and scale of impact is understood, then government must make a decision as to whether promoting such a scheme (with its undoubted benefits) is of overriding importance compared against the undoubted impacts.

Due to the importance of the environmental impacts in limiting uptake of tidal range technology to date in the UK, some of the principal recurring issues are described further below in a generic sense, with some specific case study examples provided in Annex B of the Annex report.

Many of the environmental issues identified in the case studies consulted in this review are generic to most developments in coastal or estuarine waters (i.e. not only tidal range technologies but also port construction, reclamation, etc.). The footprint of large engineering structures and the methods used to install them are frequently similar across disciplines; e.g. changes in geomorphology and physical processes, disturbance, habitat loss, and deterioration of water quality often occur as underlying themes. All these can have either direct or indirect effects upon flora and fauna, or the geomorphological landforms on which they rely. The following paragraphs provide an outline summary of potential cause and effect relevant to tidal range proposals.

4.3.1 Geomorphology and physical processes

The construction of a tidal range scheme in an estuary or in coastal waters will have an impact on the geomorphology and physical processes. The schemes are purposely designed to impound water and release it through turbines during the ebbing tide once a differential in head has been established. This directly alters the tidal processes and in turn can alter the patterns and rates of sediment erosion, transport and accretion, thereby changing the morphology of the system. Some schemes will truncate the length of an estuary, causing major direct change in its geomorphology and processes. This could have knock-on effects wider throughout the whole system.

Studies on the Severn estuary have shown that a large barrage between Cardiff and Weston would result in a raising of mean upstream water levels by some 2,5 to 3m in ebb-generation mode and a greater than 50% reduction in the upstream tidal range to 4,5m on spring tides and 2,5m on neap tides (STPG, 1986). High water height would be reduced by as much as 1m on spring tides but approximately 0.5m on neap tides. The tidal influence downstream of such a barrage showed a slight reduction in high water and raising of low water, resulting in a net reduction in tidal range of around 1m in the sea outside the barrage. This effect diminishes with distance away from the barrage, but was still predicted at distances of around 100km seaward, indeed a reduction of 0.05m in tidal range was predicted at Morte Point (Department of Energy and Climate Change, 2009).

The changes in tidal range will result in a large change to the exposure of intertidal flats in the estuary, although this may be reduced through mode of operation and/or lagoon configuration. Flora and fauna, in turn will be impacted if the geomorphology changes. This is considered as one of the greatest adverse impacts associated with tidal range schemes in the UK due to the heavily protected nature of many inter-tidal areas, through international designation, reflecting the importance that society places on these features.

4.3.2 Primary productivity

Light penetration of the water column is a function of the water turbidity and, since turbidity is likely to decrease within an impounded basin compared with the open estuary, it is possible that phytoplankton productivity within lagoons may increase. Whilst such increases in productivity may be beneficial, it is possible that certain phytoplankton species may bloom (increase in abundance) to problem levels. Such species include "red tide" phytoplankton, which produce toxins harmful to humans, and *Phaeocystis*, a common UK species that forms a frothy scum in marginal areas when present in the water in high concentrations. Without complete and regular flushing, elevated production could also be enhanced by increased nutrient levels within lagoons or holding areas, and predicting the conditions that could lead to such changes would be essential.

Saltmarshes and other intertidal areas play an important role in estuarine ecosystems. Saltmarsh in particular acts as a potentially significant source of detritus for the food chain and as a sink and source of sediment for adjacent exposed intertidal areas. They also provide an important habitat for a range of specialist flora and fauna that are adapted to the variety of environmental conditions that occur within the natural environment. Because of their ability to stabilise sediments and dissipate wave action, saltmarshes also provide protection from shoreline erosion where present. Changes in the tidal regime and wave climate arising from lagoon or barrage development may lead to alterations in the extent and composition of saltmarshes in an estuary or low energy coastal environment, particularly if they had become established on a large scale.

The development and management of saltmarsh habitats is an important issue in national and European conservation policies and guidelines. Subsequently, such habitats are often protected under designation as a Special Area of Conservation (SAC) in accordance with the European Habitats Directive.

4.3.3 Invertebrates

Estuaries and inshore waters may contain stocks of shellfish that are of commercial importance to fisheries and there are specialised estuarine invertebrate species and communities that are of intrinsic conservation interest because of their restricted distribution.

The main reason for examining the invertebrate populations in the context of tidal power is the crucial part they play in the estuarine food chain. A large number of invertebrate species in and on the sediment and in the water column feed upon the abundant detrital matter, and less abundant primary plant material, making these energy and nutrient sources available to the fish and bird populations that feed upon them.

It is not clear what impact tidal range systems would have on invertebrate populations. If the tidal phase in intertidal areas changes significantly then there are likely to be significant changes in the invertebrate population.

It is also possible that changes in sedimentation in adjacent open estuary or coastal waters will have an effect on the distribution and abundance of invertebrate communities. The extent to which this could occur would need to be determined through a combination of sediment transport and ecological modelling.

4.3.4 Fish

Estuaries are at the interface between salt and fresh water and provide important feeding, breeding and nursery areas for a wide range of fish species. In addition, there are migratory species of fish that pass through inshore waters and estuaries in order to complete their life cycle. Many migratory fish species are of conservation significance by virtue of their rarity or geographical isolation, and some form the basis of valuable fisheries (and therefore lead into potential socio-economic effects).

Species of conservation significance in the Severn Estuary include the salmon, allis shad, twaite shad, bass, European eels, sea lamprey and river lamprey. The management and conservation of salmonid species, especially salmon is nationally important and subject to significant time and effort by the Environment Agency in accordance with European and UK legislation, policy and guidelines. Similarly, other estuaries in the UK are also affected, although the species assemblage may change; however, salmonids, eels and lampreys are commonly found in UK rivers and coastal waters.

Although tidal lagoons may not affect fish populations to the extent that a barrage might there are important considerations to take into account. Firstly, fish could be drawn through turbines where they will be subject to potential damage from turbine blades (Solomon (1988)). A possible solution is the use of behavioural barriers, such as lights or sound fields, that would discourage fish from entering protected areas around the barrage; however, work in this area of research is still at an early stage, and deterrence of sensitive species (inc. sea mammals) by noise propagation underwater has been the subject of much debate in the EIA of offshore wind projects.

Migratory fish are known to respond to changes in river flows (Moore et al. (1998), Priede et al. (1988), Creutzberg (1961)). It is possible that periodic flows caused by banks of turbines generating on the ebb tide may present a disruptive stimulus to them (Sustainable Development Commission (2007d)).

4.3.5 Birds

The extent and diversity of habitats in UK estuaries provide significantly important winter feeding grounds for up to 1,5 million European wading birds and wildfowl. Many of the estuaries suitable for tidal power generation are acknowledged to have nationally or internationally important over-wintering populations. The use of habitat within an estuary varies from species to species, some using salt marsh and surrounding fields for roosting areas and the mudflats as feeding grounds, and some roosting on mudflats whilst feeding in salt marshes or fields.

The construction of a barrage or lagoon system has the potential to affect birds in several ways, for example:

- Loss of existing intertidal feeding resources where areas may become permanently submerged;
- Other areas may be exposed for an altered period thus affecting feeding opportunity;
- The nature of the sediments may change, altering the abundance, distribution and diversity of the invertebrate prey species;
- Safe roosting areas may be lost; and,
- Increased recreational pressures may lead to greater disturbance.

Before the numbers and distribution of birds can be predicted for a post-barrage estuary or a lagoon development it is important to obtain a baseline and to understand how they use the existing estuary. Studies on the Severn Estuary for example have confirmed that bird populations are highly variable, both between winters and within a single winter, and that birds are very unevenly distributed from year to year. Predicting the effects lagoon systems could have on bird numbers will depend on the extent and location of intertidal areas they will affect. If the lagoon completely displaces an intertidal feeding area then the bird population will be displaced permanently and this would be unacceptable to current environmental legislation except in extreme cases where unavoidable over-riding public interest could be demonstrated.

The links between sediment type, invertebrate and bird distribution need to be established and other factors also need to be taken into consideration; e.g. climate change can be expected to further complicate estuarine ecosystems partly because of predicted increases in extreme conditions but also because sea level rise will alter the intertidal areas and sediment distribution.

4.3.6 Marine Mammals

The presence of significant impediments to movement within an estuary, such as a barrage or a collection of tidal lagoons, could have a serious impact on marine mammals. They may be prevented from using their usual routes or blocked from important breeding or feeding grounds. The presence of tidal stream devices is less likely to have a serious impact, although it is possible that marine mammals may need to take significant detours around large farms. The presence of a tidal development may result in displacement of marine mammals from the area, although a level of habituation to the structure may occur.

Marine mammals may be able to detect and avoid tidal energy schemes, as they are able to perceive the underwater environment well, and are very agile. This may not be the case for older or diseased animals which are less agile and have a lower ability to understand and react to changes in the environment. Juvenile mammals may have a high level of curiosity coupled with less experience, and may also be more vulnerable as a result. The placement of tidal stream devices in fast flowing water may also reduce the ability of marine mammals to avoid them. In addition to this, if tidal energy schemes act as refuges for fish and other prey items, marine mammals may be attracted to them.

Noise produced during scheme operation may assist marine mammals in detection and avoidance, or it may result in avoidance of the area and the consequent displacement of sensitive species.

4.3.7 Landscape and seascape implications

The development of both tidal energy lagoons, and tidal barrages would be expected to take account of impacts on the landscape. Visual impacts of tidal generation schemes will be greatest for those with structures which pierce the sea surface. For all types of technology there will be the requirement for land-based structures such as sub-stations and landward transmission lines, and the possibility of infrastructure developments such as ports, housing and road networks which will impact the coastal landscape value. The level of the effect will depend on the characteristics of the seascape; placement of tidal generation schemes in 'pristine' seascapes is likely to have more of an effect than their placement in an area which already has a significant level of visual impact [55]. Similarly, areas of coastline with high amenity value (for example, exceptional coastal views) may be more affected by the placement of a tidal generation scheme than other areas.

Visual impacts are not just associated with the device itself during operational stages of development. Construction, maintenance and decommissioning stages of tidal developments will also have associated temporary visual impacts as a result of the use of specialist ships/barges and heavy machinery.

In the UK, a full landscape/seascape character assessment would be required, including photomontages from key viewpoints and areas of high use within an identified Zone of Theoretical Visibility (ZTV). Assessments would also need to take account of cumulative impacts; for example, overhead grid connection or access roads. If developments were close to an area with a landscape designation such as an Area of Outstanding Natural Beauty (AONB) or a National Park, an account of development policies and planning guidelines that relate to those designated regions would be required.

4.3.8 Potential climate change impacts

The potential for climate change to impact on existing and developing energy generation technologies, especially those in coastal environments, is necessary when developing strategies or projects with a long term design life. Renewable energy generation is generically perceived as being sensitive to envisaged climate change effects due to its dependence on the prevailing weather patterns and / or vulnerability to sea level rise or increased storminess where sediments in suspension, or near field sediment movements could affect the maintenance or service life of turbines or sluices. The range of sea level rise by the year 2100 reported from the IPCC (Intergovernmental Panel on Climate Change) varies between 0,18 m-0,59 m dependent upon the various assumptions made during the analysis (Intergovernmental Panel on Climate Change (2007)).

4.3.9 Environmental impacts on lagoons

The environmental impact issues described are especially valid for tidal barrage schemes. Great geomorphologic alterations are expected, causing changes in the following elements of the ecologic system:

- Phytoplankton;
- Invertebrates;
- Fish;
- Mammals;
- Birds.

For tidal lagoons the kind of effects on the ecology (phytoplankton, invertebrates, fish and birds) are the same as with a tidal barrage. But a big advantage of these alternatives is the flexibility of finding a location. Therefore area's can be chosen that have less impact on the environment than tidal barrages.

The links between sediment type, invertebrate and bird distribution need to be established and other factors also need to be taken into consideration; e.g. climate change can be expected to further complicate estuarine ecosystems partly because of predicted increases in extreme conditions but also because sea level rise will alter the intertidal areas and sediment distribution.

4.4 Role of the Government and Legislation issues

Role government

Government intervention should be necessary to promote a scheme, placing costs on consumers and/or taxpayers. All schemes should require Government support through planning and possibly construction due to the sheer scale of capital costs and impacts. As for most renewable energy generation, consumer-funded revenue support would be needed to make for example the Severn tidal power scheme commercially viable (Department of Energy and Climate Change, 2009).

The private sector is likely to be able to own, finance and take on most, if not all, construction risk for a smaller scheme (i.e. one with a construction cost of <£4bn). For larger schemes, the private sector would not have the capacity to finance or build the scheme without Government sharing some of the risks (and costs) involved. Possible delivery options according to the Severn Tidal Consultation (2009) are:

For smaller schemes (costs up to 4 billion euro):

- Fully privatised – privately owned and delivered, supported through a fixed-price or variable revenue support mechanism.
- Public Private Partnership – where the private sector would construct, finance, and operate the barrage under contract to Government for a fixed period from the commissioning of the asset. This would be supported through a fixed price revenue support mechanism.
- Regulated Concession – A private operator develops the asset under the oversight of a regulator which is appointed to oversee the price at which the electricity output could be sold. A regulated fixed price revenue support mechanism would be used to support this option.

For larger schemes (costs over 4 billion euro):

- Government-financed construction then privatised – Government recoups investment when the asset is privatised post-construction. A revenue support mechanism provided to allow the private sector owner to recoup costs.
- Government-financed construction then franchised – Government recoups its investment when the asset is sold as a franchise post-construction. A revenue support mechanism is provided to allow the private sector owner to recoup costs.
- Government-financed construction then regulated concession - Government recoups its investment when asset privatised as regulated concession post-construction. A fixed-price revenue support mechanism is provided to allow the private sector owner to recoup costs.
- Multiple Public Private Partnerships (PPP) – Government appoints an integrator to deliver the project through a series of linked Public Private Partnership contracts. The PPP contractors would operate the asset through a contract with Government for a period of 35 years. This would be supported through a fixed price revenue support mechanism.
- Regulated asset – A stand-alone regulated Company is created to construct and own the scheme, capitalised by Government and benefiting from a certain amount of Government support (primarily guarantees of debt finance).

Legislation

The Sustainable Development Commission's report, although supporting a sustainable Severn Barrage (Cardiff-Weston), acknowledged a number of issues that would have to be addressed before a Severn project could be built, including an open and transparent assessment of pros and cons, compliance with environmental protection legislation and Government ownership of a scheme given its high costs and long operational lifetime.

Relevant European legislation is the European Water Framework Directive and the European Fisheries Directive, EU Marine Strategy and the European Habitat and Birds Directive (Natura 2000).

Natura 2000 is a coherent, European wide ecological network of protected sites recognised as supporting the most important wildlife habitats and species of animals and plants in Europe. Each country within the European Union has the responsibility to designate sites as Special Areas of Conservation under the Habitats Directive, for sites supporting specific habitats and/or species, and Special Protection Areas under the Birds Directive, for sites with priority bird species.

Relevant UK legislation is the Renewable Energy Strategy. Political agreement has been reached on a UK target to deliver 15% of the energy from renewable sources by 2020. This is a challenging goal. In 2007, only around 1,78% of UKs final energy consumption came from renewable sources. To meet the proposed 2020 targets, UK has to increase the proportion of our energy coming from renewables ten-fold from 2007 levels.

4.5 Discussion on results from interviews with experts

During the study we have contacted several experts. The interview reports can be found in Annex D of the Annex report.

Below some of the most important aspects mentioned by the experts are described. In general, a large part of the comments are related to the knowledge of the experts on the Severn estuary. The following experts has been spoken with:

- Prof. Roger Falconer. He is Halcrow professor water management at Cardiff University.
- Roger Morris. He is a Senior Policy Specialist in Ports & Estuaries within Natural England's Policy Team.

Economic and commercial viability

- Costs are a concern. Many people believe that there a better investments. It is noted that the government is not expected to invest in the (Severn) barrage and private investors are expected to participate in the barrage project.

- The barrage would bring a lot of development (housing, airports and tourism). On one hand this is a benefit, on the other hand, for some persons this is a major concern.

- There is a lot of opposition from groups from other estuaries. They fear that if this (Severn) barrage is built all the other estuaries will get barrages.

- Smart design could help to overcome some of the principal issues on tidal energy:
  - a two way tidal generation. This alleviates some of the issues and could reduce the intertidal habitat loss;
  - Modern turbine design. Fish migration can be reduced by modern turbine design and fish passes and well designed sluice gates.

Environmental impacts

Much debate in the UK has focused on possible ecological and water quality implications (both positive and negative) of proposed barrages and lagoons, especially with respect to implications for migratory birds. The river Severn f.i. is a migratory river (salmon, and other types). However, reliable assessment of these implications is critically dependent upon interpretation of geomorphological evolution following barrage construction.

Estuaries are the best locations to realize tidal energy. High flow energy and high tidal levels make the estuary unique. Changing this raises many issues. Principal issues to deal with in those areas are a loss of intertidal habitats. As a result several rare birds would be lost. Also, the area is protected by EU regulations.

The critical relationship that emerges from analogues with other schemes (both tidal energy barrages and other forms of structure such as storm surge barriers and barrages) is between sub-tidal deposition environments and the effects of wind-driven wave erosion within the inter-tidal zone.

Geomorphology and sedimentation

- With respect to geomorphological aspects, the form of an estuary is directly related to the levels of energy imparted upon it. If there are changes in energy then the estuary will respond, or try to respond. There are numerous analogues for this – including the Dee Estuary in north-west England which has experienced considerable in-filling following foreshortening due to canalization and the Wansbeck estuary in north-east England which has experienced siltation following construction of an amenity (lake impoundment) barrage.

- Erosion by wind-driven waves leads to sediment suspension and subsequent deposition in deeper sub-tidal water where reduced tidal propagation also limits re-mobilisation that is needed to return sediment onto the inter-tidal environments during sediment-building phases.

- In summary, geomorphological implications of barrage schemes have not adequately been addressed, particularly in relation to impacts on salt marshes and mud flats (including changes in tidal range and changes in suspended sediment supply to these areas) and impacts on geological conservation (e.g. submergence of features, impeded access to view features, direct impacts of engineering works). There is greater need for 'top-down' geomorphological approaches (such as those reported in EMPHASYS) to be employed at an earlier stage on schemes so that the longer-term geomorphological implications can be more readily assessed. Such approaches should be used to (1) develop a conceptual understanding of the estuary system and (2) assess how it will respond to the perturbation introduced by construction of a barrage.

- There is perhaps more need to also consider implication on the following topics: geomorphology (particularly top-down approaches such as regime modelling and EGA), floating debris (causing blockages and operational downtime), water quality (shifts in salinity gradients, implications for diffuse pollution) and fish (species and population age distributions).

Stakeholder involvement (mainly based on information about the Severn estuary)

- British government is handling this (Severn) project well and all relevant parties have been involved from an early stage.

- This is not a party political issue. The large parties have a neutral position and await results of studies.

- There are expert panels in all relevant fields, e.g. modelling, environmental issues. The strategic environment committees include members of environmental groups. There are talks of bringing in international expertise (hydro environmental, fish etc.). Several workshops covering all relevant topics are organized.

- There is a lot of support, even from some environmental groups. They are supporting idea of sustainable energy generation while aiming to minimize the impact.

Further research necessary?
On the whole there is sufficient information to make (engineering) decisions. However, there are a number of fields that require more research: a) limited knowledge of fish migration and interaction between fish and turbines; b) dynamic interaction sediment – water quality; bio kinetic processes c) ground water effects. In a later stage mitigation measures could be taken based on knowledge that is developed during the project.

4.6 Summary principal issues and lessons learnt

General
The UK is well suited to generating energy from its tidal resource since it has high tidal ranges and high tidal currents in much of its nearshore waters. It has been estimated that tidal energy in the Severn estuary could produce more than 5% of the UK's electricity needs.

Tidal range technologies previously considered in the UK comprise both tidal barrages and tidal lagoons. Both technologies have been considered as concepts for several decades, but no single scheme has yet to be implemented in the UK. Optimum locations for tidal range technologies in the UK are in the Irish Sea, the Severn Estuary/Bristol Channel, the Wash, the eastern English Channel and around the Channel Islands.

The main constraints on scheme implementation have been:
- (i) Cost of energy;
- (ii) Environmental impacts.

Economic and commercial viability
The main factors identified from the review which affect the economic and commercial viability of tidal range energy generation in the UK are:

- The size and accessibility of the tidal range resource;
- The amount of electricity which can be generated by a scheme;
- The ability to transmit this electricity to consumers;
- The cost of constructing, maintaining and decommissioning the scheme;
- The actual cost of the electricity produced; and
- The competitive sale price of the electricity produced.

Commercial viability of a scheme may be deemed greater if a wider range of economic benefits could be incorporated, such as:

- Crossing (improved transport networks);
- Leisure and Tourism (Visitors centre on Tidal energy), amenity and educational potential;
- Flood control (decrease flood risks elsewhere in the estuary);
- Temporary and permanent job creation through the construction and operation of the scheme.

Costs
Capital costs of small schemes such as the Loughor Barrage (5MW) is estimated 25 million Euro, for the Severn (8640 MW) 17000 million Euro or approx. 2 million euro/MW. The unit cost of generation for the Severn, with a discount rate of around 6% is estimated approx. 7,5 eurocent / KWh, for Loughor around 12 eurocent/KWh. The unit cost of generation for offshore wind parks in the Netherlands is approx. 15 eurocent / KWh. The investment costs around 1,5 to 2 million euro per MW.

Tidal barrages, such as the large schemes such as Severn and Mersey, give a competitive sale price of electricity. Though, the private sector would not have the capacity to finance or build the scheme without Government sharing some of the risks (and costs) involved.

For smaller schemes and lagoons, the private sector is likely to be able to own, finance and take on most, if not all, construction risk for a smaller scheme (i.e. one with a construction cost of < 4billion euro) but government can participate in providing subsidies.

Carbon pay-back
Large schemes in particular could considerably reduce carbon dioxide emissions from energy supply, helping avoid dangerous climate change.

A new study from CIWEM (March 2009) showed that the Severn Barrage tidal power project would save the amount of carbon dioxide emissions created in its construction within six months.

Environmental impacts

The very characteristics that make suitable sites attractive to developers, such as large tidal range, also make them intrinsically valued for their nature conservation importance and a conflict between these aspects is inevitable. Consequently a government decision needs to be made as to whether the benefits of any scheme override any impacts.

The main issues that have caused concern on previous schemes are relatively common and include:

- Changes in geomorphology and processes – including sedimentation and associated impacts on navigation and dredging.
  - Impact on patterns and rates of sediment erosion, transport and accretion, thereby changing the morphology of the system. In turn, impacts on flora and fauna.
  - Studies of the Severn estuary show:
    - Rise of mean upstream water levels
- Turbidity and primary productivity (algae)
  - Decrease of turbidity and increase of phytoplankton productivity.
- Invertebrates
  - Negative impact on fisheries (shellfish);
- Fish
  - Impact on feeding, breeding, nursery areas;
  - Impact on migratory species of fish that pass through inshore waters and estuaries in order to complete their life cycle).
- Birds
  - Decrease or loss of existing intertidal feeding resources ((partly) submerged).
  - The nature of the sediments may change, altering the abundance, distribution and diversity of the invertebrate prey species.
  - Safe roosting areas may be lost; and,
  - Increased recreational pressures may lead to greater disturbance.
- Marine mammals
  - Impact on usual routes to breeding or feeding grounds.
- Landscape
  - Visual impacts;
  - Land based structures (sub-stations etc).

Role government and private initiatives
There is presently much renewed emphasis on tidal range technology in the UK, with individual private initiatives, regionally-funded initiatives linked to regeneration, and central and regional government initiatives linked to national energy supplies running in parallel.

Government intervention would be necessary to promote a scheme, placing costs on consumers and/or taxpayers. All schemes would require Government support through planning and possibly construction due to the sheer scale of capital costs and impacts.

Government is consulting stakeholders in the process of tidal energy.

Legislation
The UK must reduce its carbon dioxide emissions from energy and at the same time have a secure supply of energy. UK has committed to reducing their greenhouse gas emissions by 80% by 2050 and for 15% of UK energy to come from renewable sources in 2020. Tidal power schemes would provide long term access to a renewable, indigenous energy resource.

Compliance with environmental protection legislation has to be taken into account. Legislation such as the European Water Framework Directive, European Fisheries Directive, EU Marine Strategy and the EC Habitat and Birds Directive.

In the UK proposals are being taken forward towards realisation of the tidal range energy resource based on the understanding that considerable environmental studies are required to be undertaken and that ultimately the decision about whether or not to proceed with a development may be a political one (assuming the commercial viability is proven). That is to say, despite recognising their acknowledged environmental impacts, *Imperative Reasons of Overriding Public Interest* (IROPI) may be invoked, predicated on the need to meet our energy demands from low-carbon and more sustainable sources.

Research and knowledge available
Investment is required in research and development, including laboratory testing and demonstration sites, for gaining a track record in use of tidal lagoon technology.

Tidal barrage technology is more readily deliverable through use of ‘conventional’ maritime engineering construction methods and use of core, proven, turbine technology similar to that used in hydropower schemes.

Some main effects for the various projects / plans that have been reviewed are summarized in the table below. The table indicates relative scores on different aspects.

Category SCHEME	**Capacity**	**Carbon Payback Period (relative)**	**Capital Cost (relative)**	**Job Creation**	**Tourism**	**Transport**	**Geomorphology**	**Habitats (fishes, birds, marine mammals)**	**Water Quality**	**Siltation (operation)**
Severn Barrage (Cardiff-Weston)	+++	++	+	+++	++	0	---	---	?	---
Severn Estuary (Shoots)	++	+++	++	+++	+	0	---	---	?	---
Swansea Lagoon	+	++	+++	++	0	0	-	-	?	-
Russell Lagoons (3)	++	+++	+	++	0	0	--	--	?	-
Mersey Barrage	+	++	++	++	+	+++	---	---	--	---
Liverpool Bay Lagoon	+	++	++	++	0	0	-	-	--	-
Loughor Barrage	+	+	+++	+	0	0	--	--	--	---
Duddon Barrage	+	+	+++	++	0	+++	--	--	?	---
Wyre Barrage	+	+++	+++	++	0	+++	--	--	?	---
+ positive - negative	+++ > 5GW	+++ = 0-6 months	+++ < €0.5B	+++ / --- Large ++ / -- Moderate +/- Minor 0 Neutral ? unknown / unquantified						
	++ > 1GW	++ = 6-12 months	++ < €5B							
	+ < 1GW	+ = >12 months	+ > 5€ B							

5 INVESTIGATION OF OPPORTUNITIES FOR TIDAL ENERGY IN THE NETHERLANDS

5.1 Introduction

This chapter focuses on the analysis of the opportunities for tidal energy in the Netherlands. The opportunities for generation of tidal energy will be evaluated for different sites along the Dutch coast based on:

- Existing plans to (re-) open estuaries, e.g. for Grevelingen, Haringvliet and Afsluitdijk;
- Tidal range;
- Energy yield potential (e.g. depending on tidal range, basin size and river flow);

More detailed information on tidal energy in the Netherlands is given in Annex C of the Annex report.

The first known tide mill in the Netherlands was located in Zierikzee around 1220. Historic examples of tidal tide mills can still be found in Middelburg and Bergen op Zoom. Sixteen tide mills are known to have existed in Zeeland. In the beginning of the 20th century, interest in tidal energy arose and plans were made to build a plant at the sluices of Hansweert. This plant has never been build because the machinery was produced in Germany, which just entered the First World War.

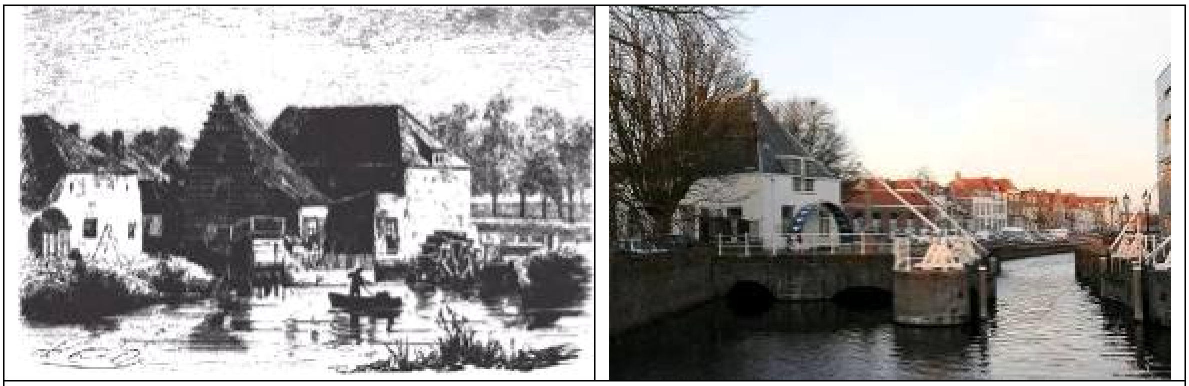


Figure 5.1 Historic tidal mill in Bergen op Zoom and historic tidal mill in Middelburg

Since recently there is an increasing interest in the development of several sources of sustainable / renewable energy. The emerging knowledge of the adverse impacts of Climate Change asks for new sustainable forms of generating energy. Development in technical knowledge in combination with an increasing price of fossil fuels, has resulted in a higher potential and demand for renewable energy methods. A method bearing a high potential of generating cost-effective sustainable energy is tidal energy.

In addition several initiatives have been undertaken to re-open estuaries that have been closed in the past. An example is the Grevelingen Lake.

In general, distinction is made between three types of generating tidal energy, including closure dams.

1. Closure Dams:
    a. Closure dams, no run-off: tidal dominated basins or estuaries (closed and open);
    b. Closure Dams, run-off: basins or rivers with a mixed influence of tide and river run-off (closed and open).
2. Existing polders and land reclamation which inhibit potential for tidal energy.

In the following paragraphs, an evaluation of opportunities is made based on several indicators for tidal energy. These indicators are than applied to the Dutch Coastal Area under the influence of tides, from Cadzand, via the Western Scheldt and the Zeeland estuaries to the North East into the Ems Dollard estuary.

In addition, a straightforward approach (formula) is presented in section 1.3, to calculate the energy potential of an area, if the tidal range, basin size and\or run-off characteristics are known.

5.2 Criteria and calculation for potential of tidal energy

5.2.1 Criteria for tidal energy opportunities

To select locations which have the opportunity for generating tidal energy, a list of criteria can be formulated. The most relevant criteria are the following:

1. Closure dams in tidal dominated basins or estuaries (closed or open):
    - Tidal Amplitude (see Figure 5.2);
    - Basin size.
2. Closure dams in basins or rivers with a mixed influence of tide and river run-off:
    - Tidal Amplitude;
    - River run-off.
3. Existing polders and land reclamation which inhibit potential for tidal energy:
    - Tidal Amplitude;
    - Polder size;
    - Ground level elevation of polder.

In the next step locations and regions have been identified to inhibit tidal energy potential. These locations have been selected based upon the following criteria, according to the list of indicators above:

- A tidal amplitude (seaward of the barrier) with a significant tidal range (>2.5m) and\or;
- A large basin behind an existing dam (resulting in significant discharge over the dam) adjacent to water under influence of the tides (i.e. North Sea or tidal estuaries);
- Polders which have been identified as possible areas of inundation[3] and have a significant tidal amplitude.

[3] In theory, every polder adjacent to the sea or estuary could be designated as a potential area of interest for generating tidal energy. However, the number of inhabitants is used to select the areas of interest as well as the ground level elevation.

The figure below shows the tidal ranges along the Dutch coastline. In red, locations are indicated which are mentioned in several plans. In blue, locations are indicated which inhibit potential for tidal energy but for which no concrete plans exist yet.

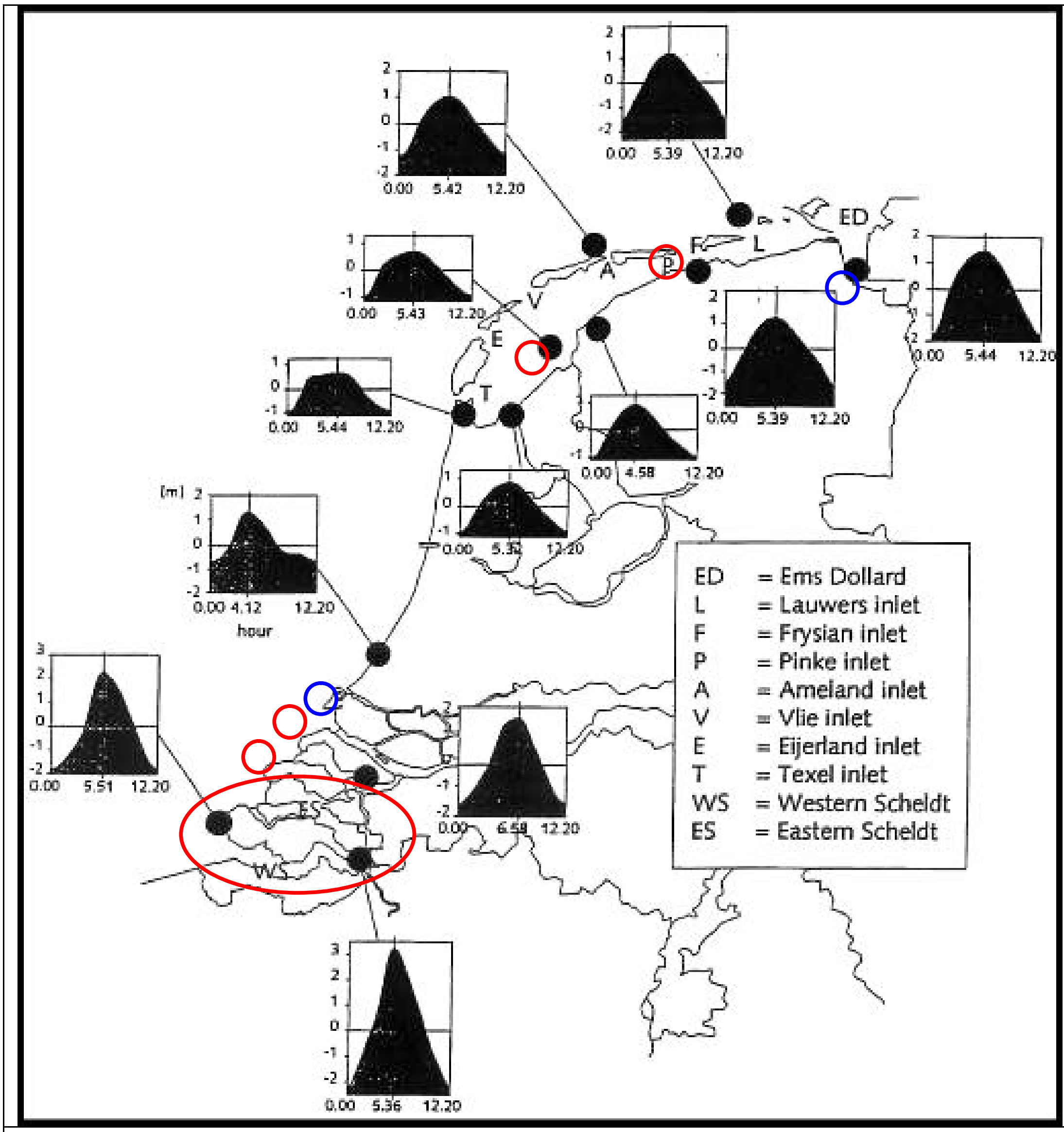


Figure 5.2 Tidal curves of stations along the Dutch Coastline. In red, areas for which plans exist. In blue locations without existing plans but with some potential

This results in the following locations which show potential for tidal range energy:

1. Closure Dams, no run-off
   a. Brouwersdam
   b. Lauwersmeer
   c. Oosterscheldekering

2. Closure Dams, run-off
   a. Afsluitdijk
   b. Haringvlietdam

3. Polders in
    c. Western Scheldt
    d. Eems Dollard estuary

The table below gives an overview of the differences in tidal range (m), river run-off (m^3/s) and basin area (m^2) for the locations as indicated in the figure above. Also a summary is given of the energy potential and installed power, see for details next sections. These figures are described in more detail in the following paragraphs.

Table 5.1: relevant indicators for tidal energy for identified areas of tidal potential.

Locatie	**Tidal range [m]**	**River Run-off [m^3/s]**	**Basin area [10^6 m^2]**	**Energy potential [GWh/year]**	**Installed Power (MW)**
Closure dams					
Brouwersdam[4]	2,5	-	117	390	94
Lauwersmeer	2,3	-	47	166[†]	32[†]
Oosterscheldekering	2,9	-	303	1706	329
Closure dams river run-off					
Afsluitdijk[5] (seaside)	1,8	500		20	13
Afsluitdijk (inside)	0,0	500			
Haringvlietsluizen (seaside)	2,4	750		57	4
Haringvlietsluizen (inside)	0,3	750			
Polder locations					
Western Scheldt: Prosper / Hertogin Hedwige polder[6]	5,0	-	13,3	64	22
Delfzijl (Johannes Kerkhovenpolder)	3,0	-	4	27	10
[†] Royal Haskoning (2002)					

5.2.2 Calculation of Tidal Energy

This section describes the theory how to calculate the energy of a tidal range energy scheme based on assumptions made for the water level variation common with tidal power plants. This method can be used to calculate the economic energy, if the tidal range and the basin area are known parameters and the amount of energy is not directly influenced by restrictions of any other form.

<u>Tidal energy – General</u>
The power which is generated by a water power plant, is calculated as follows.

$$N = \eta \cdot \rho \cdot g \cdot H \cdot Q$$

[4] Vrijling, J.K., J. Van Duivendijk, et al., 2008, Getijcentrale in de Brouwersdam, TU Delft, Delft

[5] For this, the highest tidal range along the Afsluitdijk has been used, at Kornwerderzand.

[6] Mooyaart, L.F, 2009, De Energiepolder, Haalbaarheidsstudie naar een getijcentrale langs de Westerschelde, TU Delft, Delft

N = installed power tidal plant [MW]
η = conversion efficiency of the turbine [-] (0,85)
g = acceleration of gravity [m^2/s] (9,81)
ρ = mass density [kg/m^3] (1025)
H = mean head difference [m]
V = displaced volume of water during one operation [m^3]
Q = average discharge through turbines [m^3/s]

The energy potential of a tidal energy plant can than be estimated using the volume and tidal range at the tidal plant:

$$E_{tidalcycle} = \eta \cdot \rho \cdot g \cdot H \cdot V$$

E = annual energy production [GWh / turbine operation]
η = conversion efficiency of the turbine [-] (0,85)
g = acceleration of gravity [m^2/s] (9,81)
ρ = mass density [kg/m^3] (1025)
H = mean head difference [m]
V = displaced volume of water during one operation [m^3]

Some more detail on the formulas is given below. Distinction is made between two types of tidal plants.

1. Tidal plants in basins, estuaries and polders.
2. Tidal plants making use of river run-off.

Tidal plants in basins, estuaries and polders discharge water into and out of the basin or estuary. They operate during flood tide as well as during ebb tide. The second type of tidal plant only discharges run-off water during ebb tide. This plant can be compared to a sluice with a turbine installed in it. The formula above applies to both types of tidal plants, although the details vary, see below.

Note that apart from deriving energy out of *potential* energy (also: tidal range energy), discussed in this report, also energy out of kinetic energy shows potential (also: tidal stream energy). Interesting information on tidal stream energy has been found during the course of this study, which is included in the Annex C of the Annex Report.

<u>Tidal Energy plants in tidal dominated basins or estuaries</u>
A tidal energy plant in an estuary or enclosed lagoon can operate during flood as well as during ebb. During both tidal movements water is flowing either in or out of the basin. It might be possible to just place turbines without installing any additional sluices. During one tidal cycle, a tidal energy plant with a two way system can operate 2 times. This has several advantages:

- The water level stays around MSL; as a consequence of this the water levels in the estuary are not too high to induce problems with quays, flood protection, etc.;
- A two-way operating plant fits better with plans to re-open estuaries;
- During a longer period energy is gained.

The total head difference over this kind of plant is, on average, 40% of the total tidal range. The variation of water level will be more or less 50% of the tidal range[7]. This type of tidal energy plant has a potential energy yield which can be calculated as follows:

[7] Estimates based on earlier studies

$$E = \frac{2 \cdot n \cdot \eta \cdot \rho \cdot g \cdot H \cdot V}{3,6 \cdot 10^{12}} = \frac{2 \cdot n \cdot \eta \cdot \rho \cdot g \cdot 0,4 \cdot R \cdot 0,5 \cdot A_0 \cdot R}{3,6 \cdot 10^{12}}$$

In which:
E = annual energy production [GWh / year]
n = number of tidal cycles per annum [-] (705)
η = conversion efficiency of the turbine [-] (0,85)
g = acceleration of gravity [m^2/s] (9,81)
ρ = mass density [kg/m^3] (1025)
H = mean head difference [m]
V = displaced volume of water during one operation [m^3]
A_0 = water surface area of basin at NAP [m^2]
R = mean tidal difference at the sea side [m]

Under the assumption of a mean head difference, a total volume of replacement, and an operational period of 30% of the tidal cycle, the expected power of the tidal plant is[8]:

$$N = \frac{\eta \cdot \rho \cdot g \cdot H}{10^6} \cdot Q = \frac{\eta \cdot \rho \cdot g \cdot 0,4 \cdot R \cdot}{10^6} \cdot \frac{0,5 \cdot A_0 \cdot R}{0,3 \cdot T_{getij}}$$

In which:
N = installed capacity tidal plant [MW]
η = conversion efficiency turbine [-] (0,85)
ρ = mass density [kg/m^3] (1025)
g = acceleration of gravity [m^2/s] (9,81)
H = mean head difference [m]
Q = discharge through turbines [m^3/s]
A_0 = water surface area of basin at NAP [m^2]
R = mean tidal difference at the sea side [m]
T_{tide} = duration of tidal cycle [sec] (44712)

Tidal energy hydro-power dams including river run-off

The difference between this type of tidal plant and the tidal plant of enclosed basins or estuaries is that the river run-off discharge is handled. This means that river run-off water is released during ebb only. Therefore turbines need to be installed that are able to turbine from the basin to the sea.

This type tidal plant is able to generate the following potential energy:

$$E = \frac{n \cdot \eta \cdot \rho \cdot g \cdot H \cdot V}{3,6 \cdot 10^{12}} = \frac{n \cdot \eta \cdot \rho \cdot g \cdot 0,75 \cdot \Delta h \cdot Q_R \cdot T_{getij}}{3,6 \cdot 10^{12}}$$

In which:
E = annual energy production [GWh/year]
n = number of tidal cycles per annum [-] (705)
η = conversion efficiency of the turbine [-] (0,85)
g = acceleration of gravity [m^2/s] (9,81)

ρ = mass density [kg/m^3] (1025)
H = mean head difference [m]
V = displaced volume of water during one operation [m^3]
Q_R = daily average river discharge [m^3/s]
T_{tide}= duration of tidal cycle [sec] (44712)
Δh = difference between Low Water at the sea side and the mean basin level during mean water [m]

It is only possible to generate energy when the water level at sea is below the level at the basin. It is therefore assumed that during 50% of the time, energy can be generated. It is also assumed that, during operation of the tidal hydro-dam, the total discharge is twice the daily average river discharge. The total installed power can than be calculated as follows:

$$N = \frac{\eta \cdot \rho \cdot g \cdot H \cdot Q}{10^6} = \frac{\eta \cdot \rho \cdot g \cdot 0,75 \cdot \Delta h \cdot 2 \cdot Q_R}{10^6}$$

In which:
N = installed power tidal plant [MW]
η = conversion efficiency turbine [-] (0,85)
ρ = mass density [kg/m^3] (1025)
g = acceleration of gravity [m^2/s] (9,81)
H = mean head difference [m]
Q = discharge through turbines [m^3/s]
A_0 = water surface area of basin at NAP [m^2]
R = mean tidal difference at the sea side [m]
Q_R = daily average river discharge [m^3/s]
Δh = difference between Low Water at the sea side and the mean basin level during mean water [m]

Tidal energy plants with polders functioning as a basin
The difference with placing a tidal power plant in an existing dam is that the basin will be filled with water even at very low water. A polder would than be dry. As a consequence of that during flood the polder is filled with a relatively low head and emptied during ebb with a relatively high head. Therefore a tidal power plant only producing energy during ebb is most feasible. With this type of tidal power plant sluices are needed to fill the polder.

During turbining the head will be 70% of the tidal difference. The water level variation is determined by the elevation of the polder and the average high water level. The annual energy production can than be calculated as follows:

$$E = \frac{n \cdot \eta \cdot \rho \cdot g \cdot H \cdot V}{3{,}6 \cdot 10^{12}} = \frac{n \cdot \eta \cdot \rho \cdot g \cdot 0{,}7 \cdot R \cdot A_p \cdot \Delta h}{3{,}6 \cdot 10^{12}}$$

E = annual energy production [GWh / year]
n = number of tidal cycles per annum [-] (705)
η = conversion efficiency of the turbine [-] (0,85)
g = acceleration of gravity [m^2/s] (9,81)
ρ = mass density [kg/m^3] (1025)
H = mean head difference [m]

V = displaced volume of water during one operation [m^3]
R = mean tidal difference at the sea side [m]
A_p = water surface area of the polder [m^2]
Δh = difference between elevation polder and average high water [m]

Under the assumption of a mean head difference, a total volume of replacement, and an operational period of 30% of the tidal cycle, the expected power of the tidal plant is:

$$N = \frac{\eta \cdot \rho \cdot g \cdot H \cdot Q}{10^6} = \frac{\eta \cdot \rho \cdot g \cdot 0{,}7 \cdot R}{10^6} \frac{A_p \cdot \Delta h}{0{,}3 \cdot T_{getij}}$$

N = installed capacity tidal plant [MW]
η = conversion efficiency turbine [-] (0,85)
ρ = mass density [kg/m^3] (1025)
g = acceleration of gravity [m^2/s] (9,81)
H = mean head difference [m]
Q = discharge through turbines [m^3/s]
R = mean tidal difference at the sea side [m]
A_p = water surface area of the polder [m^2]
Δh = difference between elevation polder and average high water [m]

5.3 Overview of existing plans: closure dams

5.3.1 Introduction

Section 4.3 and 4.4 give an overview of plans for tidal energy, along the Dutch coastline. These plans cover a period of almost a century starting with the initiative to introduce tidal energy in Hansweert.

An overview of tidal energy in the Netherlands including references is given in the "*PAO Course Energy Hydraulic Engineering*". This is included in Annex C of the Annex Report. First, the closure dams in the South Western Delta of Zeeland and Zuid-Holland are being discussed. Secondly, the Afsluitdijk and other locations in the North are discussed. Lastly, polders along the Western Scheldt and the Eems Dollard are discussed. In figure 5.3 the closure dams in the South Western Delta, all part of the Delta Works, are presented.

Figure 5.3: Closure dams in the South Western Delta, all part of the Delta Works.

The discussion starts with a general description of the specific area. Secondly, the existing plans related to tidal energy in these areas are given. The overview of existing plans and studies is completed with estimates of energy potential in the areas of concern, based on the approach as given in section 1.3. Note that this potential expresses the energy potential given the basin characteristics and the tidal range at the sea side. The installed power will eventually have to be determined according to the length of the closure dam. If a dam is not sufficiently wide to accommodate for the installation of the turbines, the total installed power will be less than which is determined out of the basin potential.

5.3.2 Eastern Scheldt \ Oosterschelde storm surge barrier (Stormvloedkering in de Oosterschelde)

The Eastern Scheldt Storm Surge Barrier is one of the barriers which encloses the estuaries in Zeeland, see figure 5.4.

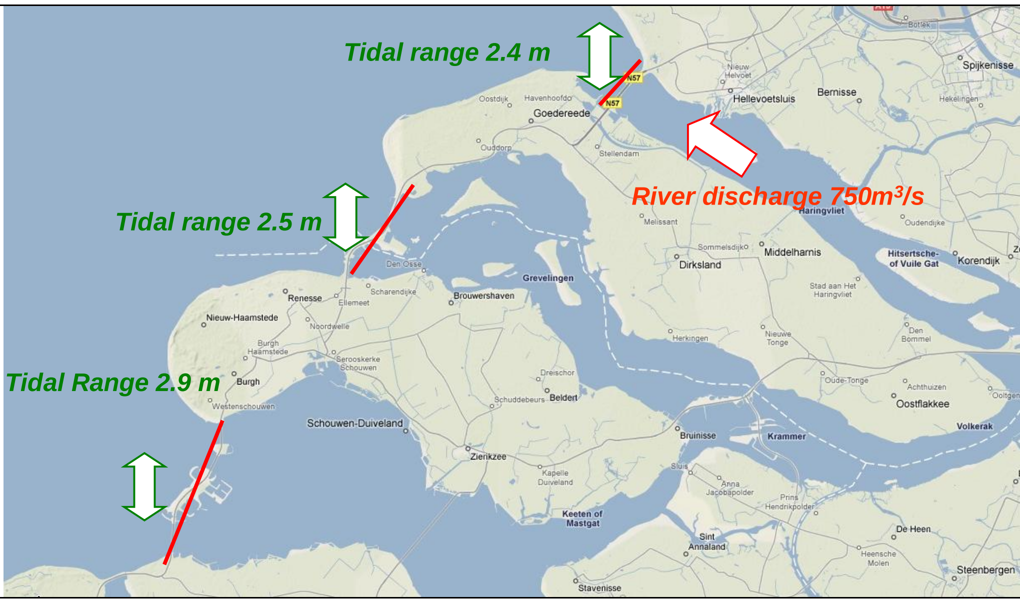


Figure 5.4: Closure dams which have potential for tidal energy. Only the Haringvliet accommodates for river run-off, which could increase in the future if the recommendations of the "New Delta Committee" are implemented.

The following studies to tidal energy in the Eastern Scheldt, have been carried out in the past, and have been reviewed in this study:

- Ecofys (2000), Kansen voor energiewinning uit getijde in de Oosterschelde;
- Rijkswaterstaat Oosterscheldewerken, "Drie Maandelijks Bericht Deltawerken". Een getijcentrale in de Oosterschelde? In Dutch. Date unknown.

Some conclusions and remarks on those studies are given below.

Kansen voor energiewinning uit getijde in de Oosterschelde (Ecofys, 2000)
This study focuses on tidal energy, both tidal stream and tidal range. A few relevant conclusions are given below.

- Implementation of a large scale energy plant in the Eastern Scheldt does not seem feasible due to conflicting interests with other objectives of the storm surge barrier. According to the report, a cost-effective tidal range plant needs a tidal range of at least 7m.

- Energy resulting from tidal stream seems more viable: the amount of energy available over the storm surge barrier is large due to the high flow velocities (in comparison to for instance the Haringvliet closure), up to 5 m/s. The study mentions however, that the effect of using tidal stream for energy generation could have a considerable impact on the water levels in the Oosterschelde estuary. As a result, the feasibility of installing a large tidal energy power plant in the Eastern Scheldt Storm Surge Barrier will depend on whether or not this increase in water level in the estuary can be justified and accepted. Small scale energy generation seems more realistic from this point of view.

The study also gives an overview of previous studies and references such as PZEM et al., 1981. This project analysed the use of one of the dry docks of the Surge Barrier as a small scale tidal plant including a peak shaving facility, see for instance the "Valmeer" in the Afsluitdijk renovation plans. The report of Ecofys also mentions the following reference Kooman, 1975. It is assumed that the results mentioned in Kooman (1975) are presented in the reference below, the report itself could not been found.

Rijkswaterstaat Oosterscheldewerken Drie maandelijks Bericht , nr. 80.
This memo investigates the possibilities for tidal energy in the Eastern Scheldt Barrier. In Annex C, Annex report the text is presented in Dutch. The following observations and conclusions have been made:

- Already in 1917, research was done to tidal energy in the area;
- In 1954, a report has been submitted to the Delta Committee, including a design for a tidal energy plant in the Western Scheldt near Bath. This seemed not to be economically feasible, mainly due to the inefficient technologies and the low price of fossil fuels like coal;
- In 1967, a new research report was prepared by the "Provinciale Zeeuwse Electriciteit Maatschappij" as a follow-up on the 1954 report, as the technology in especially turbines had improved significantly;
- The cost and benefit calculation for installation of a tidal stream generating turbines suggest this is not economically feasible. Bulb turbines have been used for the cost calculation. Main reason for this low efficiency is the relatively low tidal range. This is in combination with a very strict requirement for maintaining a water level in de Eastern Scheldt Estuary during high waters, hence setting a requirement for discharge over the Barrier thus limiting the capacity.

The tidal energy potential is summarized below (taken from the original reference for completeness). It is not very clear what the last 2 columns in the reference mean, but it is assumed that these numbers resemble the installed power using spring and neap tide figures instead of mean tide.

Table 5.2: Tidal energy potential [Rijkswaterstaat Oosterscheldewerken).

	Average tide					
Average tidal range, Yerseke	P max	E per tide	E per year	P eq	P max	P max
1.85 m	478 MW	1793 MWh	1265 GWh	144 MW	677 MW	311 MW
2.30 m	497 MW	1761 MWh	1243 GWh	141 MW	730 MW	309 MW
2.60 m	431 MW	1195 MWh	844 GWh	96 MW	673 MW	243 MW

P	Installed power
Peq	Power of conventional scheme
E	Energy production
1 GWh	1 M KWh

Information on more recent plans for tidal stream energy in the Eastern Scheldt is included in Annex C of the Annex report.

An estimate of the potential energy following the method as presented in section 1.3 is included in the table below.

Table 5.3: Tidal range and total tidal energy capacity according to studies from Ecofys, Royal Haskoning and Deltawerken.

Report	Basin area [10^6 m^2]	Tidal difference [m]	Energy production [GWh/jaar]	Installed power [MW]
Royal Haskoning*	303	2,9	1706	329
Ecofys	-	2,5	-	*734*
Memo Deltawerken	-	1,85 Yerseke	1265	677
		2,30 Yerseke	1243	730
		2,60 Yerseke	844	673
*For this estimate, the method in section 1.3 has been used				

5.3.3 Brouwersdam – Grevelingen Lake

The Brouwersdam closes the Grevelingen Lake from the North Sea, since 1971. The lagoon became a fresh water lake since. As a result of this, the surface area of intertidal and brackish ecology decreased. The water quality has been deteriorated over the past decade(s). This is the main reason for the initiative to reopen the Brouwersdam. Salt sea water will flow into the Grevelingen lake again.

The Grevelingen Lake was also closed from the Volkerak by the Grevelingendam and the Philipsdam. The Room for the River project and more recently the Delta Committee both indicate the Volkerak and the Grevelingen Lake as a corridor and storage area for high water peaks from the Rhine. Pumping capacity should be increased for this. To increase the water quality in the area, reintroducing tidal influences and salt water in the Lake is preferred as well.

The following reports have been reviewed which have looked at the Brouwersdam as a potential location for a tidal energy hydro-dam:
- Verkenning Grevelingen water en getij, 2009. Witteveen en Bos;
- Getijdecentrale in de Brouwersdam, 2009. Vrijlingh et al. TU Delft.

Verkenning Grevelingen water en getij (Witteveen en Bos, 2009)
Main observations and conclusions related to tidal energy are the following:
- Tidal energy is not realistic below 0,5m tidal range in the Grevelingen lake;
- Whether tidal energy in the Brouwersdam is economically feasible has not been investigated in detail in this report;
- Part of the conclusions made in the report are based on the study below.

Getijcentrale in de Brouwersdam (Vrijling, 2008)
A number of alternatives has been reviewed in this study. The study reviewed ebb tidal, flood tidal and two-side, so-called TT, turbines. Also, different lay-outs, locations and tidal ranges in the Grevelingen Lake have been reviewed. Main observations and conclusions:
- The small tidal range is not suitable for all types of turbines. Low head difference turbines with large capacity are necessary, diameter 3m to 5m. Only a bulb turbine seems feasible here;
- If the turbines are not able to reverse and function as sluices, than additional space has to be reserved for sluices (as is done now);
- Preferably the hydro-dam will be designed using reverse turbining and reverse pumping: these turbines can be used two sides and are also able to pump water. In

addition, these turbines should also be able to go into orifice-mode, meaning that the system can be used as a sluice;

- In theory, the complete Brouwersdam could be used for tidal energy. In this report, the section north of the work harbour and south of the work harbour has been taken into account.

Table 5.4: Basin area, tidal difference, tidal range, run-off, turbines, energy production and installed power for the Brouwersdam / Grevelingen Lake according to different studies.

Report	Basin area [10^6 m^2]	Tidal difference [m]	Tidal Range Grevelingen Lake [cm]	Run-off (m^3/s)**	No. Turbines	Energy production [GWh/jaar]	Installed power [MW]
Royal Haskoning*	117	2,5	-	-	-	490	94
Witteveen en Bos	117	2,5	50 70 100	500 550 1300	-	-	50 70 100
TU Delft	117	2,5					
Ebb tidal			150		158	392 max	94
Flood tidal			150		158	280 max	94
TT			110		186	353 max	65

*For this estimate, the method in section 1.3 has been used

**Maximum runoff capacity In case the Grevelingen Lake is connected to the Volkerak Zoommeer

Figure 5.5: Overview of the Brouwersdam.

Near Future
Secretary Huizinga and the Alliance of governmental bodies responsible for the Grevelingenmeer have agreed to perform a joint investigation in the so-called MIRT[9] (Meerjarenprogramma Infrastructuur, Ruimte en Transport). This investigation, which has to be completed at the end of 2011, addresses all recreation, economic and environmental interests from a national regional and local point of view. A similar investigation has been issued by Huizinga for the renovation of the Afsluitdijk. The costs of the investigation are covered by “het Grevelingenschap” (€ 0,9 milion euro) and the National Government ((€ 0,6 million euro).

Figure 5.6: Close-up and overview of plans for a tidal plant in the Brouwersdam (www.zichtopgrevelingen.com).

5.4 Afsluitdijk

The Afsluitdijk was constructed between 1927 and 1932. The dam closes of the Lake Ijssel. Closing off the Lake Ijssel was necessary, because occasionally, large areas of land adjacent to Lake Ijssel flooded. Also, the polders around Lake Ijssel would highly benefit from a fresh water lake, because siltation of the low lying polder had become a problem. Also increasing demand for clean drinking water was a driver for the Lake Ijssel closure.

[9] See http://www.verkeerenwaterstaat.nl/onderwerpen/begroting/mirt/

It is not known whether at the time of construction, tidal energy was considered an option at this location. The tidal range over the Afsluitdijk is relatively small, 1.8m.

Figure 5.7: Satellite image of the Afsluitdijk.

The following information has been reviewed:

- Dijk en Meer, 2009. Rijkswaterstaat, Provincie Noord Holland, Provincie Fryslân;
- (Internet) information about experiments of Torcado.

Dijk en Meer, 2009. Rijkswaterstaat, Provincie Noord Holland en Provincie Fryslân

This report covers several studies and ideas for renovation of the Afsluitdijk. In this report, several plans include the generation of (tidal) energy out of water power. The consortium[10] "Natuurlijk Afsluitdijk", specifically looked at generating and storing energy near the Afsluitdijk using different techniques and methods. One of the options is to create a "Valmeer", a very deep polder with turbines and pumps which can be filled and emptied whenever necessary. Doing so, excess energy in the grid, for instance during the night, can be temporarily stored and returned to the power grid later. The tidal range can be used optimally to improve the efficiency of this concept. The direct use of tidal range energy was thought to be no option due to the small tidal range at the Afsluitdijk.

[10] Eneco, Rabobank, Royal Haskoning, BAM, van Oord, Wubbo Ockels BV

Figure 5.8: Renovation plans of the Afsluitdijk including the construction of a energy storage "Valmeer" according to the Natuurlijk Afsluitdijk consortium.

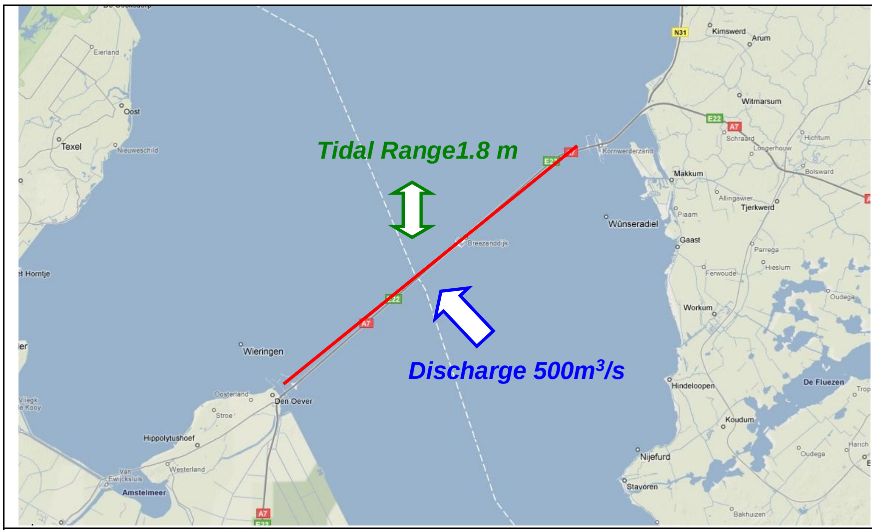


Figure 5.9: Tidal range and average river discharge.

An analysis of the potential for tidal energy in the Afsluitdijk is shown below, following the approach of section 1.3. The table below gives an overview of the energy potential near the Afsluitdijk. Note that this is energy from tidal range and run-off rather than tidal stream like the Torcado experiment.

Table 5.5: Estimation of the energy potential for the Afsluitdijk.

Location	**Discharge [10^6 m^2]**	**Δh [m]**	**Energy production [GWh/jaar]**	**Installed power [MW]**
Afsluitdijk	500	0,7	20	4

5.4.1 Haringvliet

The Haringvliet is an estuary which has been closed off as part of the Delta Works since 1970. The closure consists of several sluices which are opened to drain river run-off from the Rhine and Meuse rivers. The surrounding agricultural areas have benefited from the estuary becoming fresh, however the estuarine ecology has disappeared. Latter in combination with an increase of blue-green algae pollution, resulted in the plans to partly reopen the sluices and thus reintroducing a semi-tidal estuary again, the "Kierbesluit".

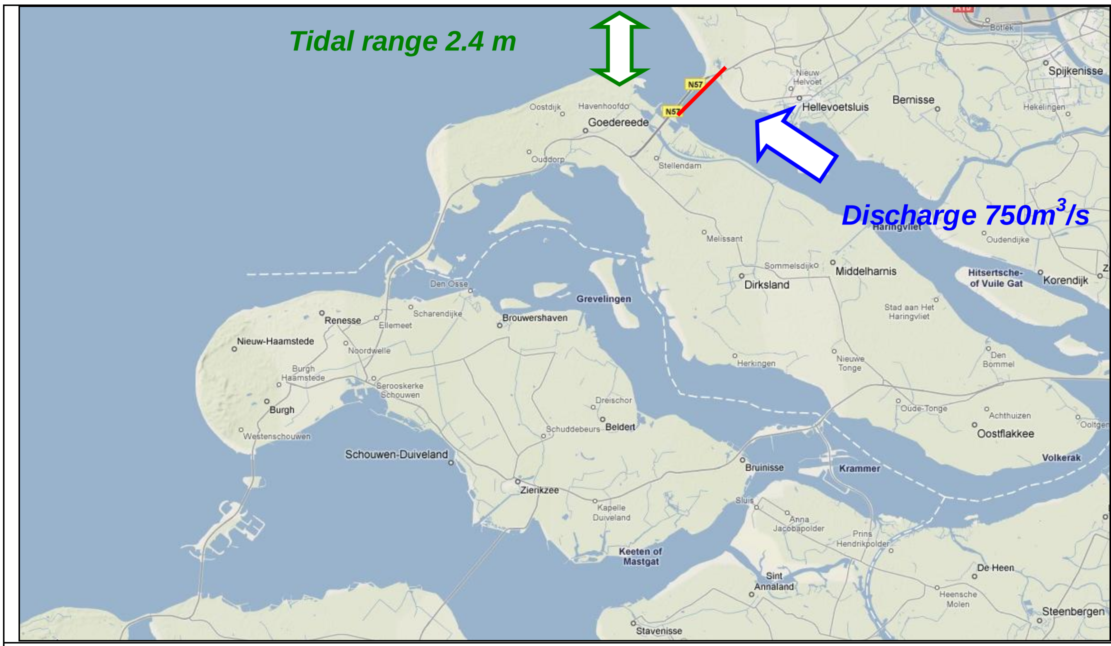


Figure 5.10: Tidal range and average river discharge Haringvliet .

Hardly any studies have been carried out, looking at tidal energy in the Haringvliet. This is probably due to the fact that at present, the discharge through the sluices is limited. It should be noted that the discharge is larger than the Afsluitdijk, but the total area used for discharging water is much larger than at the Afsluitdijk.

Table 5.6: Estimation of the energy potential for the Haringvlietsluizen.

Location	**Discharge [10^6 m^2]**	**Δh [m]**	**Energy production [GWh/jaar]**	**Installed power [MW]**
Haringvlietsluizen	750	1,4	57	13

5.4.2 Lauwersmeer

Figure 5.11: Tidal range and location of tidal plant in the Lauwersmeer.

- Watervisie Lauwersmeer;
- Grounds for Change \ Energy Valley;
- Provinciaal omgevingsplan Groningen.

Watervisie Lauwersmeer (BOWL, 2006)
An interprovincial committee called "Bestuurlijk Overleg Watervisie Lauwersmeer (BOWL)" has carried out several studies looking at the future of the Lauwersmeer. Considerations have been presented in a Water Vision Report. Key driver of the study was the notion of an increasing sea level and the requirement of more nature development following Natura2000. It was concluded that the most favourable alternative was to allow tidal influences to return in the Lauwersmeer. The negative effects of siltation of the Lauwersmeer would be compensated by the increase of biodiversity and mitigation of drastic adverse effects.

Nevertheless, restrictions have been posed on the tidal range in the Lauwersmeer. This is due to the fact that the Lauwersmeer functions as a storage area for drainage water for water management purposes, hence the water level can not be too high. The maximum allowable water level is NAP – 0,5m. The Water Vision Report does not mention tidal energy, but gives reference to the project Energy Valley, see below.

All documents are accessible on the internet through:
http://www.provinciegroningen.nl/landenwater/water/lauwersmeer
An overview of all the plans and regulations as of 2002 is given in Royal Haskoning (2002).

Grounds for Change \ Energy Valley
More ambitious plans come from the project "Grounds for Change", see *http://www.groundsforchange.nl/*

These plans include tidal energy in the Lauwersmeer, but the documents do not mention an estimate of expected capacity.

Provinciaal Omgevingsplan Groningen
The provincial plans of the Province of Groningen also mention the Lauwersmeer as a potential for tidal energy, but no indication of expected capacity nor any proposal for types of energy.

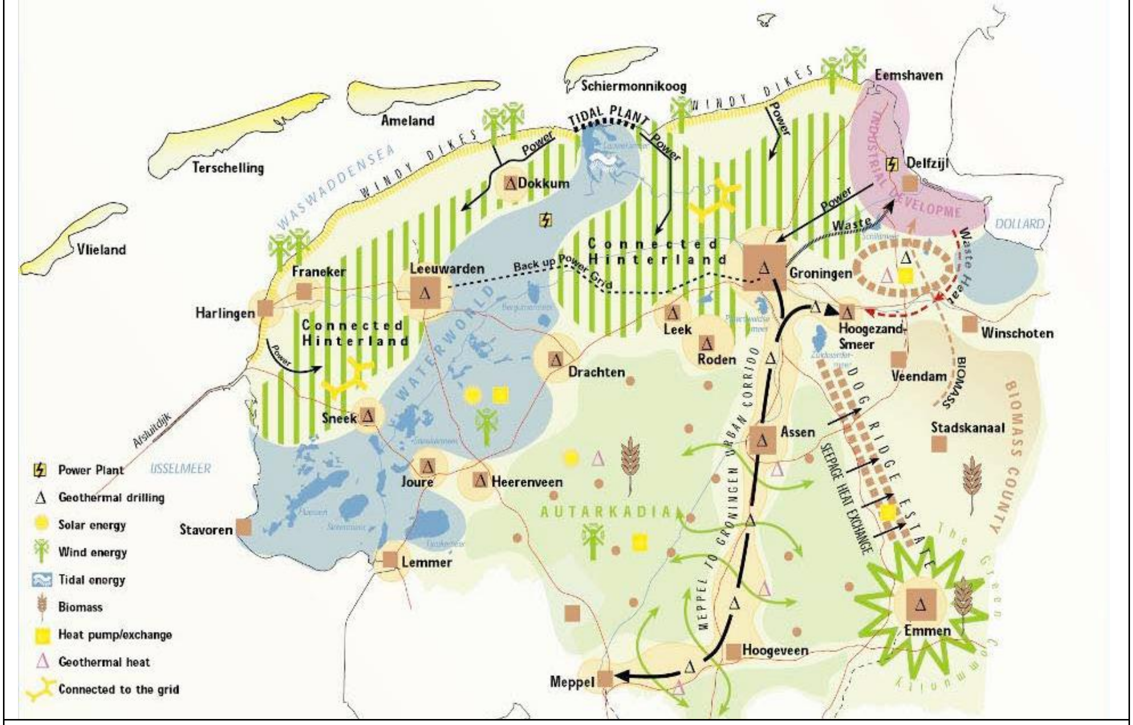


Figure 5.12: More ambitious plans for the North of the Netherlands including tidal plant in the Lauwersmeer and beyond → Grounds for Change.

The potential for tidal energy is shown below, not taking into account any restriction out of environmental, water management or other considerations.

Table 5.7: Energy potential and installed power Lauwersmeer

Location	Area [10^6 m^2]	Tidal range [m]	Energy production [GWh/year]	Installed capacity [MW]
Lauwersmeer (RH 2002)	47	2,3	166	32

The tidal range of the Waddenzee near the Lauwersmeer is not very large, and the basin is not very large either. Other functions of the Lauwersmeer, especially as a drainage for rainwater, should have to been taken into account in a proper feasibility assessment.

5.5 Overview of plan in the Netherlands: Polders

5.5.1 Introduction

In this section an overview is given of the polders in the Netherlands interesting to consider for implementing tidal energy.

5.5.2 Western Scheldt

The Westerschelde has always been looked at as an area for tidal energy due to the large tidal range in the area. The following plans and studies have been reviewed:

- Advies Commissie Natuurherstel Westerschelde, http://www.commissienatuurherstelwesterschelde.nl/;
- De Energie Polder, Haalbaarheidsstudie naar een getijcentrale langs de Westerschelde Thesis report of Leslie Mooyaart, TU Delft 2009.

Advise Commission Nijpels

The minimal depth of the Western Scheldt is secured by periodic maintenance dredging. Without this, the port of Antwerp would not be accessible for large seagoing vessels. To compensate for the adverse effects of dredging on the environment, 600 hectares in the vicinity of the Western Scheldt has to be designated as new nature. One of the options to create this vast amount of space for nature is to remove some of the primary sea defences along the Western Scheldt, and thus returning polders into areas under influence of the tides. This is called “Depoldering”, referring to the opposite of creating a polder and reclaiming land from the sea. The notion of depoldering resulted in public debate in the region as well in politics. The Government of the Netherlands assigned a committee to accommodate the depoldering discussion with the public and to define suitable solutions. The committee is known as the Committee Nijpels, after the Chairman Drs. E. Nijpels. They have formulated several conclusions and appointed several polders suitable for new tidal nature, without compromising to much public sentiments. The most suitable polder is the Hedwigepolder. Other options include, in order of decreasing preference:

- Introduction of tidal influences in the Zimmermanpolder, including parts of the Fredericapolder, by removing the primary sea defense completely;
- Introduction of a reduced tide in the Zimmermanpolder, including parts of the Fredericapolder, by construction of sluices;
- Complete depoldering of the Molenpolder and Perkpolder, including some adaptations to small tidal creeks (the Braakman for instance);
- depoldering of several small polders including adaptation of small tidal creeks.
- introduction of reduced tides in small polders including adaptations of small tidal creeks.

De Energiepolder, Haalbaarheidsstudie naar een getijcentrale langs de Westerschelde (Mooyaart, 2009).

This study investigates opportunities for tidal energy along the Western Scheldt estuary. The study has incorporated many different polders. An estimate of tidal energy in all polders of the Western Scheldt is presented in table 5.8 below. Apparently, not all polders are suitable for tidal energy. This is due to the following considerations:

- The ground level elevation of some of the polders is too high for sufficient storage area;
- Some of the smaller polders have too small surface for storage of water reducing the possible discharges significantly;
- The number of inhabitants in some polders is too high for depoldering (not shown in the table below). Depoldering Perkpolder for instance does not seem viable because of the number of inhabitants.

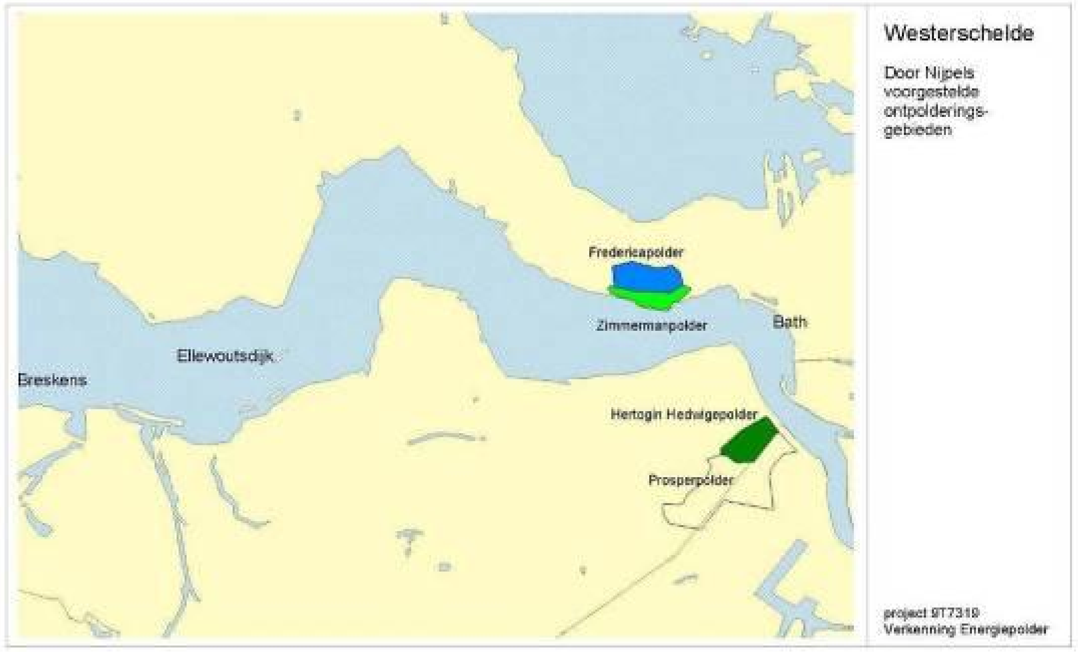


Figure 5.13: Location of the various polders showing potential for tidal energy.

Polder	H [m]	V [10^6 m^3]	Q [m^3/s]	P [MW]	E [GWh/jaar]
Prosperpolder	3,3	13,4	599	18	74
Fredericapolder	3,2	5,6	250	7	30
Hertogin Hedwigepolder	3,3	3,0	133	4	17
Zimmermanpolder	3,2	2,8	123	3	15
Perkpolder	3,0	2,8	125	3	14
Margarethapolder	2,7	3,0	134	3	14
Beukelspolder	2,7	2,8	125	3	13
Eendragtpolder	2,8	2,3	101	3	11
Zuidpolder	2,8	2,1	94	2	10
Paulina polder	2,7	2,1	94	2	10
Wilhelmuspolder	3,0	1,7	76	2	9
Kleine Huissenspolder	2,7	1,8	81	2	8
Emanuelpolder	3,2	1,5	67	2	8
Everingepolder	2,8	1,7	74	2	8
Hellegatpolder	2,8	1,2	54	1	6
Nieuw-Hoondertpolder	3,0	0,8	36	1	4
Coster-Zwakepolder	3,0	0,8	36	1	4
Noordpolder	3,0	0,8	36	1	4
Heer-Geertspolder	3,0	0,8	36	1	4
Boonepolder	3,0	0,8	36	1	4
Molenpolder	3,0	0,7	31	1	4
Thornaespolder	2,7	0,3	11	0	1

Table 5.8: Overview of tidal energy potential of various polders along the Western Scheldt. H is the tidal range, V the volume discharged during a full tidal cycle. Q is the maximum discharge, P the power and E the total energy potential per year.

The following conclusions and observations are made in this study:

- An ebb-tidal or an TT plant will be most effective in this situation;

- Two types of turbines could be used, a Straflo turbine or a bulb turbine. The bulb turbine seems however the most suitable although more expensive. Because the Straflo turbine has only been used once in Annapolis, with bad experiences, it was not chosen for further study. Bulb turbines are also used in run-off river plants.

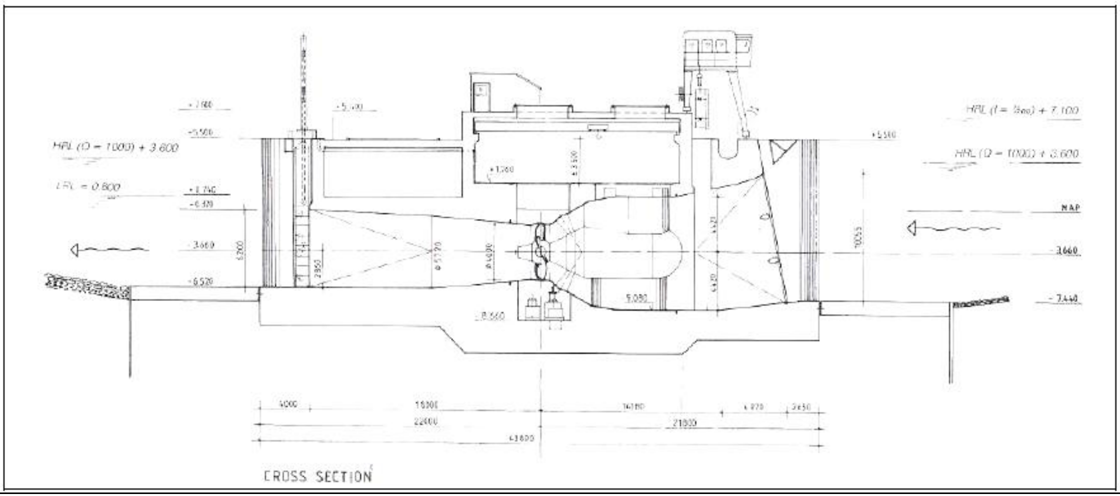


Figure 5.14: Example of a bulb turbine at Alphen a\d Rijn.

Hertogin Hedwigepolder in combination with the Prosperpolder in Belgium has been investigated in more detail in Mooyaart (2009). Results of this are presented in the table below:

Table 5.9: Estimation of the results on potential tidal energy for the Prosper and Hedwige polder.

Location	**Area [10^6 m^2]**	**Tidal range [m]**	**Polder ground level elevation [m NAP]**	**Number of turbines**	**Energy production [GWh/year]**	**Installed capacity [MW]**
Prosper- en Hedwige polder	13,3	5,0	Hedwige: 1,9 Prosper: 1,3	5	64,3	21,5

Eems Dollard Estuary

An area which is mentioned in only one existing study is the Eems Dollard Estuary. The potential for tidal energy here mainly lies in:

- The considerable tidal range (3m);
- The low lying polders nearby (up to -3m NAP);
- The relatively small number of inhabitants in the area.

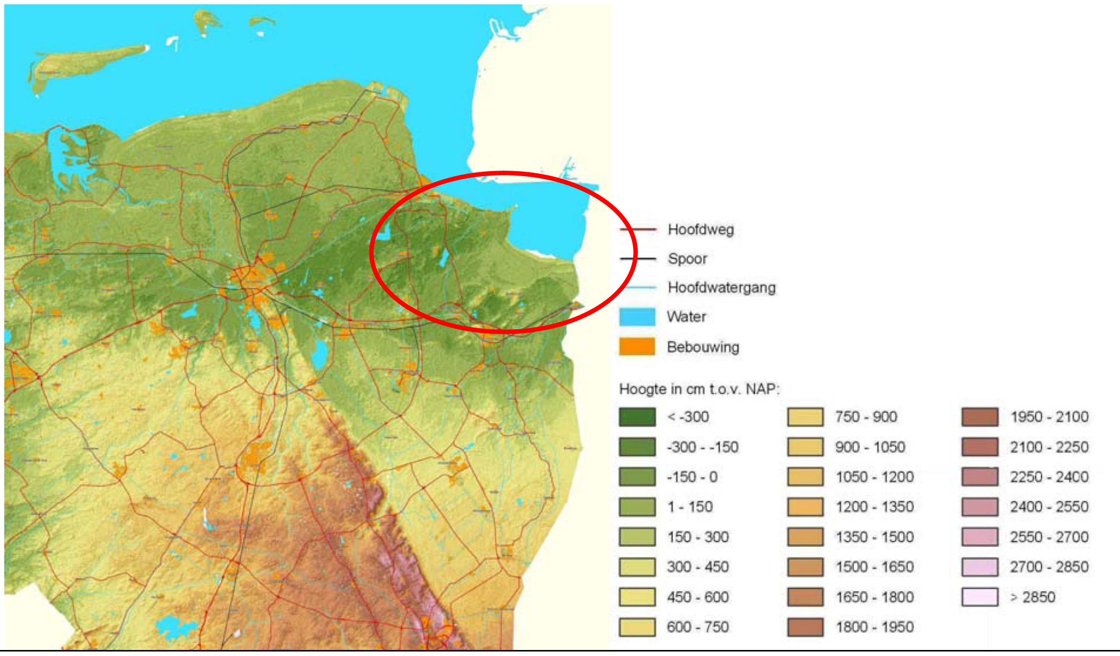


Figure 5.15: Elevation map of Groningen. Dark green is <-3m NAP.

The only study which was found during the investigation was a report prepared for the Province of Groningen called:

- Naar een energiegestuurd omgevingsplan Groningen (TU Delft, 2007).

This study was prepared for a new "Provinciaal Omgevingsplan", an area management plan for the Province of Groningen by TU Delft. The study does not go into much detail on tidal energy. They mentioned the area Noordelijke Oldambt en het Duurswold, which is the lowest lying area in the province, as a possible inundation area for high waters. During inundation of the polder energy could be generated. One village is located in the area, Woldendorp, and also industrial developments are planned in the area.

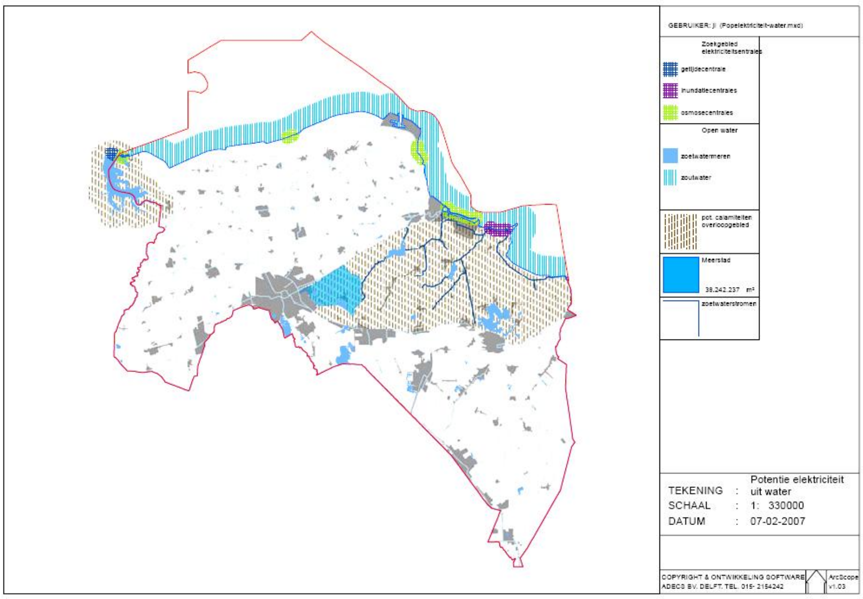


Figure 5.16 *"Naar een energiegestuurd omgevingsplan Groningen p .46"*.

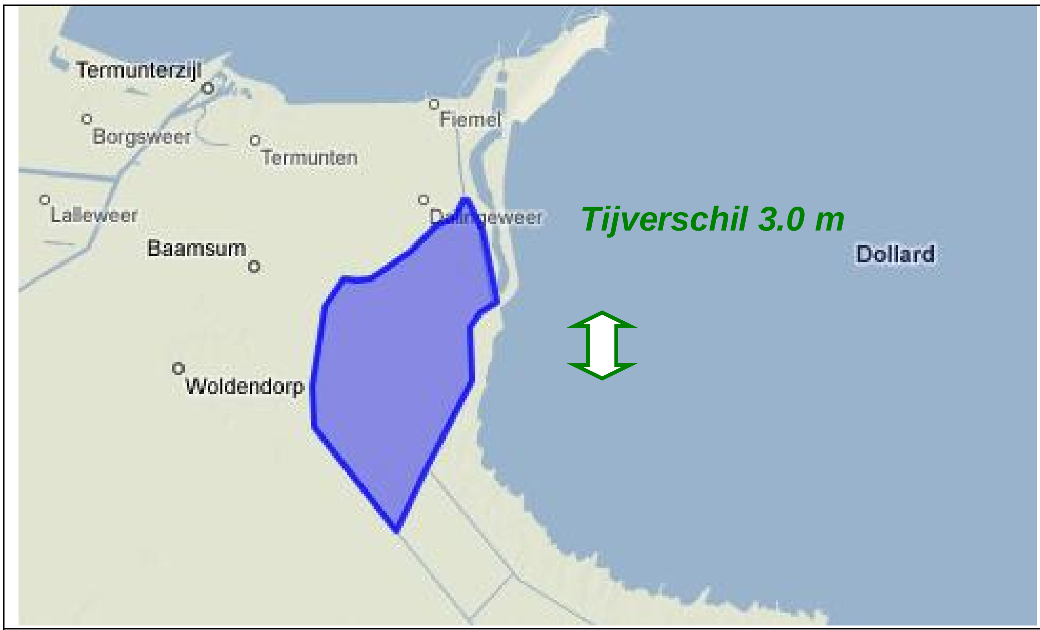


Figure 5.17: Location of the Johannes Kerkhovenpolder.

An estimation of the Potential tidal energy for the Johannes Kerkhovenpolder is estimated with the approach mentioned in section 1.3. Results are given in the table below. Although the area is quite small, the potential is quite large especially because of the large tidal range and the low ground elevation of the polder.

Table 5.10: Estimation of the results on potential tidal energy for the Johannes Kerkhovenpolder.

Location	**Area [10^6 m^2]**	**Tidal range [m]**	**Polder ground level elevation [m NAP]**	**Energy production [GWh/year]**	**Installed capacity [MW]**
Johannes Kerkhovenpolder	4	3	-0,5	27	10

6 LESSONS LEARNT FOR REALISATION OF TIDAL ENERGY IN THE NETHERLANDS

6.1 Introduction

Case studies in United Kingdom and principal issues and lessons learnt from those case studies have been described in the former chapters. Also, an investigation for tidal energy in the Netherlands has been presented in previous chapter.

In this chapter it is described how the information investigated in former chapters can be used for the development of tidal energy in the Netherlands. In addition to the information from previous chapters, information from the interviews with experts (see Annex D in Annex Report) and information gathered from the workshop held in Rotterdam at September, 29 2009 (see Annex E in Annex Report) is used.

6.2 Differences between UK and Netherlands

The situation in the UK concerning the development of tidal range power, differs from that in the Netherlands. In the UK the main goal of the construction of barrage is to generate tidal energy.

In the Netherlands various barrages / dams already exist and these have been realized several decades ago with the main goal to reduce flood risk behind the barrage. Presently, approximately 30 to 80 years after construction, problems occur in the water quality and ecology as a result of closing off the estuaries. The main goal to re-open these estuaries is therefore to improve the water quality at various locations in the estuaries by recovering estuary's dynamics. As a part of these plans, implementing a tidal power plant can become attractive.

As such, the main rationales behind the development of tidal range energy in the Netherlands and UK are different. As a consequence, the positive and negative implications of these projects will be different between the two countries. For example, the introduction of tidal barrages in the UK will have a negative effect on the water quality and the environment. However, in the Netherlands the re-opening of closed estuaries is expected to improve the water quality and environment.

Anticipating on the results in this section the following figure already presents a general ranking of the different effects of tidal energy projects in the Netherlands and UK. The scale ranges from very negative ("show stopper") to very positive. The two axes also show that there are some main differences between the effects of tidal energy projects in the Netherlands and UK.

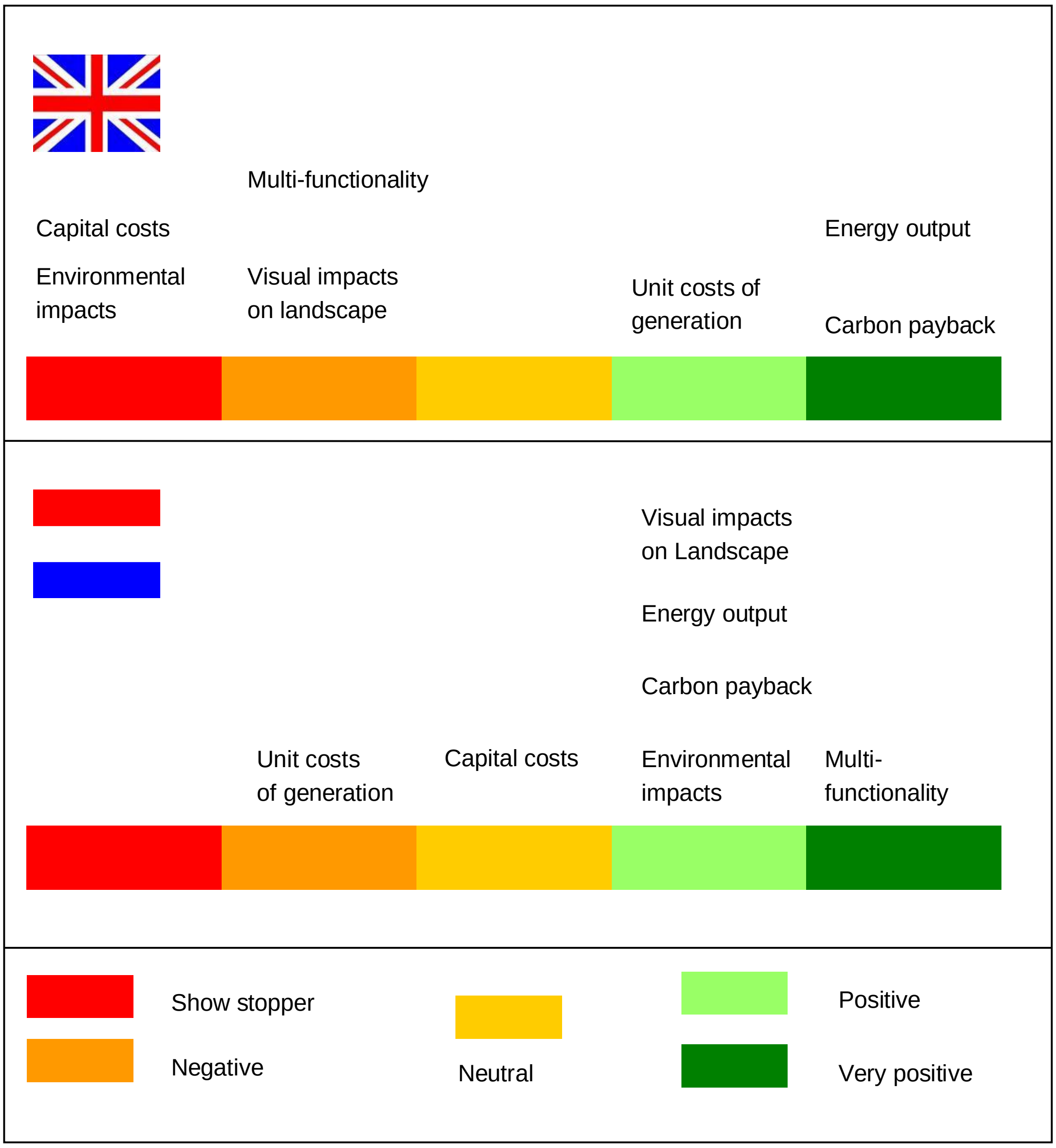


Figure 6.1: Differences between UK and the Netherlands.

6.3 Economic and commercial viability

6.3.1 Installed power and annual energy output

In summary: the UK tidal ranges are higher than in the Netherlands. As a result the potential energy output is higher.

To obtain an impression of the annual energy output in the Netherlands a regression analysis has been done based on studies from La Rance (France), Severn (UK), Mersey (UK) and the Western Scheldt (Mooyaart, 2009). This is another method than opposed in chapter 4, which is based on results of a model used for calculation of the annual energy and installed power for the Brouwersdam.

The regression analysis is based on more extensive studies (La Rance, Severn Mersey) and is therefore more precise for determination of the economic annual energy output and economic installed power.

First the characteristics of a tidal power plant were identified. The characteristics for dams with / without river run-off and for polders are the following:

- For dams without river run-off, the relevant characteristics are: the surface area of the basin (A), the tidal range (R);
- For dams with river run-off these are the river flow (Q) and the difference between the average basin level and the average low water (Δh);
- For the polders three parameters are of importance; the surface area of the polder (A), the tidal range (R) and the difference between average high water and elevation of the polder (Δh).

The method used to estimate the figures for the most economic energy output (E) and installed capacity (P) is elaborated in Annex F in the Annex Report. The results are shown in table 6.1.

Table 6.1: Economic installed power and energy output in the Netherlands.

Location	A [km^2]	R [m]	Q [m^3/s]	Δh [m]	P [MW]	E [GWh/year]
UK						
La Rance	22,5	8,5	-	-	240	650
Severn Barrage	480	10,5	-	-	8640	17000
Mersey	63	8	-	-	700	1450
Duddon	18 (estimated)	5,8			100	210
Netherlands						
Oosterscheldekering	303	2,9	-	-	413	918
Brouwersdam	117	2,5	-	-	118	**263**
Lauwerszee	47	2,3	-	-	40	90
Haringvliet	100*	2,3*	750	1,4	10,6	37
Afsluitdijk	1100*	1,8*	500	0,7	3,5	12,3
Eems-Dollard	4,0	3,0	-	2,0	4,6	13,9
Western Scheldt	13,3	5,0	-	1,3	21,5	64,3

*not used for determination of P and E.

No references were found for tidal power plants which use river run-off. An assumption between the potential amount of energy and the economic energy is chosen, using figures from the other plans (La Rance, Severn, Mersey & Western Scheldt). As both river flow as tidal range differ daily finding the most economic installed power can differ from results from tidal power plants like La Rance. These figures (Haringvliet, Afsluitdijk) are therefore more uncertain than the other figures presented.

In table 6.1 is shown that the energy output of the Duddon Barrage (210 GWh/year) comparable is to the Brouwersdam (263 GWh/year).

6.3.2 Costs

In summary: in the UK the absolute investment costs (construction costs) for tidal energy schemes are quite high due to the size of the projects. For example: capital costs of small schemes such as the Loughor Barrage (5MW) is estimated 25 million Euro, for the Severn (8640 MW) 17000 million Euro or approx. 2 million euro/MW.

The unit costs of generation expressed in eurocent per kilowatt-hour lies close to conventional energy sources. For example: the unit cost of generation for the Severn, with a discount rate of around 6% is estimated approximately 7,5 eurocent / KWh.

In the Netherlands the investment costs for the plans are smaller, as the projects are smaller and because the barrage is already existing. The unit costs of generation (cent/kWh) are in the range of 10 - 40 cent/ kWh. The unit costs in the Netherlands are thus higher than in the UK, as the tidal difference is lower in the Netherlands.

The costs during the life time of a tidal power plant are mainly determined by the investment costs (>90 %). These costs can be divided in two main categories:

- Civil and maritime works (such as caissons, turbines, sluices, embankments, scour protection, fish passes).
- turbine costs.

In addition to the investment costs, there are operational and maintenance costs. With a tidal power plant operational costs and maintenance costs are low compared to investment costs.

Considering tidal energy schemes in the Netherlands related to costs a few things can be taken into account:

- The Dutch Government aims at increasing the use of renewable energy till 20 % in the year 2020, consequently decreasing use of CO_2 over the coming years. Tidal energy will help both aims pursued by the Dutch Government.

- It may be clear that the role of the government is very important to make a tidal energy scheme viable. Their roles will be multi functional:

    - Role as initiator in tidal energy projects aiming to achieve their national goals on the generation renewable energy;
    - Create viable project opportunities by combining several aims together: multi-functional. Consultation with stakeholders and combine different aims of stakeholders in one plan (improvement of water quality, improvement of flood risk, tidal energy).
    - Role as regulator to provide permits;
    - Role to set up subsidies programmes and provide subsidies (see text box) focused on generation of renewable energy in such a way that (private) parties will become interested to be involved and invest;
    - Role as financer of (parts of) tidal energy schemes.

The Government can decide to start with a pilot project to promote tidal energy and to get a better insight in the impacts.

Subsidies renewable energy in the Netherlands

- SDE-regulation (in Dutch: Stimulering Duurzame Energieproductie, SDE)
  In the Netherlands on shore wind energy projects and tidal energy project (less than 5 meter tidal range) can make use of the SDE regulation. Based on an economical analysis the price of energy is calculated. The difference in energy price up to 12,5 cents will be paid via the SDE- regulation up to 15 years. Available budget for 2009 is 60M€.
  For more information, see http://www.senternovem.nl/eia/

- EIA-Regulation (in Dutch: Energie Investerings Aftrek, EIA)
  44% of the invested capacity can be deducted from the profit. Regulation can be used up to 10 years.
  For more information, see http://www.senternovem.nl/sde/

6.3.3 Design turbines

Turbines as proposed in the tidal power projects in the UK are quite similar to turbines that are used in run-off river plants all over the world (also in the Netherlands). As the first run-off river plants were placed in France, Switzerland and Austria, most experts come from these countries. Experience about designing these turbines exists here for over many decennia and is applied in many other countries all over the world.

Although there are a lot of similarities in the design of turbines placed in run-off river plants and tidal power plants, there are two main differences:

- As the turbines are placed in a marine environment, corrosion-inhibitive materials should be used.
- Due to the tide water can flow in both directions through the turbine. It can therefore become attractive to add extra modes to the turbine, such as turbining in the other direction and pumping.

When designing the turbines for a power plant it is first important to determine the size and number of the turbines required. In general it can be said that costs are lower when placing a power plant with a few turbines with a large diameter than a lot of turbines with a small diameter. But the size of the turbines can not be chosen too large as there are technical limitations.

Firstly in the current state of technology it is not possible to construct the most common type of turbine for tidal power projects, the Bulb-turbine, with a diameter larger than 10 meter. Another large scale but less often used turbine, the Straflo-turbine, can maximally have a diameter of 9 meter. Secondly the possible maximum turbine diameter is related to the head the turbine will start at. This is because the momentum needed for the rotor to start rotating depends on the starting head. The required momentum is determined by the weight of the rotor and therefore its diameter. But the exact relation between starting head and diameter is not known here. The starting head probably has a relation with the design head though. In table 6.2 the diameter of different designs for tidal power plants and one Dutch run-off river plant are shown.

Table 6.2: Turbine characteristics on different locations (Mooyaart, 2009).

Location	Diameter	Rated Head	Starting Head
Kislaya Guba	3,3	1,28	-
Maurik (NL)	4,0	3,00	1,50 *
Linne (NL)	4,0	4,00	0,90 **
La Rance	5,35	5,65	-
Sihwa	7,5	5,82	2,00
Severn	9,0	10,0	-

* Starting head used at operation, ** Starting head given by turbine manufacturer

From experience with run-off river plants it is known that mortality of fish that swim through a turbine can occur. Three processes can explain the fish mortality while passing the turbine:

- Local high pressure differences;
- Turbulence;
- Collision with rotor blades.

At the tidal power plant of La Rance the experience is that fish mortality is very low, but that the fish community changes. At Annapolis in Canada the fish mortality is relatively high. This can be explained by the fact that Straflo-turbines in stead of Bulb-turbines are used here. Because of the relative low rotational speed of Bulb-turbines this type is seen as the least fish unfriendly turbine. This is an extra reason to chose a Bulb-turbine when designing a tidal power plant.

6.3.4 Multifunctionality

In the UK as well as in the Netherlands, commercial viability of a scheme may be deemed greater if a wider range of functions and related economic benefits could be incorporated. Examples of such functions are the following:

- Infrastructure (improved transport networks);
- Leisure and Tourism (Visitors centre on Tidal energy), amenities and education;
- Flood control (decrease flood risks elsewhere in the estuary, additional use tidal scheme as pumping station for high river discharges or high water levels on the lake);
- Temporary and permanent job creation through the construction and operation of the scheme.

6.3.5 Carbon payback

Reduction of the carbon dioxide production per kWh is an advantage of placing a tidal power plant. The carbon payback period in the UK for the Severn will be less than a year. A study from CIWEM from March 2009 showed that after less than six months, the carbon emissions saved from using less fossil-fuel based electricity would be the equivalent to the emissions associated with the nine year construction of the project, from production of the materials to their transportation and installation.

As the energy output of the tidal power plants proposed for the Netherlands in this report is lower and still quite a lot of structural work is needed, it is expected that the carbon payback period is a few years.

6.4 Environment

In summary: in the UK, the proposed tidal energy schemes are situated in ecologically valuable estuaries. Those estuaries will be (partly) closed off from the sea. As a result there will be impacts on geomorphology, turbidity, fishes, marine mammals and birds. Concerning geomorphology, patterns and rates of sediment erosion will change and thereby changing the morphology of the system and associated flora and fauna. Concerning turbidity, the phytoplankton productivity (algae) will increase as a result of decreased turbidity. Fishes, marine mammals and birds will also experience impacts of the tidal energy scheme such as a decrease or loss of feeding, breeding grounds and routes.

In the Netherlands currently existing barrages have been built decades ago. After closing off the estuaries in the Netherlands, the system was not a dynamical system anymore which resulted in a relatively constant water level.

Presently, Government, Provinces, ministries etc. initiate at least one plan to re-open the estuary. The main aim of re-opening estuaries is increase the estuary dynamics. For example, in case tidal energy scheme should be placed in the Brouwersdam the estuary dynamics will increase and the water level variation will increase. In general it can be concluded that an increase of estuary dynamics will result in an improvement of the water quality and ecological system of the estuaries.

Table 6.3 : Water management and environmental differences (in general) between Dutch Locations.

Location	Water management	Environment
Brouwersdam	Water level variation increases	Tidal energy scheme restores (part of) the estuary dynamics.
Lauwersmeer	Water level variation increases. Fresh water becomes salt.	Tidal energy scheme restores (part of) the estuary dynamics. Impact on agriculture as fresh water inflow will decrease.
Oosterscheldekering	Water level variation decreases, less estuary dynamics.	Ecology may not improve.
Haringvliet	No changes in water level	Changes on ecology will be relatively minor.
Afsluitdijk	No changes in water level[11]	Changes on ecology will be relatively minor.
Polders (Western Scheldt and Eems-Dollard)	Becomes under influence of tide. Salt water introduced	Tidal energy scheme introduces estuary dynamics in area.

It may be clear that the water system in the estuaries will change after implementing tidal energy schemes. Impacts on the environment and on the social environment need further investigation.

Aspects which has to be taken into account in the Dutch situation are the following:

- Knowledge and research
    - Further investigation of social en environmental impacts:
        - Social impacts (impacts due to changes in water quantity and water quality on water supply for agriculture, fisheries, drinking water, etc.);

11 Idea of commission Veerman to increase average water level of Ijssel Lake is positive for energy output.

    - Environmental impacts (impacts due to changes in water quantity (waterlevel (variation)) and water quality (oxygen, nutrients, salinity etc);
    - Monitoring of environmental impacts;
  - Design turbines while considering fish unfriendliness;

- Involvement of stakeholders:
  - Involvement of stakeholders in an early stage;
  - Combine different aims of stakeholders in one plan (improvement of water quality, improvement of flood risk, tidal energy).

- Legislation:
  - Compliance with legislation ad investigate the possibilities to improve the ecological system / minimize the environmental impacts;

6.5 Legislation issues

Compliance with all environmental requirements would be an important requirement for any estuarine barrage proposal. The specific requirements of the Habitats Regulations are likely to present the most significant challenges in seeking approval for a project in UK. It must be remembered that the Natura 2000 network comprises all European sites and direct effects on one interest feature may indirectly affect another on a distant site. This is especially true where species migrate between sites, or are displaced from one site to another.

For a barrage proposal to proceed in accordance with the requirements of the Habitats Regulations, it would need to demonstrate that there were no less damaging alternatives, that the project met the grounds for IROPI (Imperative Reason of Overriding Public Interest) and that all necessary compensatory measures could be delivered to secure the overall coherence of the Natura 2000 network.

Also in the Netherlands compliance with environmental requirements are necessary. In table 6.4 is presented whether the locations in the Netherlands are defined as valuable areas within the Habitats and Birds Directive or is defined as International Important Wetlands area within the Ramsar Convention.

Table 6.4 : Legislation (some) for Dutch Locations.

Location	Ramsar	Birds directive	Habitats directive
Brouwersdam (Grevelingen)	Yes	Yes	Yes
Lauwersmeer	Yes	Yes	No
Oosterschelde	Yes	Yes	Yes
Haringvliet	Yes	Yes	Yes
Afsluitdijk (Ijsselmeer)	Yes	Yes	No
Polders (Western Scheldt and Eems-Dollard)	Yes	Yes	Yes

In the Netherlands the following sequential approach has to be applied to developments affecting European Sites in the following order:
- Screen for likely significant effects on a European Site.
- Fully assess implications of a scheme if likely significant effects cannot be ruled out.
- Take measures to avoid or mitigate any adverse effects.

- If adverse effects cannot be eliminated, determine whether there are alternative solutions that avoid adverse effects.
- If there are no alternative solutions, determine whether a scheme is necessary for imperative reasons of over-riding public interest.
- If there are shown to be such reasons, take any necessary compensatory measures to protect the coherence of the Natura 2000 network of European protected sites.

The condition of a number of biological, chemical and physico-chemical components have to be defined according to the Water Framework Directive (WFD). It is possible that a tidal power scheme would change the condition of the components that define the status of the transitional and coastal water bodies in the river basin, and may alter some of the freshwaters too. The scale of the impact may mean that the WFD's objectives cannot be met in some of the water bodies. However, this does not necessarily mean that it is impossible to comply with the Directive. If the objectives of the WFD cannot be met article 4(7) of the Directive may apply. Article 4(7) provides that a Member State shall not be in breach of the Directive where failure to achieve good groundwater status, good ecological status or potential or to prevent deterioration in the status of a body of surface water is the result of new modifications to the physical characteristics of a surface water body and the following conditions are met:

- All practical steps are taken to mitigate the adverse effect on the status of the body of water;
- The reasons are explained in the River Basin Management Plans
- The reasons are of overriding public interest and/or the benefits to the environment and to society of achieving the objectives are outweighed by the new modifications to sustainable development; and
- The beneficial objectives cannot, for reasons of technical feasibility or disproportionate cost be achieved by other means which are a significantly better environmental option

Further investigation is needed to make a complete overview of legislation when implementing a tidal energy scheme. This is dependent on the activities and impacts. Environmental and Social Impact Studies are necessary to obtain a better insight. It is advised to investigate the possibilities to improve the ecological system AND minimize the environmental impacts. The involvement of stakeholders in an early stage is therefore important.

6.6 Role government

For the realization of tidal energy projects political support is needed. In the UK the two main parties keep a neutral position on tidal energy projects. This is considered as advantageous as the tidal project do not become the subject of political discussions. Given the differences between the political systems of the UK (two main parties) and the Netherlands (many parties) it is questionable whether it will be possible in the Netherlands to prevent that tidal projects will become the subject of extensive political debate. It is expected that many political parties will take a position in the early stages of the planning and the debate.

The government in the Netherlands is committed to produce electricity from renewable energy sources (20% by 2020). Tidal energy in the Netherlands offers an opportunity to achieve the aim to produce use more renewable energy sources in the future.

The government will have an important role in making a tidal energy plant viable. Earlier in this section the different roles of the government has been presented, being initiator, financer, regulator etc.

6.7 Knowledge gaps

Expertise to design and construct maritime works required for a tidal power plant is available in the Netherlands. In the UK this knowledge was used when designing tidal power plants. But both the UK and the Netherlands are not as experienced when it comes to turbine technology. This knowledge is available in France, Switzerland and Austria as many turbines in run-off river plants (quite similar to tidal power turbines) were built there. When designing a tidal power plant experts from these countries are required.

Fish mortality is often linked to turbine technology. Some possible reasons for fish mortality are known from run-off river plants. But fish populations in rivers and in marine environments differ quite a lot. And as there is only one large tidal power plant built, the effects on the fish population by placing a tidal power plant are not well known.

Additional studies are necessary to gain insight into the fish and also in mammal population, the impacts of a tidal energy scheme on those species (physical disturbance, noise, changes in biodiversity and habitat). and the way how to mitigate the impacts. The results can be used in the design of a tidal power plant to f.e. reduce fish mortality (fish passes, traps, etc.).

6.8 Summary (table)

Tidal energy in NL is promising notwithstanding the small tidal variations in NL when environmental benefits are valued. In table 6.5 an overview is given of the differences between the UK and the Netherlands.

Table 6.5 : Differences between UK and the Netherlands.

UK	NL
Economic and commercial viability	
Tidal Range high The UK is well suited to generating energy from its tidal energy output since it has high tidal ranges and high tidal currents in much of its nearshore waters.	Tidal ranges in the Netherlands are smaller than in UK.
Capital costs high. For example: capital costs of small schemes such as the Loughor Barrage (5MW) is estimated 25 million Euro, for the Severn (8640 MW) 17000 million Euro or approx. 2 million euro/MW.	Capital costs moderate. Dams do already exist in most of the tidal energy locations.
Installed capacity high. For example, the Severn barrage could produce 8640 MW	Installed capacity will be lower than in UK.
Unit costs of generation moderate positive. For example: the unit cost of generation for the Severn, with a discount rate of around 6% and a lifetime of 120 years is estimated approx. 7,5 eurocent / kWh, for Loughor around 12 eurocent/kWh.	Unit costs of generation higher than in UK
Cost-benefit ratio comparable with conventional energy sources. But according to reports in UK, all schemes would still require Government support through planning and possibly construction due to the sheer scale of capital costs and impacts.	Subsidies needed to make the cost benefit ratio comparable with conventional energy sources
Carbon pay-back Large schemes in particular could considerably reduce carbon dioxide emissions from energy supply, helping avoid dangerous climate change.	Carbon pay-back dependent on scale of scheme. Will be lower than in the UK.
Environmental impacts	
Proposed tidal energy schemes lay in valuable ecological areas. As a result the estuaries will be closed off partly.	Proposed tidal energy schemes lay in valuable ecological areas. Dams are already existing, estuaries will be opened partly.
Geomorphology. Impact on patterns and rates of sediment erosion, transport and accretion, thereby changing the morphology of the system and associated flora and fauna.	Geomorphology, less difference with reference situation than in UK.
Decrease of turbidity and increase of phytoplankton productivity (algae).	Decrease of phytoplankton productivity (algae).
Negative impact on fishes, marine mammals and birds (decrease or loss of feeding, breeding grounds and routes)	Impact on ecology. Difference to reference situation is less than in UK. Positive effect on marine mammals and birds. (Increase of feeding, breeding grounds and routes). Negative and positive effects for birds.
Landscape / seascape impacts	

Visual impacts in landscape (land based structures) and seascape (barrage / lagoon).	Hardly any visual impacts as barrages are already in place.
Other functions (transport, tourism, flood risk etc.)	
Social aspects / job creation	Idem, but less than in UK.
Combination with other functions is not always taken into account. Is not the main aim. Possibilities and interest available: road, tourism, flood risk.	Main aim of Dutch plans with barrages is to improve water quality and ecological circumstances. Multi-functionality plays important role in commercial viability (ecology, tourism, flood risk).
Role government and legislation (rules & regulations)	
Compliance with legislation such European Water Framework Directive, European Fisheries Directive, EU Marine Strategy and the EC Habitat and Birds Directive.	idem
Reduce carbon dioxide emissions.	idem
Neutral position of the two main political parties.	It is expected that most political parties in the Netherlands will take a position early in the planning
Government concessions and maximising benefits from ancillary beneficiaries (e.g. improved amenity, flood protection or transport infrastructure) could help schemes become more commercially viable.	Idem
Government is consulting stakeholders in the process of tidal energy.	Future activity; N.B. In the Grevelingen (Brouwersdam) studies involvement of stakeholders is already taken place.
Government intervention would be necessary to promote a scheme, placing costs on consumers and/or taxpayers. All schemes would require Government support through planning and possibly construction due to the sheer scale of capital costs and impacts.	Future activity

7 REFERENCES

Bestuurlijk Overleg Watervisie Lauwersmeer (BOWL). (2006) Watervisie Lauwersmeer.

British Trust for Ornithology (2006). British Trust for Ornithology website http://www.bto.org/webs/alerts/alerts2006/Results/UK9005131/siteaccount.pdf.

Collier M.P., Banks A.N., Austin G.E., Girling T, Hearn R.D. and Musgrove A.J. (2005). The Wetland Bird Survey 2003/04: Wildfowl and wader counts. BTO/WWT/RSPB/JNCC, Thetford.

Collins N.R. and Williams R. (1981). Zooplankton of the Bristol Channel and Severn estuary. The distribution of four copepods in relation to salinity. Marine Biology 64: 273-283.

Coull, K.A., Johnstone, R. and S.I. Rogers (1998) Fisheries Sensitivity Maps in British Waters, pp.58, UKOOA Ltd.

Countryside Council for Wales Swansea Bay Scoping response 23rd June, 2006. http://www.ccw.gov.uk

Countryside Council for Wales (2002). Development of a methodology for the assessment of cumulative effects of marine activities using Liverpool Bay as a case study, pp.77 http://www.ccw.gov.uk/Images_Client/Reports/ACF13B.pdf.

Creutzberg F. (1961). On the orientation of migrating elvers (Anguilla anguilla Turt.) in a tidal area. Netherlands Journal of Sea Research 1,3,1961,p.257-338.

Davies J (1998). Bristol Channel and approaches (Cape Cornwall to Cwn yr Severn Estuary tidal energy from non-barrage options Eglwys, Newport Bay) (MNCR Sector 9). In: Hiscock K (Ed). Marine Nature Conservation Review. Benthic marine ecosystems of Great Britain and the northeast Atlantic. Joint Nature Conservation Committee, Peterborough, pp.255-295.

Davies J (1990). Benthic marine ecosystems of Great Britain: a review of current knowledge. Western Channel and the Bristol Channel and approaches (MNCR coastal sectors 8 and 9). Marine Nature Conservation Review Report MNCR/OR/009, Nature Conservancy Council, Peterborough, 113pp.

Department of the Environment, Fisheries and Rural Affairs (2000). Quality status report of the marine and coastal areas of the Irish Sea and Bristol Channel. DEFRA website http://www.defra.gov.uk/environment/water/marine/uk/science/irishbristol/ index.htm

Department of Energy and Climate Change (2009). Severn Tidal Power Annex 2: Strategic Environmental Assessment Scoping Report. DECC/Pub 8777/0.5k/01.09/NP. URN 09/524.

Department of Energy and Climate Change, South West RDA and Welsh Assembly Government (2009). Phase One Consultation.

Department for Trade and Industry (2004). Atlas of UK marine renewable energy resources. A Strategic Environmental Assessment Report, December 2004. Report to the Department of Trade and Industry, 154pp.

Ecofys (2000). Kansen voor energiewinning uit getijde in de Oosterschelde.

Environment Agency (2005). Mersey Estuary Catchment Flood Management Plan – Scoping Report November 2005, Environment Agency, Bristol, 116pp. + Appendices 63pp.1&

European Wind Energy Association (EWEA) + consortium (2009). Wind energy, the facts. The economics of wind energy. WindFacts is a European project financed by the Intelligent Energy - Europe programme of the Executive Agency for Competitiveness and Innovation that runs from November 2007 to October 2009.

Evans, S E, Poole, J E P and Williams, K P (2007). The North Wales offshore tidal impoundment scheme: a preliminary study of requirements, constraints and opportunities.
http://walescoastalpartnership.sequence.co.uk/images_client/resource/North%20Wales%20Offshore%20Tital%20Impoundment. Doc

Henderson PA (2003). Background information on species of shad and lamprey. Countryside Council for Wales Marine Monitoring Report No.7, Bangor, 30pp. A1.21
JNCC (Joint Nature Conservation Committee) (1999). Seabird vulnerability in UK waters: Block specific vulnerability. Joint Nature Conservation Committee, Aberdeen, 66pp.

Intergovernmental Panel on Climate Change: Climate Change 2007: The Physical Science Basis; February 2007.

Joint Nature Conservation Committee (1999). Seabird vulnerability in UK waters: Block specific vulnerability. Joint Nature Conservation Committee, Aberdeen 66pp.

Joint Nature Conservation Committee (1994). British coasts and seas, Region 13: Northern Irish Sea, pp.182, Coastal Conservation Branch, Peterborough.

Jones PD (2006). Water quality and fisheries in the Mersey estuary, England: A historical perspective. Marine Pollution Bulletin 53: 144–154.

Kooman, D. ir. (1975). Getijcentrale Oosterschelde, nota W-75.060, Rijkswaterstaat, Deltadienst. Waterloopkundige afdeling.

Laing I., Walker P. & Areal F. (2005). A feasibility study of native oyster (Ostrea edulis) stock regeneration in the United Kingdom. CARD Project FC1016 Native oyster stock regeneration - A review of biological, technical and economic feasibility. CEFAS 97pp.

Langston W.J., Chesman B.S. and Burt G.R. (2006). Site characterisation of European marine sites: The Mersey Estuary SPA. Marine Biological Association Occasional publication No. 18. Plymouth Marine Science Partnership, Plymouth, 190pp.

Langston W.J., Chesman B.S., Burt G.R., Hawkins S.J., Readman J and Worsfold P (2003). Site characterisation of the south west European marine sites: Severn Estuary pSAC, SPA. Marine Biological Association Occasional publication No. 13. Plymouth Marine Science Partnership, Plymouth, 206pp.

Mackie A.S.Y., James J.W.C., Rees, E.I.S., Darbyshire T., Philpott S.L., Mortimer K, Jenkins G.O. and Morando A. (2006). The Outer Bristol Channel marine habitat study. Studies in marine biodiversity and systematics from the National Museum of Wales. BIOMÔR Reports 4. National Museum of Wales, Cardiff, 249pp. plus Appendix 228pp.

Marshall J.E.J. (1999). West Coasts of England and Wales Pilot, 14th Edition. Admiralty Charts and Publications, United Kingdom Hydrographic Office, Taunton,311pp.

Metrotidal Ltd (2008). An integrated Lower Thames Tunnel solution for the Thames gateway. Metrotidal. London. 13 pp.

Mooyaart, L.F. (2009). De Energiepolder. Haalbaarheidsstudie naar een getijcentrale langs de Westerschelde. TU Delft (master thesis). Delft.

Moore A., Mead T.A. and Talks L. (1998). The migratory behaviour of wild Atlantic salmon (Salmo salar L.) smolts in the River Test and Southampton Water, southern England. Hydrobiologia 371-372: 295 – 304.

Noortgaete, Tom van den (september, 2009). Overzicht stand van techniek voor kleinschalige waterkracht. Machines toepasbaar voor kleinschalige waterkracht. Royal Haskoning, in opdracht van Deltares. Projectnummer 9V3951A0.

Northen K, Moore J and Little M (1998). Severn estuary. In: Moore J, Smith, J, Northen K and Little M (eds.). Marine Nature Conservation Review Sector 9, Inlets in the Bristol Channel and approaches: area summaries. Joint Nature Conservation Committee, Peterborough, pp.51-65.

NWP Offshore (2002). North Hoyle Offshore Wind Farm Environmental Statement Non Technical Summary, pp.12

Pawson MG, Pickett GD and Walker P (2002). The coastal fisheries of England and Wales, Part IV: A review of their status 1999-2001. Science Series Technical Report No. 116, Centre for Environment, Fisheries and Aquaculture Science, Lowestoft, 83pp.

Pethick J & Thompson A (2002). Some aspects of the geomorphology and sediment dynamics of the coast of south east Wales. Report no. 140/57472/OD/11/Draft 02. Supplementary report to The Welsh Assembly Government. Symonds Group Limited, 24pp plus appendices.

Priede, I. G., De L.G. Solbe, J. F., Nott, J. E., O'Grady, K. T., and Cragg-Hine, D (1988). Behaviour of adult Atlantic salmon, Salmo salar L., in the estuary of the River Ribble in relation to variations is dissolved oxygen and flow. Journal of Fish Biology 33 (Supplement A) 133-139.

PZEM, ECN, Rijkswaterstaat (1981). Rapport ENERGO-project.

Reid J, Evans PGH and Northridge S (2003). An atlas of cetacean distribution on the northwest European continental shelf. Joint Nature Conservation Committee, Peterborough, 77pp.

Rijkswaterstaat Oosterscheldewerken, “Drie Maandelijks Bericht Deltawerken”. Een getijcentrale in de Oosterschelde? In Dutch. Date unknown.

Rijkswaterstaat, Provincie Noord Holland en Provincie Fryslân (2009). Dijk en Meer.

Solomon, D.J. (1988). Fish Passage through Tidal Energy Barrages, ETSU TID 4056.

Sustainable Development Commission (2007). Turning the Tide: Tidal Power in the UK. October 2007. 148pp.

Sustainable Development Commission (2007a). Tidal Power in the UK. Research Report 1 – UK Tidal Resource Assessment. October 2007. 125pp.

Sustainable Development Commission (2007b). Tidal Power in the UK. Research Report 2 – Tidal Technologies Overview. October 2007. 152pp.

Sustainable Development Commission (2007c). Tidal Power in the UK. Research Report 3 - Severn Barrage Proposals. October 2007. 250pp.

Sustainable Development Commission (2007d). Tidal Power in the UK Research Report 4 - Severn non-barrage options. An evidence-based report by AEA Energy & Environment for the Sustainable Development Commission. October 2007. 106pp.

Sustainable Development Commission (2007e). Tidal Power in the UK. Research Report 5 - UK case studies. October 2007. 153pp.

Tappin DR, Chadwick RA, Jackson AA, Wingfield RTR and Smith NJP (1994). United Kingdom offshore regional report: the geology of Cardigan Bay and the Bristol Channel. HMSO for the British Geological Survey, London, 107pp.

TU Delft (2007). Naar een energiegestuurd omgevingsplan Groningen. In opdracht van Provincie Groningen.

Vrijling et al. (2009). Getijdecentrale in de Brouwersdam, TU Delft.

Watkins H & Colley R (2004). Harbour porpoise Phocoena phocoena occurrence: Carmarthen Bay-Gower Peninsula-Swansea Bay, December 2002-February 2004. Gower Marine Mammals Project 98pp.

White Consultants (2001). Seascape character project: Swansea Bay. Final report for Countryside Council for Wales 32pp.

Williams R and Collins N.R. (1986). Seasonal composition of meroplankton and holoplankton in the Bristol Channel. Marine Biology 92: 93-101.

Witteveen en Bos (2009). Verkenning Grevelingen water en getij.

=0=0=0=